# An Eco-Design and Innovation Feasibility Study of Low-Carbon Illumination Technologies for the Tertiary Sector in Denmark

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# An Eco-Design and Innovation Feasibility Study of Low-Carbon Illumination Technologies for the Tertiary Sector in Denmark

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To

Anders, Kristian and Sophia

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# Abstract

This thesis presents an eco-design and innovation feasibility study that focuses on the Danish lighting sector. The main general research objective is: To identify possibilities for further innovations that can contribute to reducing $CO_2$ emissions and reduce the use of fossil fuels. An integrated objective is to contribute by discussing the elements that a new framework for eco-design and innovation feasibility studies could provide to the evaluation of technologies that will facilitate a response to the climate, energy and economic development challenges the illumination sector in Denmark faces today.

To achieve these goals, this study integrates three different levels of systemic analysis: Firstly, the product system analysis, where technological possibilities to improve energy efficiency are discussed and new technological improvements identified. Secondly, it takes into consideration the product-service system, where the new technological improvements are assessed in relation to consumers' needs and relevant technological and institutional capacity. Finally, this study uses a technological-innovation system perspective to assess existing conditions for the establishment, further development and implementation of new illumination technologies.

The study uses both quantitative and qualitative methods, since it is directed towards an understanding of the technological aspects when designing concrete solutions aimed at reducing environmental impacts by improving energy efficiency, while at the same time, focusing on the structural and qualitative elements of the technologies. Thus, this analysis takes into consideration consumer preferences, policy instruments, and innovation system structural conditions as the material or hardware technological aspects to be considered when designing and innovating low-carbon technologies to solve current environmental and energy global challenges. The main empirical material to develop this research is obtained on the basis of an intensive/participatory case study.

The practical results of this work can be summarised as follows: It contributes to the development of a new emerging technology, bringing together and activating a group of relevant actors and their capacity to continue developing such solutions. Finally, the work discusses the relevant elements to be considered in a more general framework for a low-carbon technology feasibility analysis.

# Abstrakt

Denne afhandling præsenterer et øko-design og -innovations feasibility studie, som fokuserer på den danske belysningssektor.

Det overordnede mål for den centrale forskning i det beskrevne arbejde var: At identificere, hvor der er muligheder for yderligere nyskabelser, der kan bidrage til at reducere $CO_2$-udledningen og til at reducere brugen af fossile brændstoffer. Det var et integreret formål at diskutere de elementer, som en ny ramme for øko-design og -innovations feasibility studier kan bidrage med i forhold til at vurdere de teknologier, der kan hjælpe med svar på udfordringer indenfor klima-, energi-, og økonomisk udvikling, som belysning sektoren i Denmark står overfor i dag. For at nå disse mål, integrerer denne undersøgelse tre forskellige niveauer af systemisk analyse: For det første benyttes en produkt-system analyse, hvor de teknologiske muligheder for at forbedre energieffektiviteten diskuteres, og nye teknologiske forbedringer identificeres. For det andet inddrages en produkt-service system analyse, hvor de nye teknologiske forbedringer vurderes i forhold til forbrugernes behov og relevant teknologisk og institutionel kapacitet. Formål er at pege på udviklingen af mere bæredygtige teknologiske løsninger inden for belysningssektoren. Endelig, integrerer denne undersøgelse et teknologisk-innovationssystem perspektiv med henblik på at vurdere betingelserne for at etablere og videreudvikle de teknologier, som der er fokus på i dette studie, altså belysningsteknologi udvikling af denne.

I undersøgelsen anvendes både kvantitative og kvalitative metoder, idet undersøgelsen skal bidrage til en forståelse af de teknologiske aspekter, der bør indgå, når man designer konkrete løsninger, som har til formål at reducere miljøbelastningen ved at forbedre energieffektiviteten. Samtidig fokuseres der på strukturelle og kvalitative betingelser for at muliggøre teknologiernes udvikling og implementering.

Således tager denne analyse hensyn til forbrugernes præferencer, de politiske instrumenter og innovationssystemets strukturelle betingelser, såvel som til materielle eller hardware teknologiske aspekter, når designes og innoveres det nødvendige kulstof reducerende teknologier til at løse de aktuelle miljø- og energi globale udfordringer.

Det vigtigste empiriske materiale til at udvikle denne forskning er opnået via et intensivt/ participatorisk studie.

Resultaterne af dette arbejde kan opsummeres på følgende måde: Det bidrager til udviklingen af en ny teknologi, og giver input til at en gruppe relevante aktører kan fortsætte med at udvikle sådanne løsninger. Endelig rejser afhandlingen en diskussion af relevante elementer, der kan indgå i en mere generel ramme for kulstof reducerende teknologiers udvikling og implementering.

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# Abbreviations and acronyms List

| Abbreviation/ Acronym | |
|---|---|
| | |
| BAT | Best Available Technology |
| BNAT | Best Not yet Available Technology |
| CD | Compact Disc |
| CFLs | Compact Fluorescent lamps |
| $CO_2$ | Carbon dioxide |
| DTU | Technical University of Denmark |
| EEA | European Energy Agency |
| EIA | Energy Information Administration |
| ENSPAC | Environmental, Social and Spatial Change |
| -eq | equivalents |
| EUPs | Energy Using Products |
| GDP | Growth development product |
| GER | Total energy requirement |
| GHG | Green house gases |
| HFOLS | Hybrid Fibre Optic Lighting System |
| Hg | Mercury |
| LCA | Life Cycle Assessment |
| LCC | Life cycle Cost Assessment |
| LEDs | Light emitting diodes |
| LFL | Linear Fluorescent Lamp |
| Lm/W | Lumen /watt |
| MU | Multiple Users (office) |
| OECD | Organization for Economic Co-operation and Development |
| OPEC | Organization of Petroleum Exporting Countries |
| PAHs | Polycyclic aromatic hydrocarbons |
| PM | Particulate Matter |
| POC | Proof of Concept |
| POPs | Persistent Organic Pollutants |
| RoHS | Restriction of Hazardous Substances (Directive) |
| SFOS | Solar fibre optic system(s) |
| SU | Single users (office) |

| | |
|---|---|
| TIS | Technological Innovation System |
| TIN | Technological innovation Network |
| UF | Utilization Factor |
| VHK | Van Holsteijn en Kemna BV |
| VOC | Volatile Organic Compounds |
| WEEE | Waste Electrical and Electronic Equipment |
| WMO | World Meteorological Organization |

Chapter 1

# Introduction

2012 will mark an important year in the history of illumination in EU. In this year, the sale of the most energy inefficient bulbs for general lighting will be phased out. This is an example of measures that are taken by the European Union aiming to achieve a transition to a low-carbon economy in the view of the already imminent effects of climate change. In order to achieve this transition, the design and implementation of new disruptive technologies will play a central role.

The disruptive and incremental technological challenges to be addressed in this transition are climate change, the energy self-sufficiency goal, and the need for sustainable economic growth. An additional challenge is to avoid worsening the level of services to which the consumers are already accustomed. In other words, the challenge is to provide the same or even better level of services to consumers by enhancing the environmental performance of technologies. In order to make a more sustainable technological planning in the context of this global transition, it is imperative to have a methodological framework that helps to identify technologies that can ensure a realistic sustainable growth.

To make the technological design and implementation of new low-carbon technology solutions possible requires the assessment of parameters, such as the material characteristics for the technologies, their subsequent environmental impact, their level of service quality, their potential for further development, and the regulative, market and financial conditions that can facilitate such implementation. In other words, studies of this kind will need to be supported by different forms of feasibility studies.

Traditionally, a feasibility study has been defined as: An analysis and evaluation of a proposed project to determine, if it (1) is technically feasible, (2) is feasible within the estimated cost, and (3) will be profitable (Business dictionary.com). This concept, however, is mainly applied within a company perspective, whereas for it to be applied within a societal perspective, turns out be too narrow, and therefore insufficient.

Designing, developing, and implementing environmental solutions produce other spillovers for the society than just economic benefits for companies. Therefore, it is important to have a broader feasibility method of analysis. What is relevant for eco-design and innovation studies that seek sustainable environmental solutions is to go beyond considering private goods by also considering public goods.

This necessity is reflected, when other additional feasibility analyses, such as, environmental feasibility, technological feasibility, or social feasibility are requested, when applying for funding for projects which aim to develop cleaner technologies (e.g. Green Growth OECD and World Bank projects and/or CDM projects). In order to be able to present feasibility studies that are interconnected and that can provide a more integrated view of the challenges and possibilities for this technological transition, it is imperative to use a holistic framework that can include all these aspects.

The need for more holistic approaches is, for example, reflected in requirements that the World Bank does in its guidelines for the life cycle of a project. The guide emphasises that project management should be supplemented by: economic, technical, institutional, financial, environmental and social feasibility studies (WB 1997). The same situation arises in the call for tenders in the areas of innovative procurement, green growth, clean-tech innovation, etc., when seeking funding from the EU (e.g. www.europroc.eu). The Innovative Actions Network for the Information Society has published one of the few guides available on this subject (ERISA n/d), however, this only includes technological, economic and financial aspects.

Confronting the climate, energy and innovation challenge will require having the analytical tools to evaluate the alternative emerging technologies while considering the availability of resources, and a technological design that reduces the environmental impacts of the service being delivered. It will also need to consider the socio-economic conditions for the design, development and implementation of such technologies. These processes will have to go hand in hand with public and private funds. Consequently, it is not only a question of providing insight for private profitability, but rather determining how the initiatives can contribute to enhancing public prosperity (including profitability) for which a new conceptualisation of feasibility studies that encompasses these issues needs to be created.

This chapter begins by identifying the main problems and considerations that cleaner technologies in the illumination sector need to resolve in order to formulate a new eco-design and eco-innovation feasibility concept. It further discusses the elements that must be considered and integrated in order to enhance the design and innovation of more sustainable technological solutions in this sector. The chapter concludes by focusing on the research area, in order to formulate the research objectives and the research question for this thesis.

## 1.1 PROBLEM AREA

### 1.1.1 Climate Change

Climate change has been on the political agenda for *at least three decades*. Some of the pioneering formal efforts to politically address climate change can be traced back to 1979 to the first "World Climate Conference" organised by the World Meteorological Organisation (WMO). In 1992, climate change was formalised in the Rio Convention, during the Earth Summit, addressing three interlinked issues, namely climate change, biodiversity and desertification. In those days, the measures for reduction of emission started as voluntary agreements setting non-mandatory limits (Agrawala 1998).

As the emissions continued to increase, so did the discussions about how to solve the problem. In 1997, with the Kyoto Protocol, limitations on greenhouse emissions were listed for developed countries and economies in transition. The emission-reduction commitments were set at 5% below 1990 levels, to be achieved between the years 2008-2012. Once the discussion turned to having binding agreements, the process of action became slow and burdensome. From 1997 to 2000, the negotiations had almost stagnated. The most notable result of these discussions during this period was the rejection of the Kyoto Protocol by the USA (McKibbin and Wilcoxen, 2002).

In 2002 the EU agreed to cut 8% of greenhouse gases (GHG) on average from 1990 emissions levels during 2005 to 2012 (COM, (2003)85).

Some of the main concerns, and specially those stated in the 2002 report from the European Agency "*Energy and environment in the European Union*" (EEA 2002:9) were the pressure that the production and consumption of energy was setting on the environment, including, among other impacts, climate change, impacts on natural ecosystems and human health. Consequently, this report suggested that European policies pursue the following three goals:

- security of supply
- competitiveness
- environmental protection (EEA 2002:9)

After long negotiations (almost 8 years) the Kyoto Protocol entered into force on February 2005. The EU announced the goals again in 2007 as part of the European Union policy to further cut $CO_2$ emissions, and in 2008, the EU agreed cut of 20% from 1990 levels by 2020, together with a 20% renewable target. In January 2008, the European Commission proposed binding legislation to implement the 20-20-20 targets (COM (2010) 265 final).

Yet, the document named "Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage" (COM(2010) 265) states that, in order to maintain the 2.0 °C global warming limit, the industrialised countries, including those belonging to the EU, should cut 80-95% of their emissions by 2050.

In February 2011 the European Council reaffirmed its intention of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990. However, taking into account the necessary efforts from developing countries, this reduction will mean only 50% in the emissions by 2050 (COM(2011) 885/2)

According to the EU's Roadmap for moving to a competitive low carbon economy in 2050, "Emissions, including international aviation, were estimated to be 16% below 1990 levels in 2009. With full implementation of current policies, the EU is on track to achieve a 20% domestic reduction in 2020 below 1990 levels, and 30% in 2030. However, with current policies, only half of the 20% energy efficiency target would be met by 2020". (COM(2011) 885/2).

Despite the good intentions of the European Union, according to the EEA: "Projections from Member States, indicate that total EU emissions will not be significantly reduced until 2020: with the current set of national domestic measures in place, the EU will reach in 2020 a level 19 % below 1990 levels, close to its 20% reduction target" (EEA Report No 4/2011).

In spite of the EU emissions reduction efforts, 2011 was again a year with record high global $CO_2$ emissions (IEA, 2011). Further as the EU's Roadmap for moving to a competitive low-carbon economy in 2050 points out: the energy efficiency still remains one of the biggest challenges to achieving this transition.

### 1.1.2 World energy demand

About 96.5% of the $CO_2$ emissions come from the use of fossil fuels due to energy-related activities (EU.org 2011). With the increasing population in China and India alone, and the raise in income for their populations, it is expected that the urbanisation process in these countries will also increase, with giant steps towards increased energy consumption (see Figure 1.1).

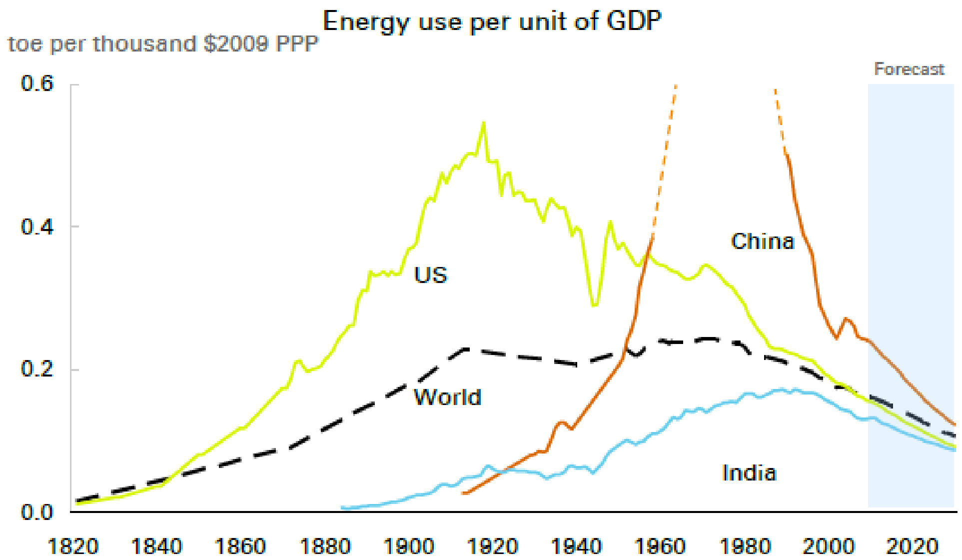


***Figure 1.1:*** *World Electricity Consumption (BP, January 2011)*

Today, electricity plays a very important role as the new disruptive technology when compared to preindustrial and industrial times, where coal and the steam engine went hand in hand.

The International Energy Outlook 2011 reference case states: "electricity supplies an increasing share of the world's total energy demand, and electricity use grows more rapidly than consumption of liquid fuels, natural gas, or coal in all end-use sectors except transportation. From 1990 to 2008, growth in net electricity generation outpaced the growth in delivered energy consumption (3.0 percent per year and 1.8 percent per year, respectively). World demand for electricity increases by 2.3 percent per year from 2008 to 2035, and continues to outpace growth in total energy use throughout the projection period" (DOE/EIA., 0484., 2011) as shown in Figure 1.2.

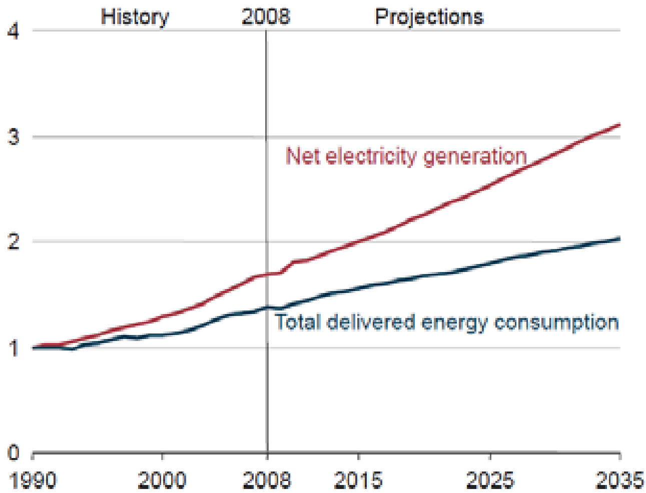


***Figure 1.2:*** *Development and projections of growth in world electricity generation and total delivered energy consumption, 1990-2035 (index, 1990=1). Source (DOE/EIA., 0484., 2011)*

Yet electricity worldwide is still mainly based on fossil fuels with a share of 69% (OECD/IEA, 2011). According to the International Energy Outlook 2011, coal continues to be the fuel most widely used for electricity generation (DOE/EIA., 0484., 2011). Therefore, it is imperative to find more sustainable solutions to reduce this trend.

The yearly World Outlook Report emphasises that in 2010, Global energy-related carbon-dioxide ($CO_2$) emissions had already reached 30.4 Gt, which is 5.3% above the 2009 level. This level increase represented almost an unprecedented annual growth. This report adds, that even with the New Policies Scenario[1], $CO_2$ emissions continue to increase, reaching an expected 36.4 Gt in 2035 and leading to an emissions trajectory consistent with a long-term global temperature increase of more than 3.5°C (OECD/IEA, 2011).

In order to generate one conventional unit of electricity for the use phase, 2.5 units of energy have to be used. Therefore, saving energy and reducing $CO_2$ emissions should be one of the highest priorities when designing and implementing all types of new energy using technologies.

### 1.1.3 Resource availability, environmental impacts and health risks

The resources to produce energy play an important role in sustaining the current quality of life that we have become used to. This availability is due to geographical distribution, the availability of resources, and the Earth's bio-capacity to renew the necessary resources to supply the raw materials for production, as well as to absorb the waste produced. This is an important issue, as even when we talk about renewable energy and the fact that there is plenty of solar energy or wind energy, the raw materials still need to be acquired, and these are limited by spatial, geographic and political boundaries. When these issues are considered, sustainable technological responses to such challenges and conscientious production and consumption are important.

Worldwide, the oil reserves-to-production ratio is estimated at 46.2 years, the world natural gas reserves-to-production ratio is estimated at 63 years. However, the EU gas domestic production proved reserves at current production rates that are estimated to only be secure for between 14 to 15 years from 2008. The coal reserves-to production ratio is 133 years (BP, 2011). However, using any kind of fossil fuel is problematic in relation to greenhouse gas (GHG) emissions.

It is a fact that the EU's energy production can hardly support half of its needs. The EU is still one of the biggest oil and gas consumer regions of the world (BP,

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1 This scenario takes into account recently announced commitments and plans, even if they are yet to be formally adopted and implemented (OECD/EIA., 2011)

2011). In ten years (1999-2009), EU-27 dependency on imported energy grew, reaching 53.9% in 2009. This represented an increase of 9 percentage points from 1999. In 2009, the EU-27 dependency on oil imports was 83.5%, which was an increase of 11 percentage points from 1999, while dependency on coal was 62.2% in the same year (Eurostat, 2011).

Further pressures to resource availability are due to the geographical and political situation of the main oil suppliers (see Figure 1.3). The main suppliers are South and Central America and the Middle East. The fact that main suppliers are from these regions, which include developing countries, means that they will require the resources themselves in order to continue developing.

The proven uranium world reserves are estimated to last for 100 years at the current production rate. However, the European Union only counts with 1.9% of the world current reserves [COM 13-11-2008]. Therefore, uranium is a non-strategic resource, if the EU is looking at being energy self-sufficient.

Energy is a basic resource, since it is considered vital for production and reproduction of the quality of human life. Consequently, it is important to replace the use of fossil fuels as much as possible, both for environmental reasons and also to ensure a self-sufficient energy supply.

***Electricity sector main environmental impacts***

Electricity generation accounts for 41% of the total world $CO_2$ emissions for fuel combustion (see Figure 1.4).

From 1995 to 2009, due to the consumption of electricity, $CO_2$ emissions grew by 138.4% (OECD/IEA, October 2011).

As electricity security of supply depends on fossil fuels, it makes it imperative to reconsider, how we are using resources, while we have them. It also makes it necessary to plan more sustainable alternative technologies and energy sources. The illumination sector has to take into account that the resource availability scenario is changing, and we have to design products for a post-fossil fuel era. This means that the supply might not be endowed by the same conventional plants, and supply sources might vary from conventional sources. The traditional electric grid and the voltages of supply might also be re-adapted for a new generation of illumination devices.

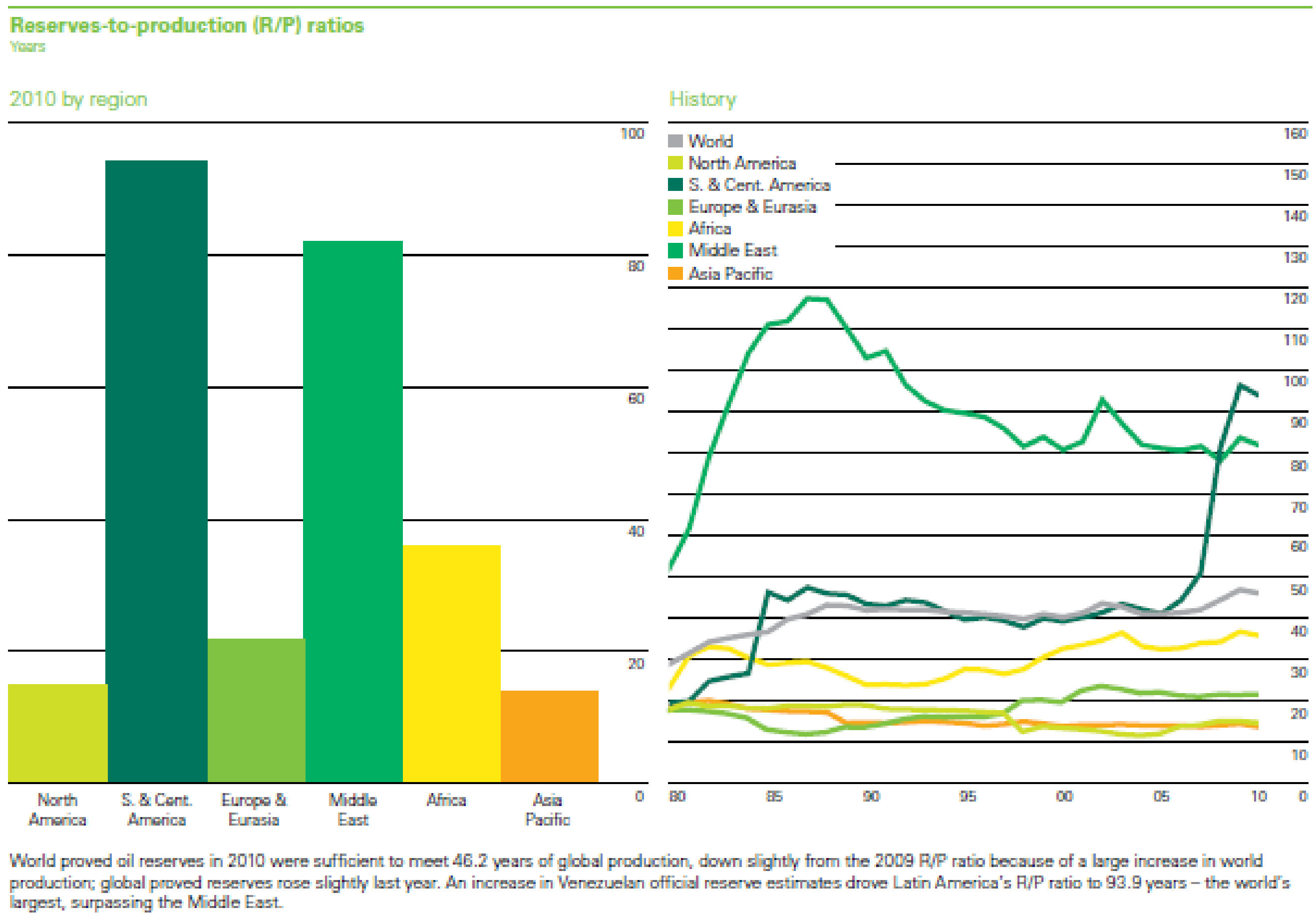



***Figure 1.3***: *Proven oil reserves at the end 2010 (Thousand million barrels). Source (BP, 2011).*

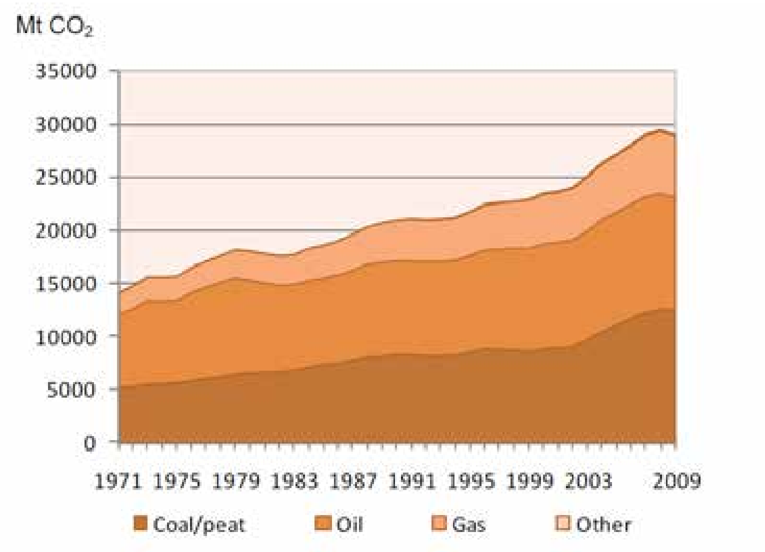



***Figure 1.4:*** *$CO_2$ emissions by sector (OECD/IEA, October 2011)*

***Other environmental impacts and health risks***

Global climate change is not the only environmental impact caused by the generation of electricity. Environmental impacts such as: acid rain, urban smog, and health risks are other important effects arising from this kind of energy use. In fact, on a global scale, some of the most important emissions, excluding $CO_2$ emissions, are: sulfur dioxide, NOx emissions, and mercury emissions (Bradley & Associates, 2010; EPA, 2009).

Illumination uses one fifth of the electricity produced globally. With the accelerated urbanisation of growth in countries such as China and India, it is imperative to focus on this sector. Consequently, even when global policies focus only on one side of the problem ($CO_2$ emissions); one should not ignore materials, chemical and other resources.

## 1.1.6 Socio-technological issues

In order solve the climate change and the global energy problem, different governmental initiatives have encouraged the design and production of more energy efficient technologies (e.g. Ecodesign Directive (2009/125/EC)). There is a broad consensus that one of the solutions to the current environmental challenge will be based on the use of low-carbon technologies (COM(2011) 885/2). Even though there is substantial potential to adopt more sustainable design and innovation, there are several elements that need to be taken into account to achieve efficient reductions of energy and $CO_2$ emissions. Several studies (Sandhal et al. 2006; Mert et al. 2008; Lefèvre et al. 2006) have pointed out that, besides technological characteristics, some of the main historical barriers to the successful implementation of energy saving devices have been lower competitive price and quality when compared to current market devices. Consequently, when looking at the possibilities for technological alternatives, one should look at improvements that can fulfil these specific client demands.

### 1.1.7 Technological and practical considerations

The high speed at which humanity has to react to the climate and energy challenge demands that sustainable and reflective solutions are found, developed and implemented. This requires solutions that can respond to real social problems for which a problem-oriented approach is imperative.

In order to make realistic technological suggestions, it is also important to be able to have an idea about the technological and practical applicability of the technology. In other words, in theory, many technological solutions could be more energy efficient than the current ones, but questions about their creation and their implementation have to be answered. Examples of these questions include: Can the necessary components be found at the right time? Have the complementary technological parts and components reached a mature enough level of development? Can the technology be easily installed? Can it last as long as it is claimed in advertisements? Can it be removed without problem, if it does not work at all? Have the technical personal skills been developed to install and manage the system? These considerations cannot be resolved without an explorative research, and they have to be tested. The way this thesis approached these considerations was by making suggestions and through personal involvement in two externally-financed research projects to develop an application using the technologies in which this thesis focuses.

### 1.1.8 Low-carbon technologies design and innovation

One of the approaches to integrating environmental concerns in relation to consumer demands has been the concept of Eco-design (see Box 1). This concept is reflected in the eco-design directives published by the European Union, particularly in the sector which this thesis focuses on: Eco-design directives for lamps, energy using products, for reducing the mercury content, etc.

> Box 1
>
> "Eco-design aims to combine business oriented design goals and environmental considerations *(Karlsson and Lathrup, 2006).*

The eco-design approach is oriented towards company customisation, organisation and commitment. However, it does not take into consideration the new socio-technological organisation that will be required to sustain the design, development and launch of the new eco-designed products.

Several authors agree that it is important to differentiate invention from innovation. They point to the central issue that innovation is the process of bringing the product to the *market* (Rogers, 2003; Rennings, 2000).

During that process, the product might be redesigned several times and tested in the market, before being launched. Though the emergence of the eco-innovation concept was more like a synonym of eco-design (considering environment and company economy), the meaning of the term has broadened to include the corresponding evolution of social arrangements and institutional support structures (Hellstrom, 2007; Mashiba, 2010).

As an example, the European Union Eco-innovation Action Plan 2011 has as a new objective in its pursuit of eco-innovation: to accelerate eco-innovation in a way "that boosts resource productivity, efficiency, competitiveness and helps to safeguard the environment!"( COM(2011) 899).

Consequently, if the objective is to formulate answers to the current environmental challenges without affecting economic growth, realistic low-carbon feasibility studies should consider assessing if the suggested technologies can help to attain the desired societal goals. Feasibility studies should also consider if the necessary social arrangements and institutional support structures exist and are of good quality.

### 1.1.9 Eco-design and innovation feasibility study definition

In order to be able work with the different feasibility levels of an analysis in this specific problem area, and in the absence of a specific concept, the author of this thesis suggested a new conceptualisation of an eco-design and innovation feasibility analysis. This concept was developed from the theoretical and methodological considerations that were developed for this thesis and from testing this framework on the basis of an intensive/participatory case study. The eco-design and innovation feasibility study is defined by the author as follows: A study which can equip policy makers and funding institutions with a broad knowledge-base of the material (environmental, resource, and risk health) impacts of a technology, the potential of the technology to improve the product-service (value) for consumers and the society, and the innovation framework conditions for a realistic implementation. These issues should be considered when taking decisions about cleaner technologies that can be financially and politically supported in order to reach climate, resources and sustainable development goals.

## 1.2 RESEARCH AREA

Lighting is a symbol of modernity and urbanisation. Many productive activities had never been possible without illumination. Reading, learning, working, selling, making businesses and even having fun would be very difficult without illumination. The main objective of this section is to identify the main problems within the illumination sector. The aim of this is to identify the strategic areas where changes need to be made in order to select the most relevant technological alternatives that can further contribute to reducing the environmental impacts of this sector in a more sustainable way.

### 1.2.1 Geographic delimitation

The study focuses on Denmark for the following reasons:

- It is one of the EU countries that has shown active political interest in developing low-carbon technologies.
- It is one of the countries with higher $CO_2$ emission reductions goals
- It has one of the highest international levels of research expertise in the photonics and environmental sectors
- The tradition of Danish lamp design is acknowledged worldwide

### 1.2.2 Why lighting technologies?

In 2007, global lighting accounted for 19% of the total electricity consumption, and its consumption of electricity was responsible for the emission of 6,000 Mt $CO_2$ (IEA, Aug 2007). In Europe, greenhouse gas emissions related to energy are rising again after they had shown a minor improvement (decrease of emissions) in the 1990s, stressing the long-term reduction targets (OECD/IEA, October 2011). Therefore, finding strategies to reduce the environmental impact of the energy used for illumination is highly relevant. Even more important is the need to focus on the right sector – meaning the sector where the largest potential for greenhouse gas emissions exists. As already stressed in 2006, the European Environment Agency (EEA) has pointed out that the growth in the service and trade sectors has been one of the causes of the increasing emissions related to electricity consumption, and lighting is an important share of this (EEA. (8/2006)). Yet most attention for the reduction of electricity consumption from lighting has been targeted at the household sector. During the development of this project, the tendencies in the energy sector have remained the same. In the EU, the Service and Trade sector continues showing the greatest growth in consumption, while the household sector has maintained moderate growth (Eurostat, 2011).

### 1.2.3 Research focus

Figure 1.5 shows that, in Denmark, the sector with the largest growth in electricity consumption from 2009 to 2010 was the trade and service sector (27.4%), while the household sector grew more modestly (2.9%) in the same period (Energistyrelsen, 2011).

In 2010, the total consumption of electricity in the household sector was of 36,738 TJ, while in the trade and service sector, it was 38,407 TJ. Recent information for the consumption of electricity by sector and appliance use is scarce (Bjarklev et al. 2009). However, the latest information in relation to that topic pointed out that average household electricity use for illumination is 11.6% (Danskenergi, 2009), whereas the trade and energy sector uses an average of 35% of electricity for lighting (Munck and Clausen, 2009). This means that, in real terms, electricity consumption for lighting in the household sector is about 4,260 TJ, while for the trade and service sector it is 13,442 TJ, according to electricity data from 2010. Thus, the trade and service sector uses three times more electricity than the household sector for lighting, and it is the sector with the faster growth rate.

***The reduction of energy in absolute terms***

The European Environmental Agency (EEA) defines improvements in energy efficiency as: "the use of less energy input to provide the same level of energy service" (EEA, 2007:3328). The European Environmental Agency suggests achieving this by using compact fluorescent bulbs. Alternatively, EEA argues that: "Improvements in

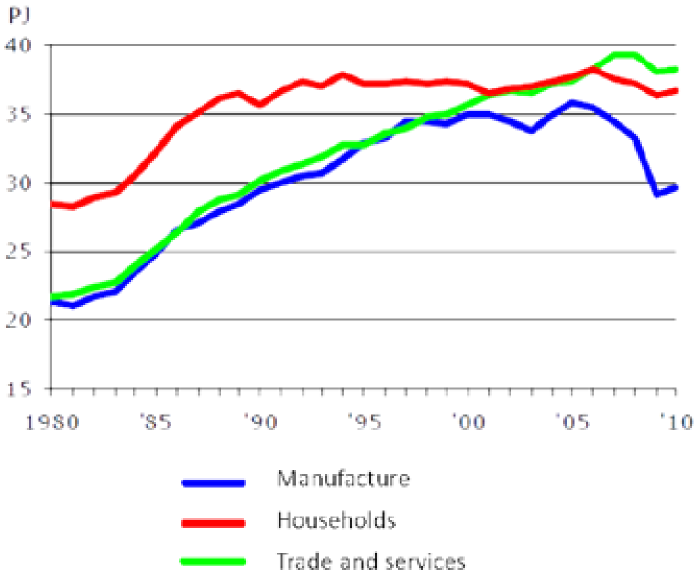



***Figure 1.5:*** *Danish electricity consumption growth by sector. Source Energistyrelsen, 2011.*

energy efficiency can be offset by increased demand. The goal is not just to improve energy efficiency or reduce energy intensity but to achieve energy savings, thus reducing energy consumption in absolute terms" (EEA, 2007:3328). Therefore, the use of daylight represents a very interesting potential to increase energy efficiency.

### *Energy losses*

As can be appreciated from Figure 1.6, the life cycle of electricity production (from the production phase to distribution and final consumption) has important losses. "Energy losses from transformation are significant, accounting for as much as a third of all the energy used in the EU. Average transformation efficiency for electricity generation is only around 40%, while losses in the transmission and distribution of electricity are often as high as 10%" (OOPEC, 2007). The import of energy also constitutes an important source of the energy production system However, it is not specified how much of this energy is also produced using non-

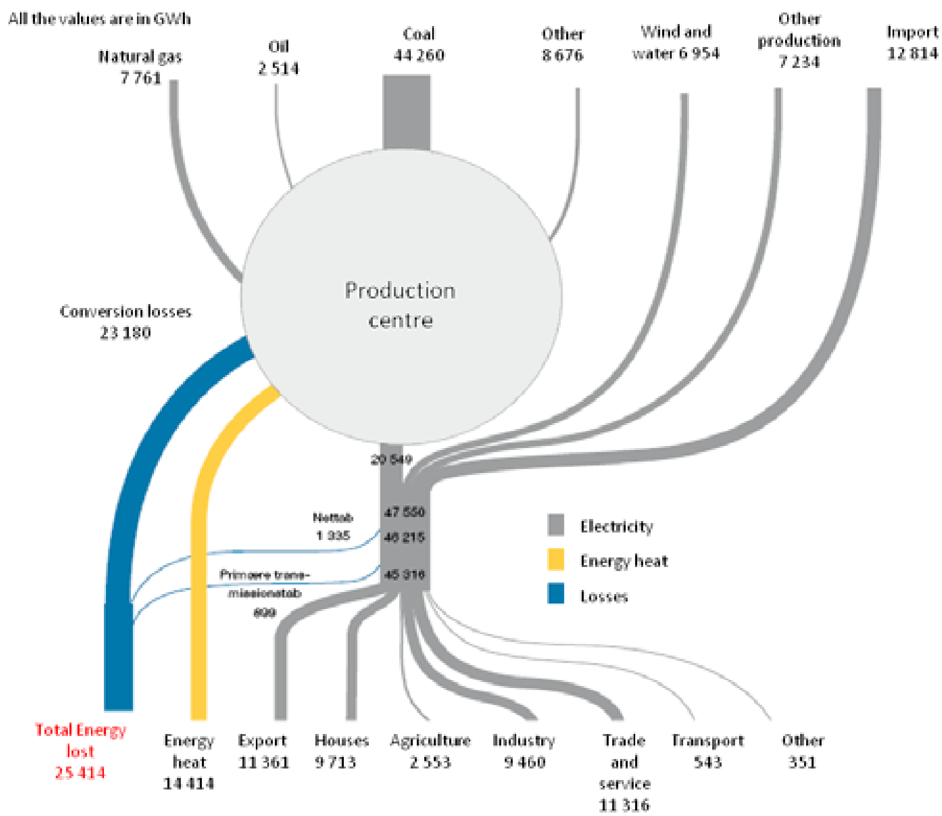



***Figure 1.6:*** *Energy balance for the el-sector in 2008. Source: DanskEnergi, 2009 and Dansk Elforsyning Statistik 2008.*

renewable energy, while energy produced by wind or water is still at the bottom of the list when compared to all other inputs. Nor is it specified what the energy losses are from the imported energy.

The European Union considers *energy efficiency* as: the use of less energy input to provide the same level of energy service. In this context, the illumination system that provides the highest potential to contribute to the enhancement of energy efficiency (highest reduction of net electricity consumption) will be the most feasible in the future.

### *Potential energy savings*

The tertiary sector in Denmark often uses old-fashioned fluorescent lamps, spots, halogen and standard reflectors (see Picture 1.1). In accordance with the status report from the Institute for the Environment and Sustainability (JRC), one could achieve more energy savings from the tertiary sector than from the residential sector (Bertoldi and Atanasiu, Feb. 2007). For example, the JRC's status report points to savings of 16 TWh/year for the residential sector as a realistic scenario, compared to a business as usual scenario for the year 2015, while, with the same scenario, the potential savings are 36 TWh/year in the tertiary sector (Bertoldi and Atanasiu, Feb. 2007), which is slightly more than double the saving. But this would only be possible if the same focus given to the residential sector is also applied to the tertiary sector.

***Picture 1.1:*** *Typical picture of illumination by spots in commercial facility in Denmark.*

Thus, the tertiary sector (trade and services) is where most of the electricity for illumination is consumed. It is the fastest growing consumer of electricity for illumination, and, compared to other sectors, this sector has the highest potential to achieve energy savings by switching to more sustainable technologies. This thesis will, therefore, focus on the tertiary sector.

***Phasing-out policies and current technological alternatives***

The interest in illumination technologies and the reason for suggesting an investigation into in this area was also driven by historical political interest in this area. At the end of the 2007 the European Commission had already pointed out that there is a big potential to save $CO_2$ emissions through phasing out inefficient products. The European commission stated then that: "The amount of saved $CO_2$ could rise to 180 Mt, representing *a quarter of the reduction target by 2020*. From this, 15 Mt could be achieved by switching to more efficient light bulbs (EU, June 2007). This concern was shared by countries, such as Australia, that was one of the first in the world to phase out the incandescent bulb in 2009 and suggest using compact fluorescent lamps. Following this example, China and the USA have done the same. On the 8$^{th}$ ofDecember 2008, the European Union announced the programme to phase out incandescent lamps (EU-ECO-design, 2008).

The activation of out-phasing policies in this sector, however, started to raise the question of what should substitute the incandescent lamp. Additionally, the EU announced that, from 2010 and over the next eight years, the most inefficient incandescent lamps should also be phased out (EU-ECO-design, 2008). From this point, the linear fluorescent lamp type T5 (LFL T5) was designated as the best available alternative for the service and trade sector.

Yet, the launch of such policies has made the illumination sector to look for other alternatives. The most important of which has been the technology known as light emitting diodes (LEDs). These, however, based on the assessment that supported the Eco-design directives for illumination, were labelled as *the best not yet available technology* (Van Tichelen, 2007).

Another important alternative derived from the preparatory studies, that gave the basis for the eco-design directives (Van Tichelen, 2007) in this sector, was the suggestion to include more daylight when providing an illumination service. However, these studies did not mention which type of light transport technologies should be used.

Right from the start, the number of alternatives has been a problem. Additionally, the implementation of many future applications will depend on assessing which of the available alternatives have further technological and efficiency development potential.

The potential health risks due to the fluorescent lamp have to be taken into account. In a communication dated the 29th of March 2007,the Danish Environmental Agency stated: *that though there was an EU-restriction against CFL due to their mercury content*, the restriction was withdrawn *due to the lack of suitable alternatives* to the incandescent lamp. It also stressed that the RoHS-Directive[2] recommends that the content of Mercury should not exceed 0.1 of the weight percentage; however, in the case of the CFL the limit was set up to 5 mg of mercury per lamp. The Directive added that the EU's eco-label "Flower" also allowed the use mercury, however, the level of mercury should not exceed 4 mg of mercury per bulb (Miljøstyrelsen, 29 / 03 / 07). Nevertheless, the emergence of lighting devices, such as Light Emitting Diodes (LEDs), could question if this is the wisest decision. Mercury is hazardous because it is quickly absorbed into the body via skin contact or inhalation. Mercury can cause damage to the central nervous and reproductive systems as well as neurological and kidney damage. If the CFL are not properly disposed of, mercury, in the form of gas, will be dispersed into the air, directly affecting human health, or it will settle into the soil and nearby water bodies, ultimately contaminating food chains.

## 1.3 SELECTED TECHNOLOGIES FOR THIS STUDY

This study takes as base-case technology the *linear fluorescent lamps T5*. This is because of the recommendation made by the EuPs Preparatory Study for the Office Lighting Sector in this area (Van Tichelen et al. 2007). In 2006, several experts in this area were already pointing out that, despite the reductions that fluorescent lamps might provide in relation to incandescent lamps, the emergence of white *Light emitting diodes* (LEDs) could open further possibilities for energy savings

2 "The RoHS Directive stands for 'the restriction of the use of certain hazardous substances in electrical and electronic equipment'. This Directive bans the placing on the EU market of new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants" (http://www.rohs.gov.uk/).

(Kage, 2006). The same statement was made again in 2009 (OSRAM press release dated 4th August 2009). Currently, OSRAM, Philips and General Electric are launching products based on LEDs. These companies already consider that LEDs will be the driving technology for at least the next quarter of this century. Nonetheless, their implementation is taking place very slowly.

The Preparatory Studies for the Eco-design EU Strategy for Office Lighting also suggested the inclusion of more daylight, in order to further reduce net energy consumption. This recommendation was followed by this study, as the reduction of energy in absolute terms, and the energy losses that could be avoided by combining artificial/daylight seemed to be very promising in the office sector (see Figure 1.7). Considering the patterns of consumption of electricity for illumination in the Danish tertiary sector (see Figure 1.7), it is remarkable that *almost a 40%* of electricity used for illumination is consumed during *daylight hours*, and 42% is used *during the night* or when most of the services and trade centres are closed.

There are different technologies for the inclusion of daylight in combination with artificial light. For example, windows, solar cells and solar fibre optic lighting systems (the latter are called hybrid fibre optic lighting systems (HFOLS) when used in automatic combination with artificial light). This study selected HFOLS due to material and energy efficiency considerations (see Chapters 2 and 4). Consequently, the base case technology for the study will be Linear Fluorescent Lamps T5 (LFLT5). A feasibility study will be created for LED technology and HFOLS (the latter as an intensive case study/action research, and also as a means to both produce knowledge about the current LED-technology system and the issues relating to the development of more radical alternative technological systems. The objective of working with HFOLS is to produce knowledge relating to both of the issues above.

## 1.4 RATIONALE

During 2005, the Commission of the European Communities launched the Competitiveness and Innovation Framework Programme [CIP 2007-2013]. The intention of this program was to set the framework for action and projects, where the focus is set on the innovation and dissemination of best practice related to European industry in general. Under the general programme of "Competitiveness

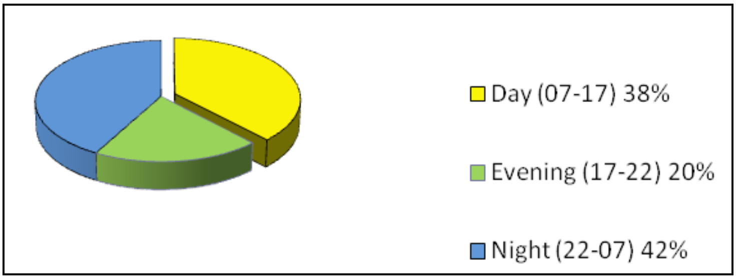



***Figure 1.7:*** *Annual average consumption of electricity for lighting. 133 work places are considered for this average in Denmark. Source: Elsparefonden, http://application.sparel.dk/ElWebUI/El/index.aspx*

and Innovation Framework" there are three programmes to attain the general goals. These are: 1) The Entrepreneur and Innovation Programme, 2) the ICT Policy Support Programme, and 3) the Intelligent Energy-Europe Programme. In the last programme, the main objectives are to find alternative energy sources and save on energy demand. This point is crucial, since the "lack of alternatives" is the only argument the EU Environment Agency has to support using Compact Fluorescent Lights (CFLs) in the future. In 2008, the EU established the Strategic Energy Technology plan –SET-plan (setis.ec.europa.eu/), an energy technology policy for Europe. The goals of this plan are to:

- Accelerate knowledge development, technology transfer and up-take;
- Maintain EU industrial leadership on low-carbon energy technologies;
- Foster science for transforming energy technologies to achieve the 2020 Energy and Climate Change goals;
- Contribute to the worldwide transition to a low carbon economy by 2050 (setis.ec.europa.eu/).

Furthermore, it has been argued that research into environmental strategies and policies concerning lighting within a broader perspective is still very limited, despite the current technology development [Pamlin and Szomolányi, 2006].

## 1.5 RESEARCH OBJECTIVES

Considering the above-mentioned issues, the main general objectives for this study will be:

- To identify the technology, or technologies, with further potential to reduce the illumination sector $CO_2$ emissions, by assessing and identifying:
- The technologies with the lowest environmental impacts;
- The technological improvement possibilities to further reduce $CO_2$ emissions
- The possibility for the alternatives to become cost competitive;
- The technological possibilities to improve the service in relation to consumer-user demands;
- The necessary components and conditions to support the technological innovation system to develop the technologies in focus, and;
- The market, policies and regulations that can support their implementation.

An integrated objective is to contribute to the discussion by proposing the elements that a new framework for eco-design and innovation feasibility studies could consist of in order to evaluate the technologies that will facilitate the transition to more sustainable technologies in relation to the climate, energy and economic development challenge that we face today.

## 1.6 CASE STUDY

To achieve these goals, this study focuses on the development of LED technologies for the office sector (a representative segment of the tertiary sector). The analysis is carried out using a combination of LEDs with solar fibre optic collectors (hybrid fibre optic system) in the form of an intensive study/action research, with the aim of producing knowledge about the current LED technology system and about the potentials and barriers to the development of technological systems for more radical alternative technologies.

## 1.7 RESEARCH QUESTION

This study explores the question:

Where and what are the main possibilities for the Danish lighting industry to efficiently reduce the $CO_2$ emissions of illumination technologies in the office lighting sector, and what conditions are necessary to support their implementation?

## 1.8 TARGET GROUP

This study is aimed at the Danish lighting sector, but is also applicable to anyone who has an interest in energy saving illumination technologies (both locally in Denmark, and at a regional level within the EU). The study also addresses the technological sectors that might make use of eco-design and innovation feasibility study frameworks to make a faster transition towards a low carbon economy.

In the next chapter, the theoretical considerations supporting the research objectives mentioned in section 1.5 will be discussed. This will be followed by the development of the working question that gives structure to the methods and the development of this study, as well as further discussion of the project design and scientific research approach.

Chapter 2

# Philosophy of Science, Theoretical Framework and Methods

This chapter has three main objectives. The first is to discuss the overall scientific approach selected to fulfil the research objectives established in Chapter one. Secondly, to discuss and suggest the theoretical framework based on the necessary elements to conduct an eco-design and innovation feasibility study. Thirdly, to discuss, based on the first two objectives, the methods used to fulfil the research objectives, the problem formulation, the project design and the structure of this dissertation.

## 2.1 OVERALL SELECTED SCIENTIFIC APPROACH

In order to develop new low-carbon technologies that can cope with the climate, energy and economic development challenge, it is important to gain knowledge for several purposes. Firstly, to understand what the problem is, what makes it a problem, to whom is it a problem, etc. Secondly, to understand how new knowledge is produced in order to make realistic solutions, and thirdly, to find ways to activate the process to develop new knowledge and concrete solutions. To achieve this, it is important to understand scientific knowledge in context (in relation to other kinds of knowledge), since it requires an analysis that both relates to the complex social and environmental (natural sciences) settings and to practice.

According to Sayer (1992) there are 4 interrelated *misconceptions* about knowledge, which make the relationship between social science and society problematic:

1. "that it is only through observation (contemplation) that we gain knowledge;
2. that what we know can be reduced to what we say;

3. that knowledge can be safely regarded as a thing or product, which can be evaluated independently of any consideration of its production and use in social activity; and
4. that science can simply be summed to be the highest form of knowledge and that other types are dispensable or displaceable by science" (Sayer, 1992:13).

In order to create adequate knowledge it is important to break with these misconceptions. Problem-oriented research deals with specific problems that require action and, therefore, it is imperative to gain practical knowledge, which derives from active participation and participatory observation, which is set in relation to many considerations so it can be used more effectively in social activities.

***Active observation***
Knowledge, according to Sayer, is gained through *activity,* both in the willingness to change our environment (labour or work) and through the *interaction* with other actors using language as a main resource (Sayer 1992:17). Consequently, the researcher needs to act in coordination with other actors, facilitating and opening for a process of mutual communication. The fact that solutions are contextualised gives better possibilities to respond to societal values and, therefore, better possibilities for more effective implementation.

This is in line with an alternative philosophy of science, coined as Modus 2, which points to the possibility of producing a more robust knowledge by going beyond narrowly circumscribed scientific communities, allowing the inclusion of other knowledge producers, main decision makers and directly affected individuals, and which can be documented by its usefulness and value in praxis (Nowotny et al. 2003).

***Practical knowledge***
The problem-oriented research (in relation to misconception 2), instead of only focusing on linguistic knowledge - either spoken or written - focuses on practical skills, which most of the time do not require much linguistic capability. Particularly in the case of producing alternative technologies, of more importance than the discourse is the need to be aware of questions, such as: what kinds of appliances are produced? What technological limitations do we have to solve to make lighting more environmentally efficient? Who can produce them? What kind of appliances do consumers prefer? What makes the preferred appliances more attractive? What

are the main barriers to develop the technology? Who are the main actors in the field? What are their capabilities and interests?

***Knowledge in relation to social activity, and how it is produced***

Knowledge is considered as *active* against misconception 3. Misconception 3 considers knowledge as a final storage product or a thing that exists outside us. However Sayer considers that knowledge is active, because it is created on the basis of a social activity. According to Sayer: "To develop (active) knowledge, we need raw materials which we can work with. These are linguistic, conceptual and cultural as well as material" (Sayer, 1992). If the aim is to produce solid and robust knowledge in order to make more sustainable technological solutions, it is important to consider the underlying concepts, the current technological solutions, current discourses or policies, knowledge in the form of data, etc.

***Science and its relation to other kinds of knowledge***

If one's objective is to design and implement realistic environmental solutions, then one must create the necessary type of knowledge to address different types of functions and contexts that those solutions require. Because of their technological nature, low-carbon technologies require engineering, environmental, socio-economic knowledge and aesthetic and value considerations. It further requires taking the technological scientific expertise and the common technical knowledge from technicians that use the current solution and who will adapt, adopt and implement the new technologies in the future. According to Sayer: "these different types of contexts are not mutually exclusive but overlapping. Scientific practice embraces several types of knowledge, including some which are general excluded as non-science and even anti-science by scientism" (Sayer, 1992:17).

To address these different knowledge contexts it is important to find a scientific method that can address different kinds of logic and that can support the scientific research with a creation (change) - perspective.

***Validity***

When looking for environmentally friendly technological solutions that can be used in practice and can produce a change in the current environmental and economic situation, it is important to find adequate knowledge that can support a real change. Here, it will be practice that will decide if the theory is valid. Our thoughts cannot prove science; it is praxis that decides if the acquired knowledge is useful or not (Bertilsson, 2007; Sayer, 1992; Kjær, 2009). In other words, validity will be reflected in knowledge or solutions that can be implemented and that are able to change the current course of action.

The relationship between knowledge and practice in problem-oriented research is interactive rather than passive, since people and ideas are included in the study's objects of knowledge. According to Sayer, this process has a critical and emancipatorial character, since adopting self-reflection, one can think about oneself and can help to change the object (Sayer, 1992).

***The logical approach***

It is important to stress that, historically; there have been two predominant ways of reasoning: Deductive and Inductive logic (see Box 2.1). However, the complexities of real-life problems in current times call for a third *way* of logic. This last type of logic was already pointed out by Aristotle, namely the logic called abduction or abstraction (Bertilsson, 2007). Nevertheless, while the two first kinds of logic have been widely reported, little has been said about the alternative: abduction (Kovács and Spens, 2005: 134).

Induction, deduction and abstraction have been regarded as the methods of thinking and as the foundations of scientific explanation. These three ways belonged to the system of logic which Aristotle called *organon*, that constitutes the tools of thought itself (Bertilsson, 2007).

When we deal with real life problems, we require knowledge, which should be practically-adequate to solve a specific issue, and which is also bound to a specific context and concept model.

Box 2.1

-Deductive approach "follows a conscious direction from a general to a specific case" (Kovács and Spens in van Hoek, 2005.135)

-Inductive research logic, "moves from a specific case or a collection of observations to general law, i.e. from facts to theory ((Kovács and Spens in van Hoek, 2005.135)

-Abductive logic can be understood as "a mode of inference where explanations are searched for (an anomalous or surprising) phenomena" (Paavola 2004.268).

As Sayer points out:

> *"To be practically-adequate, knowledge must grasp the differentiations of the world; we need a way of individuating objects, and of characterizing their attributes and relationships. To be adequate for specific purpose, it must 'abstract' from particular conditions excluding those, which does not have significant effect in order to focus on those which do. Even when we are interested in wholes, we must select and abstract their constituents" (Sayer, 1992).*

The most common name for this kind of logic is *Abduction*, although other authors call it abstraction (Sayer, 1992). When taking illumination as a study object, a logic that can both reveal the nature of things and can put forward decisions regarding causal and structural analysis is required. This will depend on judgments about the nature of causation and structures and, therefore, Abstraction logic is more useful.

## 2.2 ABSTRACTION THEORY

Environmental problems are immersed in very complex contexts; these are of a social and a natural character. In order not to get lost in, and be able to react in such complexity an abstraction of the complexity needs to be created. Grasping reality is a process where one needs to make a selection of the most important elements that define the object of our attention. Science can help by making a reproduction in one's thoughts of the world. For example, look at Figure 2.1.

***Figure 2.1:*** *Reality, or a picture of reality?*

Looking at Figure 2.1 one can say it is a house. However, what we see is a picture of a house. This example is relevant to the understanding that science is the action of reproducing the world that surrounds us in our thoughts, so we can act in the world. When we work with real problems, we deal with problems that are very complex. If we mean to react in that vast complexity, we are forced to use abstractions or a selection of the most important elements that constitute the reality. The abstractions need to be valid, useful and dynamically sufficient so that using them can help us to react in the world. Neither induction nor deduction can do this. Working with environmental problems we challenge ourselves with different logics that have to be connected: natural science, which focuses on the object, and social sciences, which focus on the subject.

Abstraction in this sense is the reverse of the common understanding of vagueness. It refers to the method of isolating in thought one-side or partial aspects of an object. According to Sayer: "What we abstract *from,* are the other many aspects which together constitute *concrete* objects such as people, economics, nations, institutions, activities and so on" (Sayer, 1992: 87).

Sayer stresses that the concept of "concrete objects", besides concerning whatever exists, has the objective of drawing attention to the fact that objects are constituted by a combination of diverse elements or forces. Thus, learning about concrete events or objects involves going from the concrete to the abstract and from the abstract to the concrete. Though this process is not always straightforward, when each one of the abstracted aspects has been examined, it is possible to put together the abstractions in a new combination that grasps the concreteness of their objects. In line with Sayer, in order to make solutions that work in the real world it is necessary to use adequate practical knowledge. In other words, to go from the concrete to the level where new knowledge (ideas) are generated, towards the generation of new concrete solutions (technology, products, processes, strategies, policies).

Bertilson argues that "logic plays an important role in all scientific activity, because of what it tells us about inferences, that it is, the necessity of drawing the correct conclusions from given premises" (Bertilson, 2000:490). In general, using abductive logic allows making meaningful, relevant and useful abstractions based on normal everyday experiences. It is a creative process, since it might help to create unforeseen relations that allow questioning those relations we already take for granted (Bertilson, 2000:491). For example, it is expected that by increasing the effectiveness of the lighting devices, the consumption of electricity will be reduced. However, everyday life experiences show that this might not be a straight conclusion, since energy consumption is still increasing. Thus, more effective devices do not automatically mean less energy consumption.

Deductive reasoning has often been used to characterise antiquity, while inductive reasoning has been characteristic of the modern period. Nevertheless, abductive logic is becoming increasingly more relevant in a variety of fields (Kovács and Spens, in van Hoek, 2005; Paavola, 2004). It is highly relevant for problem-based research and for environmental issues that encompass trans-disciplinary fields.

Using the deduction method, researchers apply a generalisation to a specific case. However, the complexity is often so huge that there is not *a single* theory big enough to comprehend it. Using the inductive approach, the researcher tries to use several examples, and then develop general laws from observations. This approach is also problematic in relation to the huge problem complexities, so the solutions cannot be used in general setting and contexts.

The usefulness of abduction for this research thesis lies in its strength when considering the context in which knowledge is created, and where solutions are generated in a more solid manner.

Consequently, most of the observations used for this research have been gathered from concrete reality, for example, visiting relevant institutions, qualitative interviews, active participation in seminars, group work with colleagues, communication with main stakeholders, selection of most relevant artefacts (new alternatives) and group work with selected relevant engineers, designers, and an electrical consultancy.

The use of theory in this research has also been developed through the selection of relevant concepts. These have been selected according to their usefulness, to either explain phenomena or to solve issues that were relevant in providing new solutions by placing these theories and concepts in new combinations. In addition to the development of a novel technology, the approach provided by this process has been supportive when identifying the necessary elements to discuss and include in a new theoretical framework to find more sustainable solutions. At the same time, it has supported the creation of an original method that was useful for the research carried out in this thesis.

## 2.2.1 Abstraction, technological and socio-economic issues

Designing, developing and implementing low-carbon technologies requires both behavioural and intentional modes of explanation where there is a duality between the exterior (observable) and the interior (perspectives, discourses or narratives). Therefore abstraction was considered the most suitable method to grasp this inherent complexity. Dealing with environmental problems appeals to trans-disciplinary analysis, since environmental problems and their solutions have both objective and subjective realities.

For example, the high emissions of greenhouse gases have a real effect on the global ecosystem, independently of the discourses that are created around this concept. But societal actions that influence this physical effect are constrained by discourses and concepts that constitute the other side of the problem.

According to Schurz (2008) and Kjær (2009), abduction is a stronger way of induction. The inductive method focuses only on the discovery of empirical generalisation. What makes abduction stronger than induction is that it introduces new concepts and models, while induction only transfers them to new examples (Schurz, 2008:202). This strength makes it possible for the researcher to move from a realistic to a constructivist position, providing the links between structure and actor, and the juxtaposition between macro and micro analysis.

In this research, different kinds of knowledge are pursued. They derive from the relationship between practice, theory and poietical (technological) issues. Therefore, the author agrees with Haig (2005), who argues that in research, where several goals are pursued, a broader research approach is required, suggesting abduction as an option capable of dealing with this complexity.

Abductive reasoning supposes the (re)search of *most* singular or relevant facts by finding the connection to explanatory-seeking 'why' questions (or sub-questions in the problem design). This is one of the fundamentals of problem-based research, where the anomalies or the most relevant abstractions can be clarified and understood through the research questions. At the same time, the research questions structure the research process. This process can be reflected in the overall research objectives and sub-objectives of this study, and will be formulated as specific research questions later in this chapter. This will also constitute the project design for this study.

### 2.2.2 Relation Subject-Object

In the abstraction theory described by Sayer, the term 'subject' is not restrictive to scientists but also relates to the knowing-subject, which can, in a broad sense, be any kind of investigator. The subject here is seen as a creative (active) agent who brings about change, and the object is defined as the thing being studied. The way in which a social science relates to everyday knowledge and practice is by including a series of dualisms: People-nature, individual-society, subjective-objective, etc. The inherent dualisms do not operate in a single way but in parallel ways and they mutually reinforce each other. Considering the dualisms in this way allows this study to:

1. recover the work and activity and create an understanding of how thought actually relates to, and functions in nature and society;
2. consider the social relationships and inter-subjectivity, so individuals are not segregated, but considered as part of society, giving the right importance to the social function of language. Doing this makes it easier to contextualise and understand the language.

Sayer also establishes that a subject must have a language in which to think about the object. From this he derives that the subject-object relationship must presuppose the existence of social relationships. Usually there is a differentiation of language communities with their own linguistic and conceptual resources (e.g. gremial expression), which presupposes a social context. In this way, the subjects are in a double relationship- to the object and to other subjects. This relationship implies that, in order to understand the world or the object, the subject can make use of the cognitive and conceptual resources of particular communities. This process is developed throughout the entire study and related project work by selecting and contrasting the existing concepts with the study object, and through active participation and communication with relevant actors in this field.

The other (interdependent) relationship is that knowledge is tied to practice right from the start, because we learn through using material work and communication. In this relationship, the nature of the practice both determines and is determined by the subject and object which it links. In the case of this study, examples of these are: architects, designers, engineers working with light, who define illumination differently according to their own field of interest. In this way, one can see different subjects with different defined objects. According to Sayer, this differentiation is mainly determined by "...their practices, in terms of conceptual tools they use and material actions and social relations in which they engage. Yet it is common to compare knowledge in different communities and at different points in history in abstraction from these practical contexts as they were merely different modes of contemplating the world" (Sayer, 1992:26).

This relationship can be seen in the following example: while working on this thesis, a suggestion was made to include the theoretical concept of the Technological Innovation system that points relevant actors in a new relationship to the technological solutions to environmental problems in focus. In this case, the author and the relevant actors worked together to develop a new technological application.

For this project, it is necessary to do more than just clarify what a concept means (e.g. LCA, or eco-innovation as terms) for those who use or work with these terms. What is important is to know under what conditions a concept is valid, and what their effects have been in the past, or what they may be in the future. The emphasis is on testing how these terms work in reality and how they are applied, both to generate a change (structural) and to create new concrete solutions (material or causal).

How are concepts used in abductive-based research? Callewaert describes this by quoting Bourdieu: "it is not a question of replacing reality by words and concepts that represent it so we are no longer working with reality but with concepts" (Callewaert, 2000). Callewaert argues that Bourdieu chose to use concepts by considering them as *tools and materials* which facilitate the creating of a piece of work that results in new concepts or theoretical frameworks, and that can assist the study to identify or develop new solutions. This kind of abductive research is considered by Schurz (2007.202) as "creative" inference, since it introduces new concepts or models. The *materials* and *tools* needed in problem-oriented research using an abductive approach consist of, using Bourdieu again, "all the words, tales, and explanations, all the skills, practices (conferences, themes, workshops), and sets of rules, all the experiences and expressions, all desires and efforts with which we already have ordered our world in everyday life, be it spontaneously and privately, but also officially and organizationally" (Callewaert, 2000). According to the experience of this study, this creative process is not only theoretical (ideas or concepts) and practical (actions), but can also be *poietical* (technological or material) (Bertilsson, 2000). This gives it a double value, when dealing with technological issues that involve both discursive and a material dimensions.

Creative inference is about discussing the phenomenon, the social problem which is not controlled by rules  formed through strategies, where the part-takers act as thinking and negotiating agents.  From this, one may derive that the material and tools should not be forced to fit into theories, but should be used as materials from which to produce new knowledge and new models. In problem-based research, the researcher (with their own experience and knowledge) starts with a real-life observation and continues to select the most relevant actors, the most important institutions, and the dominant concepts. The resercher makes a selection of concepts in order to find a new and unique framework with which to solve the problem that the research is dealing with (see Figure 2.2). However, this process is not linear. The main purpose is to understand the problem and be able to provide new concepts that can help to solve the problem.

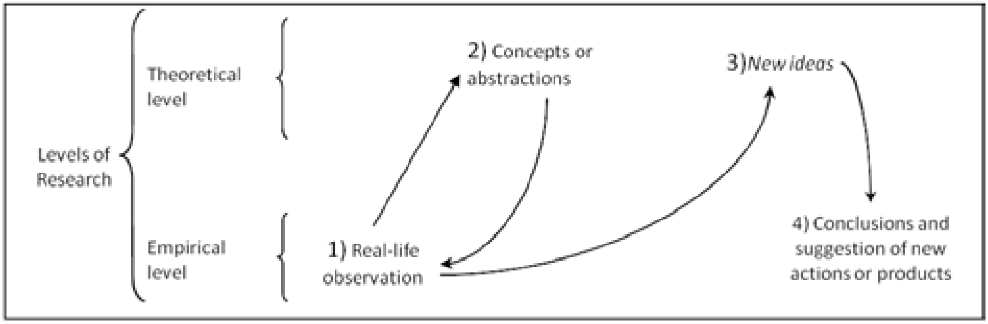



***Figure 2.2:*** *The abductive research process in problem-based research. Adapted from Kovács and Spens, in van Hoek (2005: 139).*

The main objective of this research is to find better alternatives than CFLs to reduce the currently most important environmental impact (the reduction of $CO_2$ emissions) of illumination. The focus will be on the illumination segment of the service and trade sector. For this, it is necessary to identify the structures and financial mechanisms to support such innovations and suggest a course of action to achieve a more strategic technological development and innovation process.
To investigate this problem, an abductive method was used. This choice allowed the author to take some starting-point, real-life observations from the Danish photonic industry and the photonic production process. Firstly, the objects of study were identified (current existing technologies), secondly, their material dimensions were analysed, as was their impact on more general natural or physical conditions

(environmental impact). From the empirical material collected, several causalities were observed. Besides looking at the current technological alternatives, it was necessary to see their technological potential in relation to societal demands and who was shaping, or will shape, the new technological alternatives. Therefore, it was important to identify who the main stake holders were, which kind of concepts they were using to discuss the problem, what were the main actions suggested in the past, and what are the main results at the present time. It was also important to see the contextual situations and how these are affecting, or will affect, the new alternatives and their implementation in praxis.

To achieve this understanding, the author became involved in research projects and entrepreneurship activity where, in collaboration with relevant actors, she attempted to find both scientific and practical knowledge to identify new technological alternatives and new strategies to further support their technological development according to the specific political and financial sector conditions for this case.

The process of fulfilling the research objectives for this study can be described as follows: Firstly, the problems had to be contrasted with the other observed facts. This made it necessary to explain observations in terms that were understandable to the people who usually have some relationship with this problem field, and to ensure that this approach also covered any new concepts that could help explaining the anomalies encountered. Secondly, to achieve the research objectives, it was necessary to use some existing concepts that could explain important parts of the problem, as well as a new combination of theory components that could help to explain and analyse the current and specific issue. By doing so, an original method of analysis was suggested that was practical for use in the research study. This method was used to structure the analysis and to work with the theory in a selective way on different levels of analysis.

In the first externally-financed research project, where the objective was to develop a new application of LEDs in combination with a solar optic fibre collector system, physical theories related to energy and optics were used. Additionally, the anomalies in relation to using artificial and natural light were discussed. To make and assess the new solution, it was necessary to construct a framework that could analyse the material (environmental) and technological phenomena. The result of this process in both cases made it possible to theorise and organise these relations, which resulted in new ideas or solutions that, it is hoped, can be developed used in the future.

The author's active participation and pragmatic approach (personal involvement in two externally-financed research projects and entrepreneurial activity) have to be seen as a derivation of Sayers' proposition of knowledge contextualisation and his abstract theory. From this conclusion, the author takes a problem (object) oriented approach, based on active research.

## 2.3 THEORETICAL FRAMEWORK

Finding new possibilities to improve the design and innovation of technological alternatives with a lower environmental impact requires three levels of analysis: Firstly, it is imperative to establish the material dimension, for example, what and where are the main environmental impacts? what are the current technological alternatives? And, what kind of technological improvements need to be done to reduce their environmental impact? Secondly, it is necessary to expand the level of analysis to include other elements that affect the development of such technologies and can be assessed in relation to their insertion on a socio-economic system, where market mechanisms are revealed (e.g. price, consumer preferences, and level of services). Finally, a third level of system expansion is required to investigate the social process in which technologies are developed, further adapted, adopted and diffused, while taking account of structural conditions. Consequently, the objective of the next section is to outline the three levels of analysis and the main concepts that constitute the methodological framework for this study.

### 2.3.1 Product system

In order to identify the major environmental impacts caused by current technologies and identify the most problematic stages of the illumination service life cycle, it was necessary to understand the material dimension of the technologies. Accordingly, the theoretical framework for this part of the analysis is based on a life cycle perspective (see Box 2.2).

This definition stresses that all parts of the life cycle process of a product have a load on the environment and therefore, all stages, from the extraction of raw materials to the product disposal, have to be considered. The environmental load considers all types of impacts upon the environment, including extraction of different types of resources, emissions of hazardous substances and different types of land use. Gunée (2001:4) defines the total system of unit processes which are involved in the life cycle of a product as a "product system'. The relevance in choosing this approach for this study's analysis is that it is useful to:

Box 2.2

LCA is defined by this project as an environmental management tool which "addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) through a product's life cycle from raw materials acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO 14044, 2006:v)

- analyse the origins of problems related to a particular product;
- compare improvement variants of given products;
- identify the areas of design improvement to make new products; and
- choose between a number of comparable products.

The strength of this approach is its holistic character at product level. However, some local environmental impacts are not considered, for example, the global scale reduction of mercury due to the reduction of fossil fuels seems very effective when substituting incandescent lamps in favour of the florescent lamps. Nevertheless the local risks posed by the accidental breakage or incorrect disposal of a lamp are underestimated. Furthermore, this approach does not include market mechanisms and, therefore, the Product-service system needs to be used in order to include these important factors.

## 2.3.2 Product-service system

Combining artificial light with daylight requires that one integrate two systems (an electrical and an optical) to deliver one service, which in this case is illumination. Thus, it is important to consider an approach that can encompass several products and their inherent environmental aspects to obtain a more sustainable solution. Putting two or several products, or pieces, together in new combinations requires, as Mont (2002) points out, that one creates products and services "that provide consumers with the same level of performance, but with inherently lower environmental burden" (Mont, 2002). This approach is known as the Product-Service System (PSS), and its main focus is on finding system solutions. The new challenge arising from using this approach is that one needs to advance from being solely product-oriented to finding system solutions which can satisfy consumer demands. Mont describes this as follows:

> *"Such system-based solutions should facilitate the shift from separate systems of producing and consuming to a system, in which products, services, supporting infrastructure, and necessary networks are designed so as to provide a certain quality of life to consumers and, at the same time, minimise environmental impacts of the system. Thus, a PSS should be defined as a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models"*
> *(Mont, 2002).*

Though the original meaning of this approach was to create a business model strategy (UNEP, 2000), this study has used this concept because it facilitates the first system expansion, where market mechanisms are also considered, not only as a business model, but also as a definition that focuses on the design of the service(s) while taking account of price, qualitative, quantitative and material criteria.

In order to provide a competitive service, one needs to consider the technological functional performance, or technological potential, consumer values, consumer acceptance and competitive prices when compared to other products or services and to comparable products on the market. This requires an investigation of the quantitative and qualitative service potential.

The International Standardisation Organization (ISO) has pointed out that it is not the products themselves that form the basis for comparison, but the function provided by these products. The definition of the service is also called "functional unit" (ISO 14044, 2006:v). However, little emphasis is made of the fact that design and innovation are actually activities and both are part of a social process. According to Karlsson and Luttrop, the concept of eco-design, or design for the environment, "...integrates multifaceted aspects of design and environmental considerations. The objective is to create sustainable solutions that satisfy human needs and desires" (Karlsson and Luttrop, 2006:1292).

By integrating an eco-design perspective one is able to include market mechanisms, such as quality of service, in relation to consumers, and price, in combination with a design perspective (LCA). Although LCA practitioners recognise the importance of the intangible dimension, the disadvantage of the LCA approach is that, in practice, the positioning properties are always defined by the designer or engineer (either working individually or in a team).

Taking into account the stages of the innovation-decision model, the study integrates user practice and opinions into the *re-design or re-invention* process (Rogers, 2003). Rogers believes that innovations *are not invariant*. On the contrary, they usually change as they are diffused (Rogers, 2003). By integrating Rogers' perspective on the re-design process, where user values and user acceptance play a decisive role, it is also possible to stress that the design, development (adaptation/ adoption to and of the product-service) and implementation are immersed in *a social process.* The advantages of integrating this approach in combination with eco-design, compared to that of the LCA, is that including *user practice* helps to achieve a more effective consumer-oriented design, since the project manager can have feedback and dialog with potential consumers/users at a very early stage of the design process, thereby improving the chances for a more effective implementation. The basic contribution of eco-design has been its environmental and economic considerations, while Rogers' stages of the innovation-decision model add the social dimension to this level. As such, this combination can also be useful in identifying, not only the users, but also other actors related directly or indirectly to the purchasing decision-process and other values in addition to the economic ones.

Taking the whole system into account,, the *entire* price of the service is considered., rather than just the price of the bulb. Thus, the concept of *total economy* is used, considering initial material investment, installation, energy consumption maintenance, and replacement. This is carried out using life cycle cost assessment as a tool. Furthermore, market mechanisms from the EU using green procurement policies request decision makers to compare and to choose one product over another. This is done through life-cycle-cost considerations. Thus, the decision was to carry out a Life-Cycle-cost assessment to compare the alternative products on the market and to establish where, and in which stages of the product life cycle, improvements can be made to make the alternatives more cost competitive. In order to analyse these values, the author has once again drawn from elements of Rogers' innovation theory (2003) and elements of Porter's competitive strategy theory (1998).

In order to avoid the misunderstanding that all consumers (by definition) are households, Toth, et al. (2008) suggests that a differentiation between types of consumers should be made. However, while Toth defined just two types of consumers:

- ***Service providers:*** *as* property developers, interior designers, installers, architects, engineers, electrical contractors, and general actors that put the service into a given building or space.
- ***Users:*** as those who live in the homes or make use of the lighting devices.

This study will use the definition of *service providers* as suggested, but instead, a further differentiation will be made for the trade and service sectors:

- ***Users:*** as those who use the service every day, but not necessarily pay for it - for example employees, sales assistants, etc.
- ***Consumers:*** Those who pay for the service, but do not necessarily use the service personally.

It is important to make this distinction, since during the development of this project it was observed that different consumer groups have different levels of influence on the demands and patterns of consumption. Furthermore, they might or might not have direct influence on the selection of type of illumination devices. In this sense, the definition used by this study of a product-service system is a combination of the eco-design and the stages of the innovation-decision model from the Diffusion of Innovation (DI) theory (Rogers, 2003). This is used to find alternatives that are technologically and market-feasible. Rogers underlines the importance of including consumers/users' values in the process of co-development or co-redesign of the planned solutions. Those communication channels are shown with blue arrows in Figure 2.3. This approach contributes an extended framework to understanding the development of new technological applications and the social relationships that take place in the design-innovation phase.

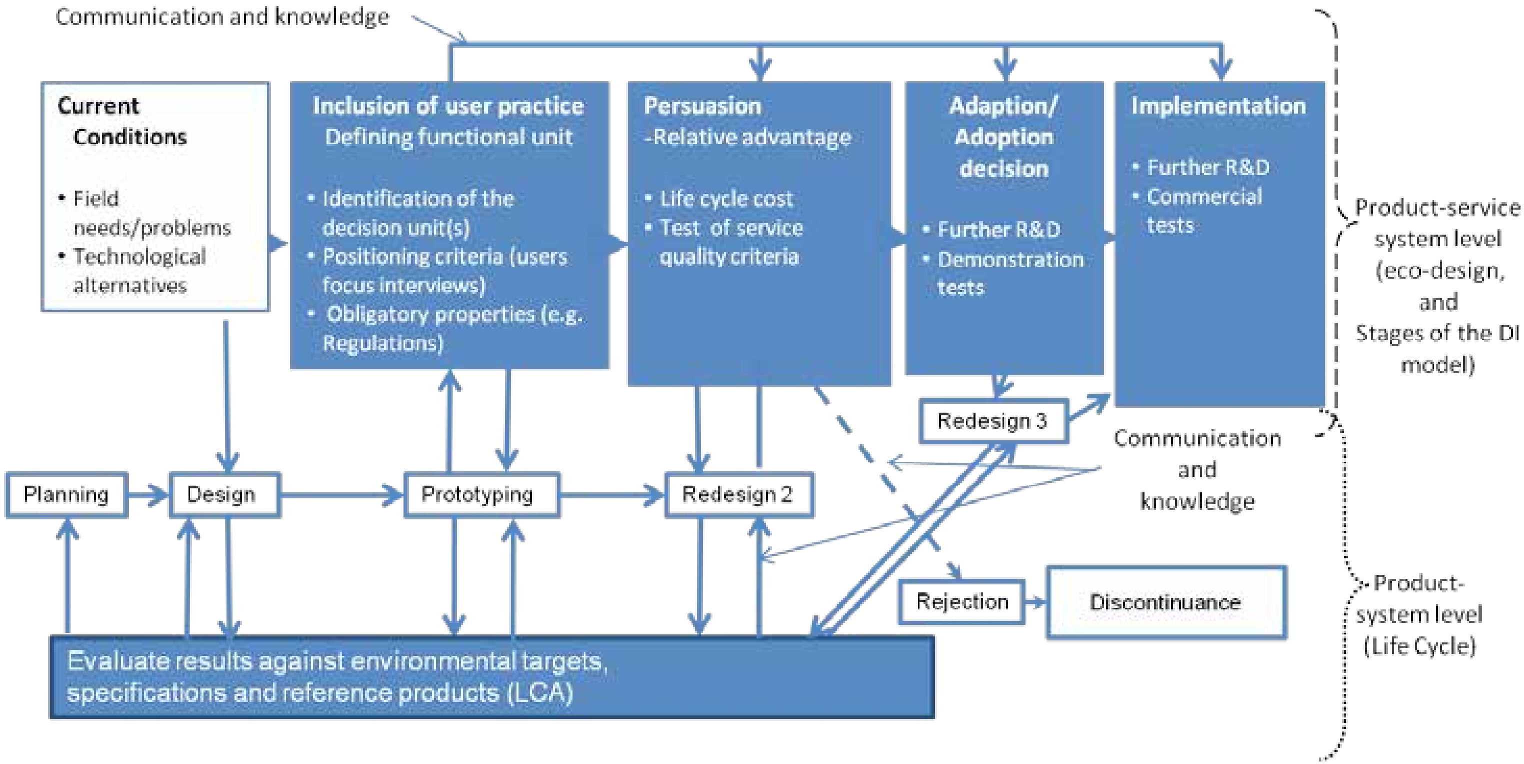



***Figure 2.3:*** *User practice inclusive eco-design and innovation life cycle framework (Author's own diagram)*

Figure 2.3 shows how a product- service approach can contribute with a stringent systemic development process that sheds light on the importance of communication and knowledge development and sharing processes that need to work between key value chain decision-makers (consumers/users) and the designer. Further, it stresses the need for an explorative research/test practice.

Even when this system provides the material and societal needs and preferences of the consumer, it does not reveal the structural conditions that are necessary to *sustain* and make possible the implementation (not only the design but a broad commercialisation) of alternative low-carbon technologies. In other words, this level of analysis does not reveal the key *innovation* actors/institutions or conditions that new products (not technologies) require to be sold on the market, thereby successfully closing the innovation life cycle. This makes it necessary to proceed to another level of analysis, namely the technological and innovation system.

## 2.3.3 Technological and Innovation System

New technological solutions might not be straightforward, and may require additional technological development so that their potential can be realised (implemented or diffused). In this section, the study draws from different, though complementary, contributions that form the conditions for its innovation framework. The development of technologies going through the process of implementation is immersed in an institutional framework that can either enable or block their development process, and even their successful diffusion (Jacobsson and Bergek, 2004). Carlsson and Stankiewicz (1991) are more precise in their definition of the Institutional Technological System network and also include actors, and networks. Porter (1998) and Sturgeon (2001) are more specific in relation to the relevant actors and point to firms or productive actors.

***Elements or components***

By their nature, low-carbon technologies can be referred to as eco-innovations. Eco-innovation is defined by Rennings(2000) as: all measures of relevant actors (firms, politicians, unions, associations, churches, private households) which develop new ideas, behaviour, products and processes, apply or introduce them and which contribute to a reduction of environmental burdens or to ecologically-specified sustainability targets. As was mentioned previously, the concept of eco-innovation is still developing, and besides including the institutional support structures, it also includes the corresponding evolution of social arrangements (Hellstrom, 2007; Mashiba, 2010). But more importantly, and from the study's own empirical experience, it also helps to shift the focus from purely a design activity towards an entrepreneurial activity, where one can not only address the technological design, but the dimension of product development. This allows the linking of the two previous systems (PS –PPS) to the technological innovation system. Further, it can make the link between achieving environmental goals while pursuing sustainable development.

***Support structures (elements or components)***

Besides considering that the material, technological dimension and consumer' demands will influence the design and evolution of the technology, one has to consider the institutional network, which will also shape and influence the development of the technology, or if the right innovation conditions are there, product development. This institutional framework is also referred to as Technological System (see Box 2.3).

Box 2.3:

A Technological System is defined as a network of agents interacting in a specific economic/ industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" Carlsson and Stankiewicz (1991:94)

Hybrid illumination systems are a technology that has not been sufficiently explored by the Danish scientific community, and therefore, it is necessary to explore what are the perceptions and the position of other actors, who are not consumers, to the develop and future implementation of this innovation.

On the one hand, it is important to consider that each of those components has, or might have, a different level of development (see Figure 2.4). This situation is valid for many technologies (windmills, solar cells, etc.) but it is even more evident in hybrid technologies. On the other hand, each of those components is dominated by its own technological system.

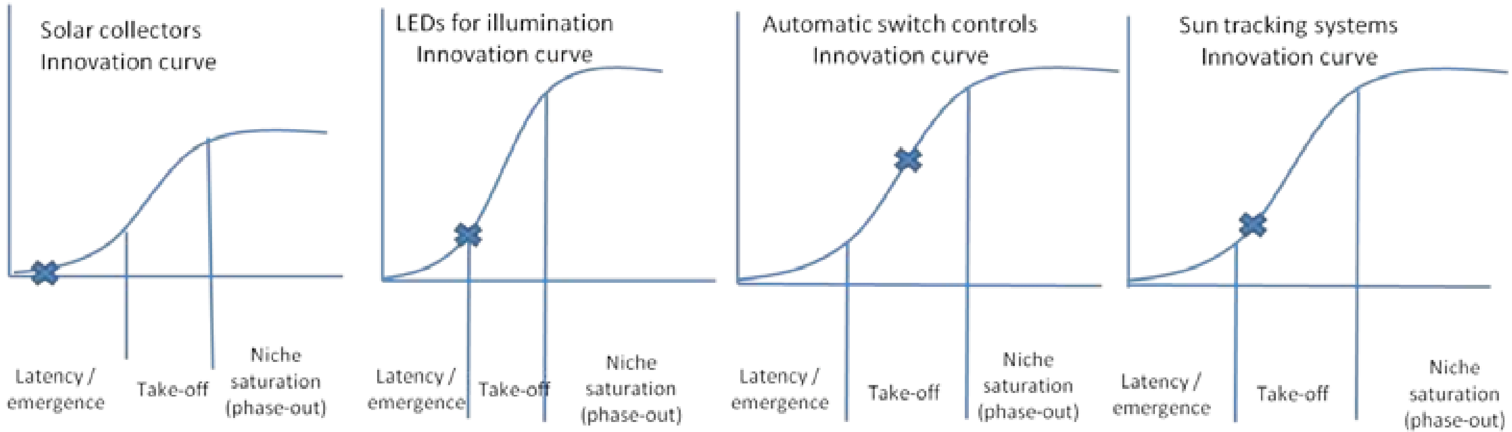



***Figure 2.4:*** *Different innovation curves for each technological component. Evaluations made by the author based on the extent and publication date of the different technologies (Author's own diagram).*

At the same time, the convergence of different technological elements may mean the emergence of a completely new technological system. Consequently, in order to provide the necessary conditions for this new system to be developed, relevant actors and institutions need to accept and comply with the new technology (Jacobsson, 2008; Bergek et al. 2008).

It is important to consider that there is not just one type of innovation system. These may be of national, regional, sectoral or technological character, depending on the level of analysis of interest, for example, one may be interested in general science and technology, particular cluster activities, a component block, a set of related products, a specific technology or a product (Carlsson et al. 2002). This study will concentrate on the Technological Innovation System (TIS) as its focus is on a set of interrelated products to deliver a specific service.

The implementation of new technologies will require adequate relationships and conditions that facilitate their development, dissemination and positioning in the market. Different institutions are attached to each of the phases of the diffusion of innovation. Thus, according to Kjær and Andersen (1993) it is important to find the corresponding institution network to enhance the possibilities of making the diffusion more effective.

Technological innovations are based, not only on the level of a technology, manufacturers and markets (value chain level), but they also converge with a structural order, where policy makers, analysts, innovators, researchers, entrepreneurs and investors interact with each other (Andersen et al. 2006).

Hybrid illumination systems, by its very name, indicates the convergence not only of two types of light (natural and artificial light) or technologies, but it also indicates the convergence of different fields of experts, designers, producers, and even investors and consumers that had traditionally focused on either one or other type of light. Therefore, it is important to see how these relationships work today and what would be their point of convergence to further innovate in this sector. Relationships (functions or conditions)

Jacobsen et al (2008) point to the qualitative elements that are necessary to support the development of a technological innovation system. They state that, apart from the components (technologies, and actors) one must look at the *functions* that impact directly or indirectly on the development, diffusion and use of the technology. These functions might be the capacity to produce knowledge, or the ability to get funding and resources, legitimation, etc.

Lundvall (2007) stresses that, both relationships and elements (or lack of them) can support or block innovation. Consequently, the framework conditions considered in this thesis encompasses both structural and inherent process and relationships between the components.

It is important to note that the focus of Jacobsen et al (2008) is pragmatic, as they suggest that the evaluation should be done on a basis of what has really been achieved. In order to evaluate how general structural conditions allow or limit the innovation initiative, this study uses a particular/intensive case. From this one can see how structural elements function in reality and under concrete situations. It is also useful to give the study a better viewpoint of what kinds of changes are necessary in order to allow a new technological alternative to enter in the illumination technological and innovation system.

***Active feedback processes***

Technologies are never fully developed and static. They change as knowledge, societal demands and context change. Contrary to Kemp (1997) who describes the innovation process as a linear one, this study agrees with Kline (1985), Rogers (2003), and Andersen et al. (2005) who describe it as a non-linear process that, instead of beginning with radical inventions, can be based on many feed-back loops between phases in the innovation life cycle. Further, Rogers and Kline (1985) state that a more strategic innovation can be applied existing technologies to modify or redesign these to fulfil real consumer needs, but they are also shaped by the general conditions in the technological and innovation system. Research also has a part to play in every stage of a technology's progress and may have different roles during the innovation process (Andersen, 2006).

According to Andersen et al. (2006) innovation is an iterative process, where it is sometimes necessary to take the existing knowledge and technology as standpoint and look for further improvements, both based on what is already known and/or on something completely new.  For example, with LEDs, one can see that the technology has been there for some time, particularly within the car industry and for decoration purposes. However, just recently, their development for use in TVs, computer screens and general illumination systems has taken off. LED development can be traced back to 1983, particularly white LEDs for illumination, but it is only since the beginning of this century that development is growing. This dissertation will argue that LEDs still have a huge potential for further development and implementation in many other applications. One of the implementation strategies could be in combination with natural light transport technologies, for example. This demonstrates that it is necessary to have a broader concept and understanding of the process of *new product* (application) development and not to limit this to technology development only.

Though traditionally the innovation process (see Figure 2.5a) is seen as a linear model of innovation, commercialisation and diffusion (Andersen et al. 2006; Kemp, 1997; Rogers, 2003), according to Nemet (2009) and Rothwell (1994), alternative emerging technologies experience a non-sequential process (see Figure 2.5b). According to Kline and Rosenberg (1986), instead of taking the research phase as a point of departure, it needs to be supported by research and development throughout the innovation process.

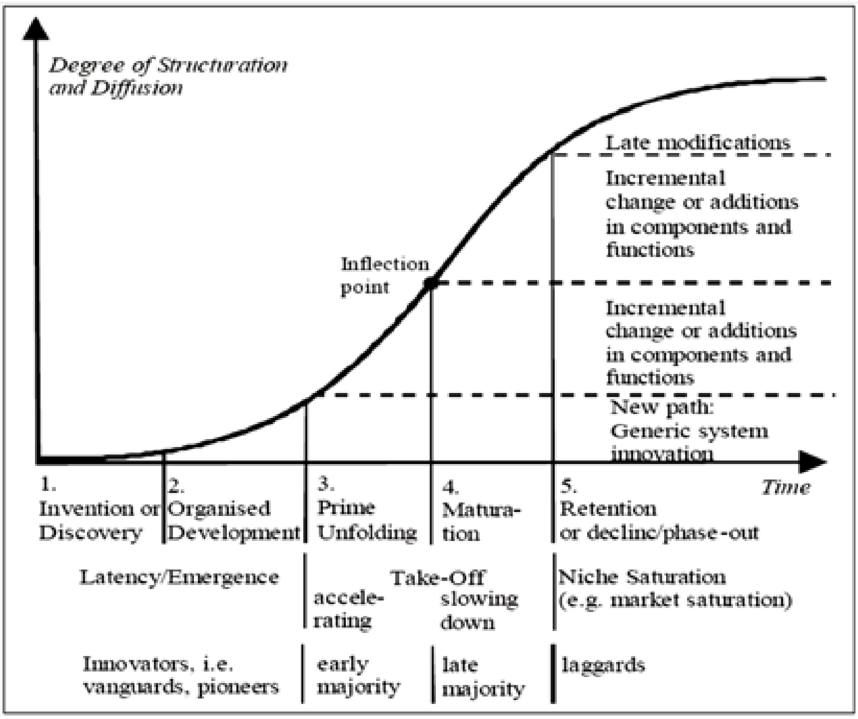



***Figure 2.5a:*** *Innovation phases or innovation life cycles (Rogers, 2003). White LEDs are between the stage of organised development and the prime unfolding phase.*

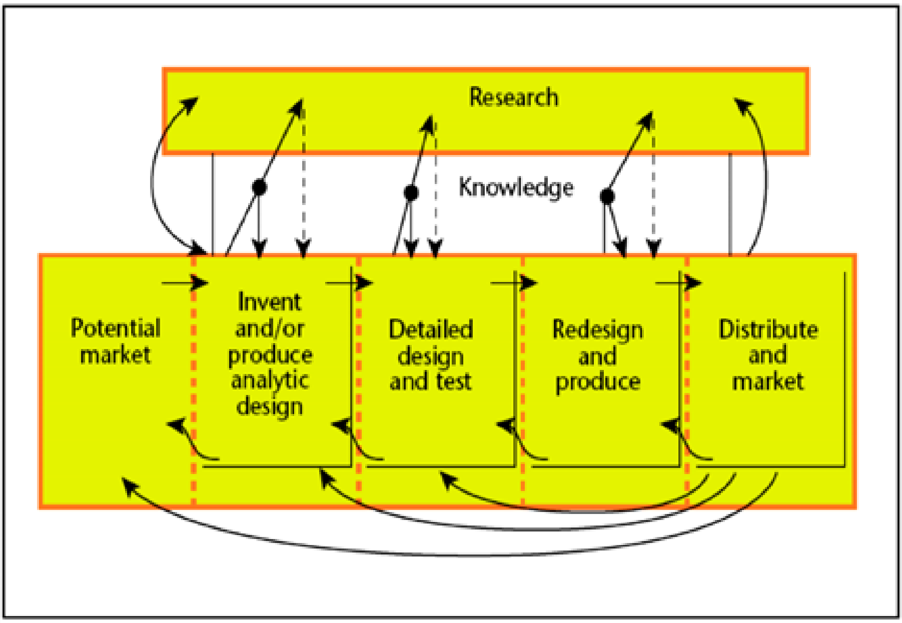



***Figure 2.5b:*** *Several feedback loops within the innovation process (Kline and Rosenberg, 1986 in Andersen; et al; 2006)*

***Drivers of the Technological Innovation system***

Furthermore, one has to consider that the implementation of LEDs for general illumination could still undergo many processes of redesign or combinations before being fully implemented. Nonetheless, one can also argue that LEDs are further ahead in the 'S' curve (see Figure 2.2) than solar fibre optic collectors, and much further ahead than hybrid fibre optic systems. Moreover, the technological potential of LEDs has gone through a very difficult period of recognition and, it is only just recently, that appreciation of their potential has increased. This is due to the political drivers in the facing-out strategies. The case for hybrid lighting systems is much further behind in technological development and, with a non-existing technological network, these systems have not yet won any ground, nor has there been any mention of their market implementation level in Denmark. Therefore, rather than pursuing a broad spreading of HFOSs on the market, what is currently important is to consolidate and demonstrate their technological potential. The problem encountered when dealing with a product-service system is that, during the convergence of different technologies, one cannot expect all the necessary technologies to be at the same development stage. This requires that one is able to evaluate the scientific and practical knowledge that is already available, as well as if there is a market and the necessary finance conditions for such technology.

The reason for improving the policy instruments for environmental technologies (as opposed to other technologies) is that environmental technologies are highly capital-intensive and this makes investment seem less attractive for the providers of venture capital. Extending the life span of the products, for example, would mean investments with long-term horizons, which would make them even less attractive. Nevertheless, it could make good "business" for the governments. Though the investment return is not measured in money, returns could be capitalised in a cleaner environment and security of energy supply (Andersen et al. 2006: 25), which are important milestones in reaching climate goals and energy sufficiency.

Apart from solving climate and energy problems, there is also the potential to create jobs and development in the region, spreading the benefits to other sectors by functioning as an engine of economic development. Thus, finding the policy instruments necessary to support the environmental innovations can contribute additional benefits through these spillover effects. It is also important to see how market-oriented policy instruments support the feedback loops mentioned above. Considering the traditional linear innovation model, two types of drivers have been described: mechanisms that either push (*technology-push*) or pull (*demand-pull*) products from the research and development phase to the invention phase towards their implementation (Foxon, 2003).

### *Technological Drivers and Market Drivers*

According to Nemet (2009), technology-push describes advances in scientific understanding which might determine or change the rate and direction of innovation (e.g. breakthrough discoveries). Such kind of research might be motivated by pure scientific curiosity or because new technological conditions make it possible. Whereas demand-pull is described by Nemet as: changes in market conditions that create opportunities for firms to invest in innovation to satisfy unmet needs. The conditions might be shifts in relative factor prices, geographic variation in demand, and identification of latent demand or potential new markets. Even when these are factual drivers, they are not exempt from failures, since, as Nemet states: "science and technology-push fails to account for market conditions, while demand-pull ignores technological capabilities" (Nemet, 2009).

### *Push-Pull Drivers*

In relation to *eco-innovations,* a third type of drivers or determinants has been described (Kline and Rosenberg, 1986; Rennings, 2000; Cleff & Rennings, 1999;

Kivimaa, 2007; Nemet, 2009). This is known as *policy or regulation push-pull mechanisms,* and these suppose a non-linear model which is mainly characterised by many feedback loops operating at the same time.

The *policy push-pull* instruments are, for example, environmental regulations that might require new scientific knowledge to find solutions to fulfil new legal or standard requirements, or market policy instruments that will create possibilities for new markets, for example, by generating unmet needs or using demand-side policies. Here, it is important to investigate financial possibilities during research and development, (private and public) financial mechanisms for research and development, and market policy opportunities which may support the innovation process within the illumination sector to complete the implementation of the innovation cycle.

The intersection between push-pull mechanisms implicates the intersection or combination of different types of (public-private) investments. Proponents of the Valley of Death theory (Murphy and Edwards, 2003) argue that entrepreneurs might face a big funding gap when passing from public to private financing, where neither private nor public finance resources are available, especially passing from technology creation to product development and towards an early commercialisation. This is called the Valley of Death because it is in this phase where many enterprises fail.

Furthermore, considering the non-linear process of innovation discussed above requires that both types of investments go hand in hand, not only when the technology undergoes the process to become a product, but during the whole innovation life cycle of invention, development and implementation. So what is relevant for this analysis is to identify where *different gaps* appear within the innovation cycle and what kind of instruments may be necessary to fill those gaps.

In this particular case, where LEDs are applied in combination with a solar fibre optic lighting system, the analysis is used in order to gain more knowledge of how general conditions will work out for a given new technology trying to gain a foothold in this technological system. This combination is called Hybrid Fibre Optic lighting system (HFOLS). Using HFOLS (as in this particular case) both the cost efficiency potential and improvement potentials according to consumers' perceptions are assessed. The objective of this assessment is to achieve a more effective dialogue and knowledge (feedback) from relevant stakeholders and from potential consumers. Together with the cooperation group, the study also aimed to provide more concrete information about the comparative advantages about this technology, thereby speeding up the rate of diffusion and, at the same time, achieving a more effective consumer-oriented design from an earlier stage of the innovation.

Apart from testing the technology, the intensive case study was used to test in praxis, how the conditions for developing an innovation can be achieved for a given new technology that is not yet part of the current innovation system in Denmark. To be able test these situations, the author participated in Venture Cup competitions and tested how private and public investors reacted when the idea of a hybrid fibre optical system was presented in a Business Plan written by the author for this purpose.

The author's suggestion for a schematic representation of the different elements of analysis in the technological innovation system (the third system of analysis) is shown in Figure 2.6.

In Figure 2.6 the conditions for innovation include both the relationships between the technological innovation network and the drivers for innovation. The solid lines represent the relation direction and the dashed green lines represent feedback from the evaluation of the conditions, suggesting changes to improve the general conditions. This study is interested in identifying changes that improve innovation in the lighting sector, but following the abstraction method, the hybrid lighting tool was used to "test" how flexible, robust and efficient those conditions are for this particular case. Through this particular experience, the study will propose changes that need to be made in the general conditions so that radical innovations (or applications in which LEDs might be incorporated), such as this one, can be further developed as a product and implemented.

The analysis of the lighting sector is placed within a white box, indicating that the general conditions in Chapters 7 and 8 will be written in plain text. The green text box indicates that in Chapters 7 and 8 the specific conditions for hybrid fibre optic lighting systems will be written within the green text boxes.

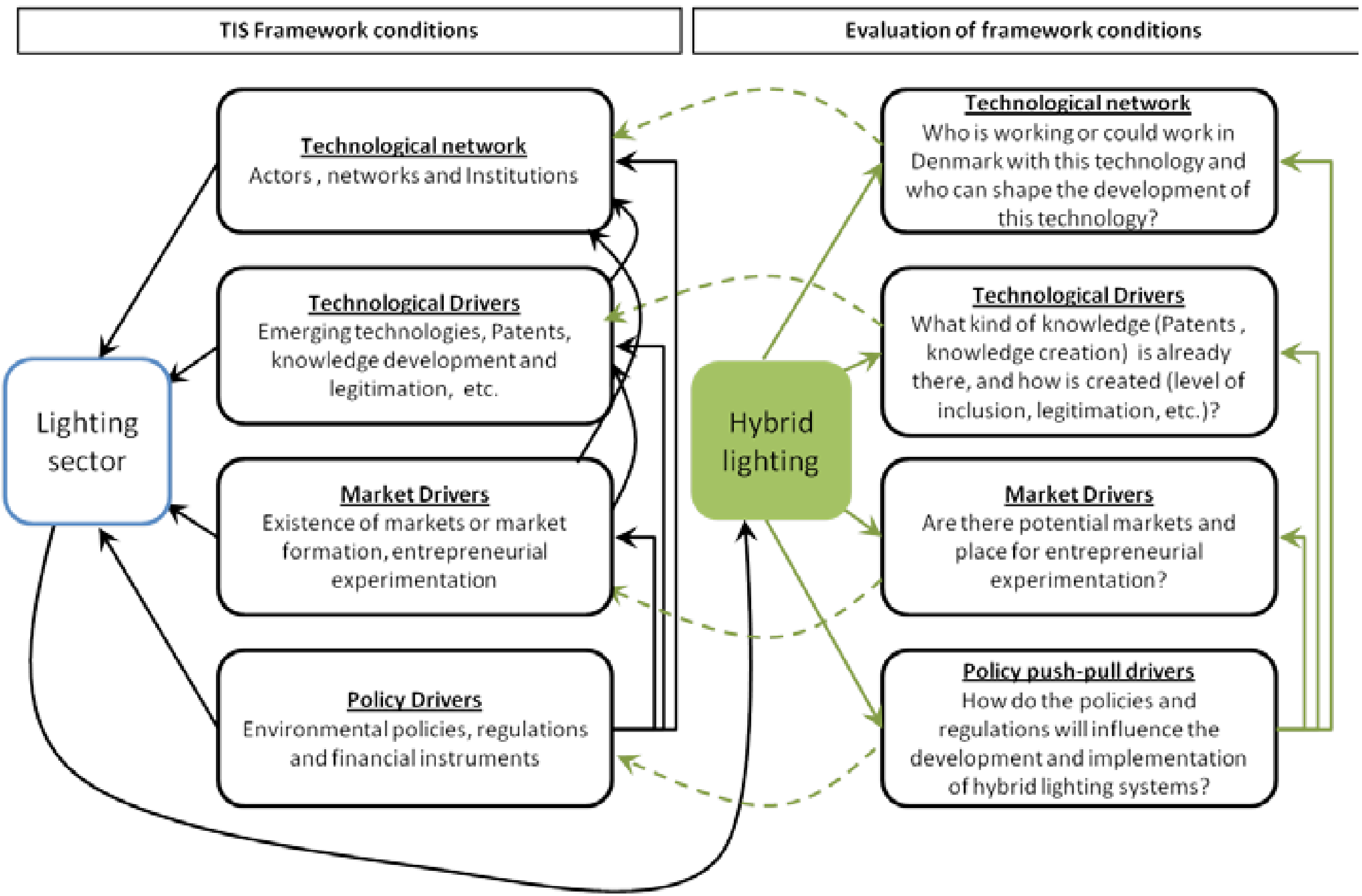



***Figure 2.6:*** *Technological-Innovation system conditions framework (Author's own diagram).*

Considering the three system levels that need to be taken into account when putting together eco-design and innovation feasibility studies, the whole methodological framework applied to this study is represented in Figure 2.7. This model considers the environmental impacts, the technological and socio-economic potential, as well as the necessary components, relationships and conditions to further develop the innovations in focus.

The three system analysis levels are indicated by the blue text boxes. Despite the several feedback loops (knowledge or/and financial support) shown in Figures 2.3 and 2.6, this framework provides a more straight-forward process, since in an early stage of the innovation process one is able to assess the environmental and socio-economic possibilities by including user practices and their perceptions to ensure that there is a real new value creation for the innovation. Furthermore, indicates the knowledge communication channels at the three systemic levels. This methodological framework also reveals the social processes that hold the three levels together.

## 2.4 METHODS

In order to fulfil the research objectives established for this dissertation, the following decisions were taken:

1. The study takes a holistic and systemic approach that ensures relevant innovation and avoids partial and unrealistic solutions.
2. The most relevant technologies that could help to solve the problem are identified and selected.
3. The study assesses the potential of the technologies, by considering three levels of interrelated systems, namely:

a. the Product system, where the major environmental impact that current technologies are causing and the most problematic stages in the illumination service Life Cycle are identified,
b. the Product-service System, where technological potential in relation to societal demands is considered. The study focuses on the technology(ies), assessing their potential in terms of fulfilling consumer demand and in terms of competitive price. And,

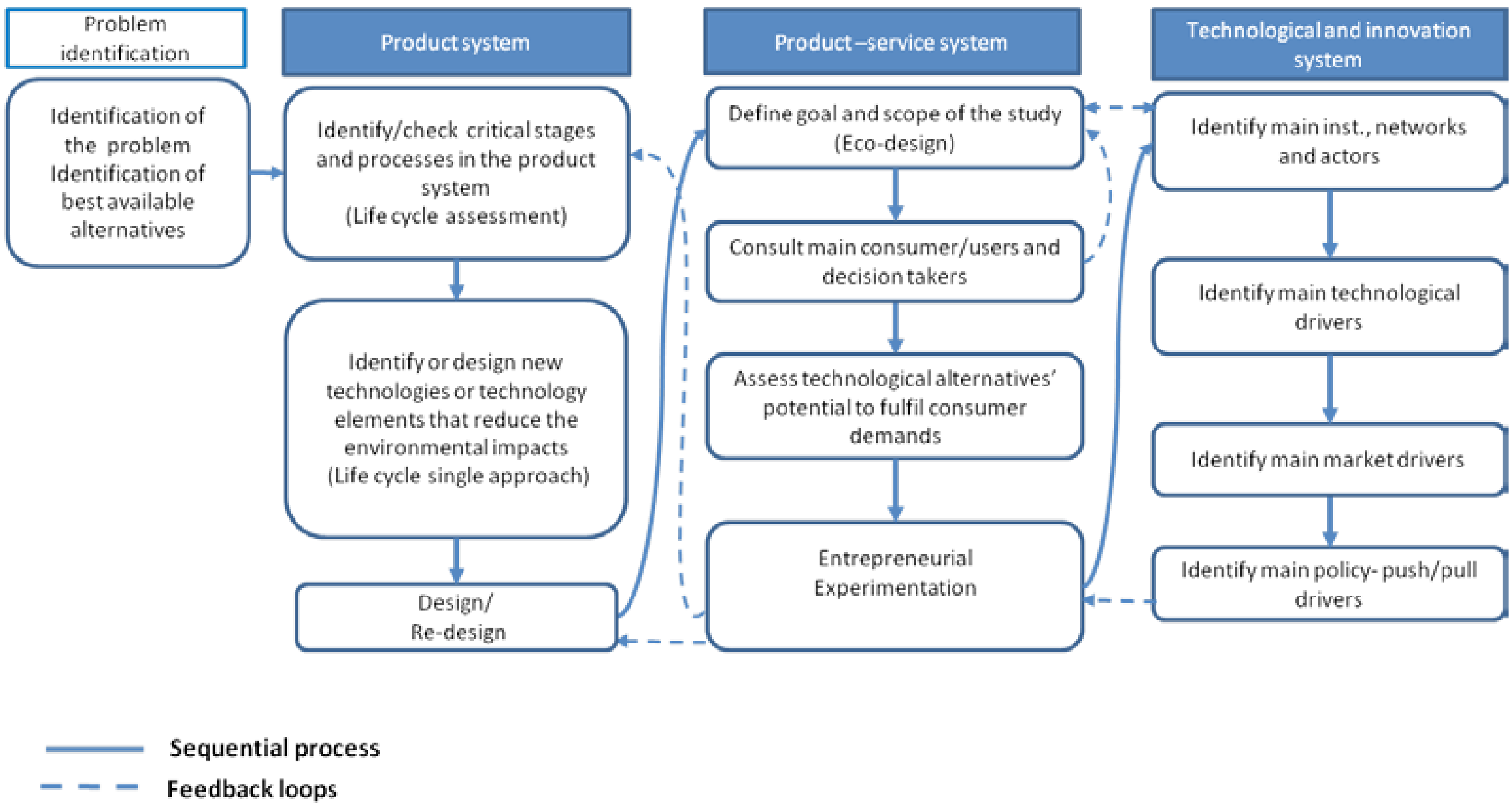



***Figure 2.7***: *Eco-design and innovation feasibility studies analytical method framework based on Figure 2.3 and 2.6 (Author's own diagram). This figure also illustrates the project design suggested for this thesis.*

c. the Technological and Innovations System, where structural conditions are assessed.

4. Drawing from level b) and c), intensive concrete research (see box 2.4) is carried out, taking hybrid fibre optic technology as a particular case to experience in praxis product service implications and structural limitations and potentials. The purpose of using a concrete case is to see how a given new alternative technology will enter this field, considering the current structural conditions in the illumination sector in Denmark. This case is carried out in parallel with, and as a part of, the study's analysis of the LED innovation system.

> Box 2.4
>
> Intensive concrete research design can be defined as an alternative research design which is characterized by a qualitative approach, concerning process, activities, relations and episodes of events. Intensive research principal concern is on how some causal process works out in a particular case or limited number of cases. (Sayer 1992)

5. Using the selected case, the author searches for solutions that can achieve energy savings by applying LEDs in combination with fibre optic solar collectors. This is done by using action research as method to achieve practical knowledge (Sayer, 1992). Here, the author, in cooperation with an interdisciplinary group of relevant actors working within same field but with different expertise, creates new knowledge by taking active part in the designing, making and testing of a concrete solution. This process is also known as "social learning" (Dyball, 2009).
6. At the Product-service system level, an eco-design perspective is combined with the Stages in the Innovation Decision Process Model from the Innovation System theory (Rogers, 2003). Further potential development within the selected case study is assessed in relation to technological, service and price improvements. Finally, using Stages in the Innovation Decision Process Model from the Innovation System theory (Rogers, 2003), the study gains overall understanding of the diffusion of an innovation as a social process.
7. As the intention is to obtain several benefits, such as the reduction of climate impact and the reduction of the use of energy based on fossil fuels in com-

bination with socio-economic aspects such as local business development, elements of eco-innovation theory are integrated into the framework.

8. In order to analyse the structural and systemic condition potentials for the development of alternative technologies (namely LED and LEDs in combination with fibre optic solar collector technology), elements from the Technological Innovation System theory (Bergek et al. 2008; Carlsson and Stankiewicz, 1991; Andersen, 2006; Hughes, 1987; Lundvall, 2007) are also integrated, in combination with conditions (drivers) of environmental innovation suggested by Nemet (2009) and Cleff and Rennings (1999). The analysis here aims to shed light on the dominant research and develop programmes, as well as capacity in the Danish technology and innovation system in relation to the feasible development of new technological alternatives within the illumination sector. The objective, considering these structural and systemic conditions, is to develop a more complete overview of the system conditions, which can evaluate the current and alternative technology strategies and see the potential to encourage faster and more radical re-adjustments.

### 2.4.1 Selection of case study

The European Assessment for Energy-using Products (EuP) for the illumination sector pointed out the tri-phosphate fluorescent lamp using electronic ballast as the best available technology for the office sector, and LEDs as the best not yet available technology in 2007 (Van Tichelen et al. April, 2007).

Yet, the EU Preparatory Studies pointed to the fact that even if the best available fluorescent lamps were implemented, electricity consumption, compared to what was used in 1990, will use *25%* more energy and produce *66% more* emissions of persistent organic pollutants in 2020, while emitting almost *30%* more $CO_2$ than in 1990 (Van Tichelen et al. April 2007)[1]. This concern is due to the fact that the consumption of lamps is projected to increase at a faster rate than their efficiency (which depends on the mercury content) and because, as mentioned earlier, there are many buildings in the trade and service sector whose illumina-

1 Note that the different percentage values are due to a changed relative distribution between the sources of power used in electricity production.

tion is below the level indicated by building norms. Complying with the norms will mean increasing electricity consumption.

The EU Preparatory Studies also predicted that light emitting diodes (LEDs) could be a feasible substitute for linear florescent lamps, if they became cheaper. However, the rapidly increasing floor space for buildings in this sector and the current level of illumination regulations, might overcome the efficiency that might be achieved by using LEDs. Furthermore, one has to consider that 1.6 billion people do not have access to any illumination service as yet. A third recommendation from the European Eco-Efficiency Preparatory Studies for the office lighting sector was to use alternatives that integrate the *use of direct sunlight in combination with artificial light* to obtain net energy savings (Van Tichelen et al. April, 2007).

Consequently, this thesis focuses on the development of LED technology, but uses as an intensive study/action research a combination of LEDs with a solar fibre optic collector (hybrid fibre optic system). The aim of this is to understand the current illumination technological system and the possibility for a re-configuration of the system, and if this has to include more radical solutions, such as hybrid systems. The objectives of the study in using this method is both to produce knowledge about the current LED technological system and about the potentials and problems related to the development of technological systems for more radical alternative technologies.

Hybrid fibre optic lighting (HFOL) systems are a combination of four technologies: solar collector(s), optical fibres to transport the natural light, a light source (lamp or bulb), and an automatic control system to switch from natural light to artificial light, and vice versa, which controls the amount of both natural and artificial light continuously during usage in the same luminaire. The overall idea is not new; the USA Department of Energy (DOE), in collaboration with the Oak Ridge National Laboratory, has published a large number of articles pointing to the advantages of hybrid solar fibre optical systems in terms of energy savings. However, when the author started this project (in 2009), it was not possible to purchase a hybrid illumination system. In the current market it was only possible to buy *solar fibre optic collectors*. This was one of the reasons why it was relevant to contact designers and experts with experience in this field. Consequently, in 2009 the author contacted a trans-disciplinary group of experts ( Dr Tech, professor Anders Bjarklev and PhD. Lara Scolari) from DTU Fotonik, who have vast experience in optic fibres and optical components; industrial designer Kent Laursen from Kolding School of Design, who has experience in luminaire design, and Ibsen el-consultant APS, who has previous experience of installing fibre optic solar collectors. They were invited to participate in a common externally-financed research project ("Hybrid lighting- directed towards a smaller ecological footprint"). One of the main results from this cooperation was the design of the hybrid lamps. This project also resulted in the design of several hybrid luminaires by students from Kolding School of Design (which took place during a five week course). Having these concrete objects gave the group the opportunity to test a hybrid system. To support the knowledge from artificial lighting devices, the author conducted further interviews with Associate professor Beata Kardynal, Senior Researcher Carsten Dam-Hansen and Professor Paul Michael Petersen who are leaders in field of artificial illumination devices research in Denmark and also from Technical University of Denmark (DTU Fotonik).

## 2.4.2 Extensive / Intensive research design

Sayers (1992) describes two methods of study cases: "intensive and extensive research designs" (Sayer, 1992). Extensive research is characterised by using as a design method, large surveys and considering many types of factors in order to establish what is underpinning innovation national level. According to Sayer (1992) even if there is an exhaustive analysis to identify the common associations and sub-groups, the result may be descriptive and uncertain. This is because there might not be a direct casual connection, yet it might be inferred that there is, because there might be a loss of information in aggregation. He further argues that extensive research designs create superficial knowledge (how good or bad things are), but there is no concrete knowledge creation of those that were surveyed. Furthermore, it may provide the basis for generalised actions that are not suitable for specific places and contexts. Sayers' *intensive* research approach to knowledge is an alternative to identify better contextual knowledge that can be used again in praxis. Consequently, this is why the HFOLS was selected as a "particular case"[2]. One of the main advantages of studies which are tied up to a particular conjuncture of a system is their potential of being generally applicable. Sayer believes this is the case because:

2 The terms "particular case" or "intensive case" will be use used indistinctly

*"…although at the level of concrete events the results may be unique, in so far as intensive methods identify structures into which individuals are locked and their mechanisms, the abstract knowledge of these might be more generally applicable, although it will take further research to establish just how general they are" (Sayer, 1992: 249).*

The advantage of carrying out this kind of research is that:

*"In some cases the unusual unrepresentative conjuncture may reveal more about general process and structures than the normal one" (Sayer, 1992: 249).*

This approach is chosen because the nature of the objects of this research are complex, heterogeneous and changing (becoming more sophisticated, more effective, etc.) and this makes it necessary to look for properties that can influence change on the behaviour of individuals. It also makes it necessary to define and chose the relevant properties and; examine them with a small number of individuals. The objective in choosing this method is that the knowledge produced can be used or be applicable to as many actors in this sector as possible, and a course of action can be recommended for the whole sector.

To achieve this, one needs a research design that generates knowledge, not only for the scientific world but especially for those that are involved, or have potential to be involved, in such change (including the researcher or the environmental planner), as the objective is to motivate changes in the environmental and economic plan. From this can be established that much of the information is of qualitative nature, but it can include processes,, measurements, activities, relationships, episodes and situations that can be cross-checked with more general situations or conditions (quantitative methods). The main intention when choosing to carry out an in-depth empirical study (an intensive study) is to learn how a process works in a *particular case* (e.g. designing hybrid lighting systems), what produces changes, and what are the actors' interests, competences and resources. This type of intensive research design was selected for its potential to see substantial relations between connections and the groups to which they are actually associated with.

### 2.4.3 Action research

One of the central objectives with a problem-oriented approach is to find the best possible understanding and organisation of phenomena and processes. Considering that science is a social activity and that scientific knowledge is not static, but rather evolving while looking for the best available explanation and organisation of phenomena and process, one needs to capture the objectivity and the subjective character of the world. One way of grasping this complexity is by using an action research as a method. Action research as a method tool fits into the approach of this study, as it derives from a general systems theory (GST) and is also grounded in a pragmatic philosophy (Greenwood and Levin, 2007).

According to Greenwood and Levin: "No system operates in isolation but it is created and bounded by structures and processes linked to other neighbouring systems" (Greenwood and Levin, 2007:58). In these systems, social relationships and processes are impacted by the physical world and the physical world is transformed by social activities. The above authors argue that action research is based on a pragmatic approach, where thought and action cannot be separated. In synthesis, the main principles stated in the abduction theory on how to generate knowledge using active observation, development of practical knowledge and knowledge development process as a social activity can be supported by action research as a methodological tool. This is relevant for this research because action research (AR) is also problem oriented and seeks contextualised solutions. As Greenwood and Levin describe it:

> *"AR aims to solve pertinent problems in a given context through a democratic inquiry, where professional researchers collaborate with participants in the effort to seek and enact solutions to problems of major importance to the local people" (Greenwood and Levin, 20007:62).*

AR is used as a method here, since the problem is not only observed from a distance, but the author herself gets involved in the process of finding a solution to the problem (using intensive research as outlined in Chapter 1). Furthermore, this method is used because in order to solve the problem it was necessary to get the relevant actors in the product-service system (potential consumers) and technological system to work together to find new solutions.

The way in which the author involves herself to achieve knowledge in relation to the specific case can be characterised as Co-creating participation. According to Dyball et al., in the Co-creating type of participation: "participants share their knowledge to create new understanding and define roles and responsibilities, within existing institutional and social constraints" (Dyball et al. 2009:188).

Consequently, during the development of this thesis the author suggested, applied and involved herself in two externally-financed research projects, in order to: 1) participate in the design and test of a hybrid fibre optic lighting system, and 2) further develop this technology and find new combinations of hybrid lighting systems. This allowed the author to go from the ideas level to the concrete level, by being involved into developing, materialising and testing the ideas. This kind of participatory research not only provided the author and her project partners with more knowledge, but had concrete material results, as it was possible to make a hybrid lamp, which were not available in the market at the time when this project began.

The author's role in this process has several implications. Firstly, she became involved at the same level as the rest of the participants and contributed from her own field of expertise. Secondly, the author acknowledged that by being part of the team, she was open to being influenced by interactions with the other actors. Thirdly, she become an agent of change, on the same level as the rest of the participants. Fourthly, in contrast to the other participants, as a researcher, the author uses a reflective attitude to observe the process both from the inside and the outside. This method is used to understand how a specific technology is implemented, and to understand how the general conditions operate as a whole. Fifthly, a reflective attitude allows the author to also observe her own position within her own system (e.g. what is her own and her institution's main contribution, and where can improvements be made).

The reflective characteristic of this approach has a two-fold purpose: on the one hand, the author wishes to understand how a new application may be implemented more quickly, and on the other, to enable her to understand and gain knowledge of the condition of the overall system as a whole.

The selection of research methods is carried out in order to gain contextual knowledge at different levels: firstly, of the characterisation of technological applications; secondly, to assess the societal implications (environmental impacts and development of new economic activities), and thirdly, of the instrumental framework (institutions, social relationships between them and financial instruments) that are necessary to support the concretisation of the societal objectives pursued by designing and innovating in this sector.

### 2.4.4 Analysis strategy

The basis for the methodological approach to problem formulation in this thesis is the recognition that there is a strong relation between the offer of lighting devices (what is already produced and its current material dimension), the way the illumination service is perceived, the way the production process for devices is organised, the interrelationships within the socio-technological network, consumer preferences, and current environmental and financial policies for eco-innovation. Because of the above, the relationship of the chosen subject area includes: the relationship between the products or services provided (life cycle of the product); the technological potential that can still be developed to satisfy consumer demands and to be competitive within the market (Product-service system); the habits and practices that dominate different fields converging in a physical space where illumination devices and services are provided (dualisms included in practice), and; the national conditions available to support eco-innovations in Denmark. Opportunities for reducing environmental impacts can be found within these relationships. In consideration of the above, the author carried out her analysis by using three levels of subsystems that, when combined, create a whole system (see Figure 2.8). The author suggests that eco-design and innovation studies should be structured in this way. Although the three different systems are used to provide a general analysis of the illumination system,  intensive concrete research is also carried out where hybrid fibre optic technology is used as an application when LEDs are used in PPS and TIS systems. In the particular case of hybrid lighting, a parallel analysis is carried out in order to assess the process, activities and relationships between the two levels of analysis using a concrete or particular case. It is additionally used to investigate how general conditions and relationships relate to the concrete case, and to argue why general conditions and relationships might change, or what the general effect may be of using those specific conditions for the Danish illumination sector as a whole.

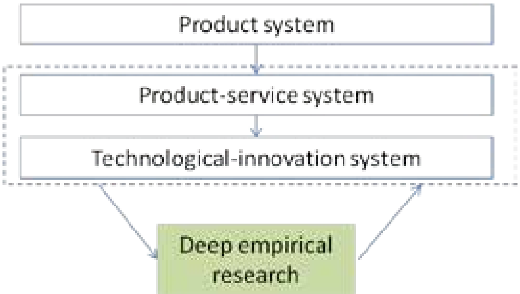



***Figure 2.8:*** *Analysis strategy.*

All these issues are found at different levels of systems, therefore, an integral approach was necessary to understand their relationship, and consequently using abstraction theory was the most logical option. This allowed the author to go from the concrete to the abstract in order to suggest concrete actions.

## 2.4.5 Research Methods

Following the discussion about the nature of the study objects selected for this research, both quantitative and qualitative methods were used. The reason for this is because, on the one hand,, it was necessary t*o explain* the environmental impact(s) of the study the object and its material-technological properties, which requires observation of causal relation to natural science phenomena. On the other hand, it was necessary to *understand* societal relationships (subject-object, subject-subject), which require the application of an inferential course of subjective meaning. In summary, it was necessary to interpret subjective perspectives that are bound to a specific context (material, spatial and time bounded).

***Data collection and validity***

Three main sources of empirical material are used to make the analysis: Interviews (explorative and in-depth), observations (direct and through active participation) and documental (scientific articles, books, statistical data and official reports). Most of the data (especially for the calculation of the energy efficient potential savings and the life cycle cost assessment) has been collected in an iterative process, which has given the opportunity to those who contributed information to check if that information is correctly managed. The iterative process was carried out by holding separate meetings with the designers and the engineers. Some of the main results of this thesis has been presented in conferences, workshops, public presentations, international conferences both in and beyond Denmark. Many of the actors who have contributed in some way to this thesis have had the opportunity to hear, discuss, use the results or comment on this work. The results of the first externally-financed project are available on the internet and these have also been communicated in public spaces such newspapers, TV and radio.

***Interviews***

*Semi-structured face-to-face interviews:*

Once the most relevant actors had been identified, face-to-face interviews were conducted, mainly carried out as semi-structured interviews. These types of interviews are neither fully fixed nor fully free (O'Lorey, 2004). Their main objective was to establish contact with the actors that were relevant to recruit as project members when carrying out more intensive research (Appendix 1).

These interviews have been electronically recorded, and a copy of each interview has been kept on CD. Relevant statements were extracted from the interviews and translated into English. These might present some bias, since translations usually are imperfect and might substrate part of the meaning of the comments. Therefore, electronic copies of the files have been stored on compact disc (CD). These copies of the interviews are stored in the original language (Danish) so that supervisors or other people who may be interested in the records (and can understand Danish) can listen to them and corroborate the statements. A total of seven face–to face interviews took place with actors in the value chain. Another three face-to-face interviews (Roblon, Parans and Velux ) took place, although, for practical reasons, these were not recorded. Nonetheless, notes were taken during these interviews and can be found in the author's thesis notebooks.

An additional three interviews were conducted with the shops assistants (Appendix 2). These were brief, since the persons interviewed preferred to answer the questions straight away rather than setting up an interview time at a later date. This interview situation placed a certain amount of pressure on the shop assistants, since they seemed impatient, as customers were waiting to be served. These interviews have been recorded, translated into English and transcribed.

***Consumer test***

To test the particular case (hybrid fibre optic lighting system) 10 face-to-face qualitative (semi-structured) interviews were conducted with office users (staff at Roskilde University) to establish the specific quality criteria for office lighting in general (Appendix 3). With this information, a "minimal statistical analysis" (O'Leary 2004) was made containing general criteria to support the study's qualitative data evaluating consumer acceptance of HFOLS. The population was university staff office users. To encourage the participants to take part in the test and avoid only recruiting participants that were interested in light, two bottles of French wine were raffled. The invitation was sent out using the intranet e-mail system at Roskilde University. Thirty-two individuals took part in the test and completed the questionnaire (Appendix 4)

Another in-depth qualitative interview was carried out for this system when the representatives of Stevns Municipality visited the exhibition and tested the system. Their participation in this test gave the impetus for the second externally-financed research project, in which collaborative work took place in order to further develop these kinds of systems. The objective of this test was not to generalise the results, but rather to explore the design issues that could be improved in this specific technology.

*Other type of communication*
Furthermore, personal meetings, telephone and e-mail communication has taken place with venture representatives, institutions supporting and promoting innovations, industry representatives participating in venture events, networking meetings and in business pitch events.

*Iterative communication*
Iterative communication has been maintained with *the respective project partners* at DTU, Kolding School of Design, IBSEN APS and Stevns County representative during the externally-financed cooperation projects.

*Stakeholder register*
The register of the main actors interviewed, identifying which companies they represent, where the interview took place, and their address and telephone can be found in Appendix 5

***Active Participation in two externally financed projects/intensive study***
This active participation had two-fold intentions: Firstly, the author wanted to enquire if it was possible to create a solution for this problem, and the second

objective was to assess a particular case study. This has value for this dissertation in terms of independent research and as an analytical strategy. Consequently, the author suggested, applied and participated in two externally financed projects:

1. The name of the first project was "Hybrid lighting systems, directed towards a smaller footprint". This project explored the energy, $CO_2$ reductions potential, the life cycle cost, technological and design possibilities of a Hybrid fibre optic system. A public report, plus information leaflets have been published and are available at: http://www.elforsk.dk/doks/341-043/341-043_web.pdf and http://www.designskolenkolding.dk/fileadmin/PDF/Hybrid_fiberbelysning,%20rapport.pdf
2. The name of the second project is "Fibre lighting goes to school". Its objective is to further develop the HFOL and make a comparison with other types of hybrid lighting systems using LEDs as base technology to supply artificial light. This project will end in March 2013 (see http://www.elforsk.dk/projektinfo.asp?projektID=203&m=4).

Both projects had been co-financed by ElForsk.

With the results of the first externally financed research project, project partners and the author became aware of more hybrid technological applications in which LEDs might be further applied. Besides further in-depth testing, by studying the HFOLS with a focus group (school students and staff), this process provided both the author and the project partners with new hypotheses that needed to be developed and tested again (second externally-financed project).

***Documentation***

The study used statistical data from Energidata, Elsparefonden, and Dong Energy, to identify where the main efforts should be directed. It also used EU and Danish reports on the development of lighting policies at a local and European level. Scientific articles and books were consulted to support the process of finding concepts, theories, methods and tools which were useful for the analysis of each chapter. Some of the articles about LEDs were provide by DTU Fotonik (Lyngby campus and Risø campus). The assessments of the compact fluorescent lamps were found on the internet pages of the Danish Environmental Authority. The reports from the LCA assessment at an EU level were also accessed through the internet from the official EU Commission pages.

***Limitations for the study***

At the beginning of this research, it was planned to make a LCA of the most relevant technologies. However, due to time and data availability concerns, it was decided to use available LCAs. The identification of critical stages in the life cycle of illumination devices is based on reports that are publicly available via the internet pages of recognised institutions, for example, Preparatory Studies for Eco-design Requirements of Energy Using products for office lighting made for the EU Commission. Although one of these is from OSRAM, it is compared with the other two available reports. In the case of the solar optical fibre system, the author requested a life cycle assessment from the firm Parans, but they replied that they have not made one. After  extensive research, it has not been possible to find a complete life cycle assessment of such products. Due to the scope and objective of this research, the assessment focuses on the use phase, but a more extensive research is required for these products. Energy consumption is only calculated using an input-output method, because the objective was to have a quick and simple overview of the energy consumption of such a system in order to see if this technology efficiency was feasible. The author is aware that an *emergy* assessment would have had a different, and even more positive, assessment when also calculating the savings in energy by using direct sunlight avoiding transformations and thereby unnecessary resources. Therefore,  a deeper research in this direction is recommended.

## 2.5 RESEARCH QUESTION EMPIRICAL- THEORETICAL CONSIDERATIONS

The research question for this thesis is formulated as:

Where and what are the main possibilities for the Danish lighting industry to efficiently reduce the illumination technology's $CO_2$ emissions in the office lighting sector and what conditions are necessary to support their implementation?

***Efficiency***

In general, the efficiency of this problem formulation is defined as the amount of inputs in relation to  outputs. In relation to illumination systems, one can argue that electricity consumption is one of the most important issues, and consequently one needs to focus on this issue. Even if the system can convert 100% of electricity to light, it does not mean that all the light can be appreciated by the human eye. It is important to consider different types of efficiency (see Figure 2.9 and Box 2.5). Schubert defines three different kinds of efficiency: *Internal quantum efficiency*, *external quantum efficiency,* and *power efficiency*.

However, although a component in a given area can produce a certain number of photons, it is uncertain if they can all be used by the device. To know how much the output really is, one needs to look at the *external quantum efficiency,* which measures how effective the process is, for example, by comparing the number of electrons that come into the system and the number of photons that one actually gets out of the device.

The third category: *power efficiency*, describes how much electric power is needed to produce a given amount of optical power. This is useful to establish, how much electric power is lost in the process, and finally, how much electric power one needs to produce one photon. (Schubert, 2007: 86 and 87).

Box 2.5

*Internal quantum efficiency* refers mainly to the input of electrons compared to the number of photons produced in a given area.

*External quantum efficiency* measures how effective the process is, for example, by comparing the number of electrons that come into the system and the number of photons that one actually gets out of the device.

*Power efficiency* tells us how much electric power was needed to produce a given amount of optical power.

*Luminous efficacy* measures how efficient a given source is to produce light that the human eye can see.

Schubert F., 2007

Although it is important to know how much optical power one can get, it is also important to know how much of that light a human eye can see, since the human eye can only perceive certain frequencies of the light. The *luminux flux* tells us how much visible light the human eye can really see. Thus, in order to measure how efficient a given source is to produce light that the human eye can see, one needs to measure it in terms of *luminous efficacy* (Schubert, 2007:284-285).

The interest for this project lies in analysing how much electricity must be used per photon (External quantum efficiency) for high luminous efficacy (so the users can see the light or have a better service of illumination, red circle). This comparison is what Schubert (2007:284-285) calls *Luminous efficacy.* Thus, from a technological point of view, this study will look at the most relevant alternatives which have the potential to further increase luminous efficacy.

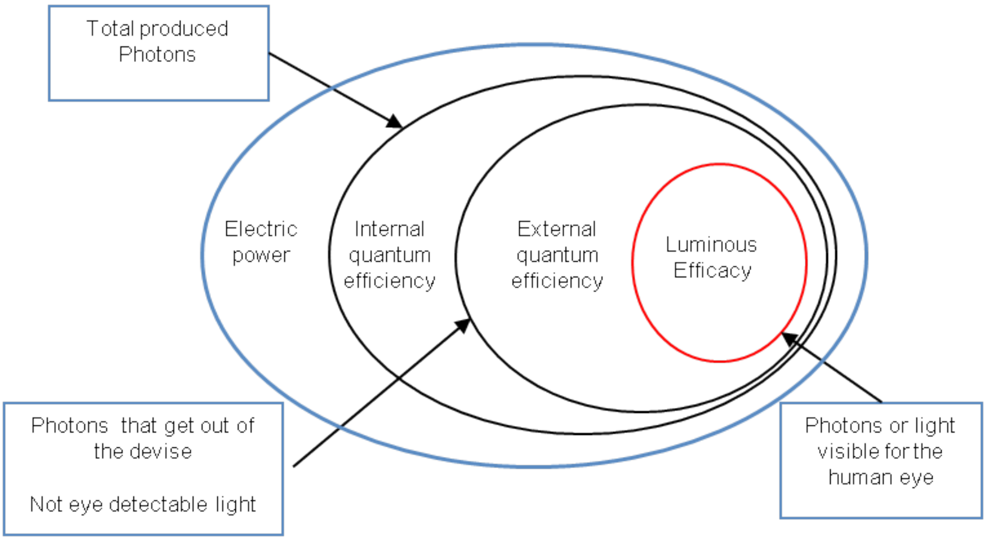



***Figure 2.9****: Illumination service, different types of efficiency.*

***Possibilities***

Possibilities in the problem formulation are viewed from environmental, technological, social, economic and financial perspectives. From the environmental point of view, one needs to look at the entire life cycle of the possibilities or alternatives and assess where the improvement potentials are. To do this, one needs to use the life cycle assessment approach and, therefore, it is important to analyse the selected alternatives in relation to energy consumption, material/resource consumption and their lifetimes. One of the main constraints is the energy efficiency on which the $CO_2$ emissions depend. From this stand point, it is important to determine which of the technologies has greater potential to improve luminous efficacy. The key objective is to reduce energy consumption and losses while *delivering a better service* (see Figure 2.10). Thus, one has to consider that in order to have illumination, one part of the problem relies on the performance of the electronic devices and lamps (the horizontal direction), and the other part depends on how the electricity is produced (vertical direction). From this, one can see that the technological possibilities lie in creating technologies that can provide the service of illumination, either by saving electricity based on fossil fuels or by making use of renewable energy.

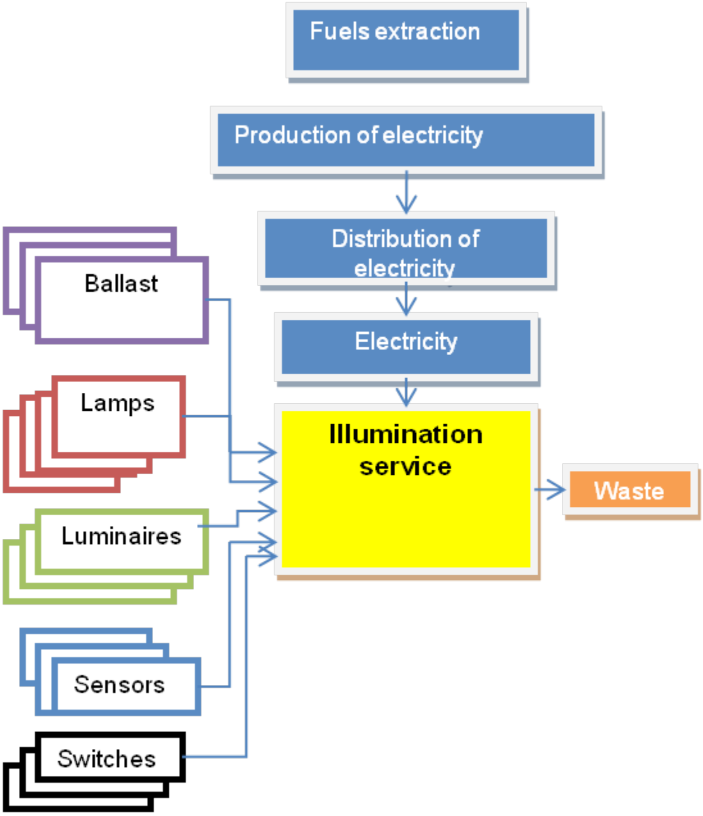



***Figure 2.10***: *Illumination systems. The illumination service is an intersection of many outputs: lamps, cables, sensors, luminaries and electricity.*

From a social perspective, one needs to be critical of the suggestion that fluorescent lamps are the right solution due to the limitations posed by the Restriction of the use of certain Hazardous Substances (RoHS) and the Waste Electrical and Electronic Equipment (WEEE) directives, since their luminous efficacy depends on their mercury content. This study believes that these two directives will set a limit for the development of the efficacy of fluorescent lamps. In relation to consumer demand, this will also set a barrier for delivering the necessary intensity. It can be argued that LEDs are still at a stage where further development in efficacy can be achieved. However, as the number of consumers is increasing and the area of offices and commercial/retail services is also increasing at a greater rate than the efficiency of the lighting, one need to supplement their performance to reduce the consequent environmental impact. As the consumption of primary energy is the main problem, attention will focus on how to reduce this consumption and, consequently, how to reduce $CO_2$ emissions. From a technological angle, one needs to establish what resources are available, in terms of research and technology, to further improve this option in Denmark by identifying the necessary research institutional networks, and if these do not exist, work out how to create them. From an economic point of view, it is important to see if the main drivers for innovation are in place (market, technological and policy drivers).

***Efficiently reducing $CO_2$ emissions:***
In the research question, the efficient reduction of $CO_2$ emissions is understood from a twofold perspective. On the one hand, this can be viewed from an eco-design angle: fewer hazardous materials and less resource consumption. Regarding resource consumption, in addition to materials, the study also places emphasis on the reduction of fossil fuels. On the other hand, an eco-innovation perspective is used to consider the possibilities for positioning the new products on the market (cost and service competitiveness).

To achieve $CO_2$ emission reductions efficiently, it requires that the technology can be developed, produced and implemented (diffused). Therefore, efficiency also has to be seen at the level of the technological innovation system. In other words, it is necessary to see how good the specific technological system is, to both generate the necessary knowledge and sustain the development and diffusion of different applications in which LEDs might be included.

***Conditions supporting development and implementation of environmental technologies***
'Conditions' refers to the relationships, institutional networks (knowledge institutions), knowledge, policy/regulations and market conditions of the technological innovation system that can make it possible for the innovations to develop and reach the market.

## 2.6 THESIS DESIGN

The theoretical, empirical and methodological considerations have generated the following sub-questions:

- What are the main environmental impacts of the illumination technologies and at which stages of the product system life cycle do the major impacts take place?
- Which technologies have further potential to reduce $CO_2$ emissions and continue to develop technologically in relation to life cycle considerations?
- What can make the new alternative lighting systems cost competitive?
- What can be improved in the product-service system so that alternatives can provide a more satisfactory service for the consumer, and what would be the added value?
- What possibilities are there to enhance the technological innovation network performance, and what can strengthen the technological drivers to further develop the suggested technologies in this sector?
- What can be done to develop a market for this sector, and what can be done to further improve the current push/pull polices and regulation to support these technologies' whole innovation process in the future?

The first and second questions are related to the Product System level, the third and fourth question are related to the Product-Service System level, while the last two are related to the Technological- Innovation System level.

These questions will be discussed as main issues in the following chapters of this thesis. Table 2.2 gives an overview of the chapters and their structure, as well as the theories and methods chosen to analyse each of the chapters.

*Table 2.2. Project design*

| Chapter | Working questions | Relevant concepts for the analysis | Empirical data | Expected result |
|---|---|---|---|---|
| **3.** **Identification of main environmental impacts in the product system** | What are the main environmental impacts of the illumination technologies and in which stages of the product system life cycle will the major impacts take place? | LCA as a concept and tool | • Relevant LCA reports on current and best available technologies<br>• Iterative communication with experts in this area<br>• EU Directives | Identification of impacts and the stage where improvements can be made, and identification of potential alternative technologies |
| **4.** **Assessing product-system technological improvement potentials** | Which technologies have further potential to reduce $CO_2$ emissions and continue developing technologically in relation to life cycle considerations? | Elements from ISO 14062 framework.<br><br>Eco-design approach to Luminous Efficacy | • Scientific articles and reports.<br>• 3 in-depth qualitative interviews with experts on photonics (DTU and OSRAM)<br>• Ten qualitative interviews with users in the office sector<br>• EU Directives | Identification of technologies with potential reduce $CO_2$ emissions and further technological improvement potential.<br><br>Assessing the energy and savings factor, adding a solar fibre optic lighting collector |
| **5.** **Assessing the life cycle cost of chosen alternatives** | What can make the alternative systems cost competitive? | Life cycle cost assessment as a concept and tool.<br><br>Elements from Competitive Advantage (Porter)<br><br>Diffusion of innovation (Rogers) | • Interview and communications with solar fibre collector producers<br>• Price information from our externally-financed project partner (electrical company owner)<br>• Internet sites<br>• Scientific reports and articles | Identification of the technology with the lowest $CO_2$ emissions, comparison of costs.<br><br>Identification of improvement potentials to reduce the costs |
| **6.** **Assessing consumer acceptance** | What can be improved in the product-service system so that the alternative systems can provide a more satisfactory service for the consumer, and what would be the added value? | Product-service<br><br>Diffusion of innovation<br><br>Eco-efficiency<br><br>Competitive Advantage (Porter) | • Consumer test (35 responses to questionnaires)<br>• Observations in the field and personal communication with architects, designers, shop owners and representatives,<br>• In-depth interview with Stevns municipality representatives | Identification of users, consumers and main decision makers in the PSS.<br><br>Further technological improvements and new added values provided by these systems |

| | | | | |
|---|---|---|---|---|
| **7.**<br>**Compo-nents and Conditions Analysis** | What possibilities are there to enhance the technological innovation network performance and what can strengthen the technological drivers to further de-velop the suggested technologies in this sector? | Technologic and innovation system,<br>Technological networks,<br>Technologi-cal innovation drivers (push drivers) | 7 in-depth inter-views with value chain stakeholders and experts in the photonic sector.<br>EU Directives, financed pro-grammes and national policy statements<br>Personal affiliation and participation in relevant networks<br>Participation in conferences and workshops | Identification of key stakeholders<br>Identification of main technologi-cal drivers<br>Identification of areas where changes need to be made |
| **8.**<br>**Market conditions, policy and regulations analysis** | What can be done to develop a market for this sector and what can be done to further improve the current push/pull polices and regula-tions to support these technologies' whole innovation process in the future? | Technological system<br>Eco innovation<br>Market drivers (pull drivers)<br>Policy &Regu-lation drivers (pull-push drivers)<br>Valley of Death theory | Experiences in two externally-financed projects<br>Experience in entrepreneurial activities | Identification of main potential markets<br>Suggestion for political and reg-ulation changes in the innovation system |
| **9.**<br>**Conclusions** | Where and what eco-innovations are possible within the current illumination sector while seeking to effectively reduce $CO_2$ emissions in Denmark, and what conditions are necessary to further support innovation in the illumination sector? | All those men-tioned above | The whole report | Answering the main question of this project. |

***Chapter 3 Identification of Main Environmental Impacts in the Product System***
This chapter assesses different publicly-available Life-Cycle Assessments on current and best available technologies and identifies the main environmental impacts, as well as where in the product's life cycle these impacts are worse. The idea here is to select the lamp(s) with the lowest environmental impacts and identify the process (inputs) that needs to be improved, and where the research needs to focus to find solutions. Therefore, life cycle assessment is used here both as a concept and as a

tool. The analysis is based on the results of the life cycle assessment made by the European Assessment for Energy using products (EuP) for the illumination sector. It focuses on the office lighting OSRAM LCA report (November 2009) and the LCA report by Navigant Consulting Europe Ltd. (2009). The study is supported by iterative interviews with experts in the photonic sector (DTU Fotonik) and information provided by the representative of OSRAM (personal interview and e-mail communication). EU Directives in relation to eco-design in the lighting sector and hazardous materials are also taken into account to evaluate the basic components of the different inputs needed to deliver the system of illumination.

***Chapter 4 Identifying Product- system Technological Improvement Potentials***
In this chapter, the technological improvement potential is assessed, focusing on technologies that, when considering their life-cycle assessment, show the best potential for providing illumination under a product-system perspective. In order to assess the environmental improvements of adding a solar fibre optic system, a single life cycle approach is used. It focuses on the use phase, which is where the worse environmental impacts occurred. The chapter is structured following the ISO 14062 for eco-design framework (definition of the goal and scope of the study). Within the scope, the functional-unit and the lifetime of the new product-system are defined. Additionally, an energy saving factor is calculated for the energy saving potential provided by a solar fibre optic collector, if it is combined with either fluorescent lamps or with LED lamps, according with available sunshine hours in Denmark. An in-depth discussion on the use of chemicals and materials is based on the EU Eco-design and Restriction of Hazardous Substances Directives. This is included in order to assess which of the technologies have further technological development potential in relation to current legislation and regulations. The assessment in this chapter is based on an iterative process with the project partners during the first externally-financed project and further interviews with experts in the Photonic sector.

***Chapter 5 Assessing the Life Cycle Cost of Chosen Alternatives***
In this chapter, the energy saving factor that was calculated in Chapter 4 is applied to assess the energy saving potential, including a commercially available solar fibre optic system to a LED based service-system (the whole energy assessment using a hybrid system). Linear fluorescent lamps are taken as the baseline technology and compared with the LED system and with a hybrid fibre optic lighting system (LEDs in combination with a solar fibre optic system). This comparison is done

using the DEEP's LCC tool (http://deep.iclei-europe.org). This tool is chosen for its simplicity of use in assessing the total energy consumption both for the initial and future cost. It takes into account the costs, such as materials, installation cost, etc. and evaluates them in terms of net present value. Future benefits are seen as the alternative(s) that, during their life cycle, have further potential to reduce the use of energy based on fossil fuels and will emit less $CO_2$.

The data collection for this assessment was carried out in cooperation with the interdisciplinary group working with the project "Hybrid Illumination Systems - aiming to reduce the illumination service footprint". The analysis in this chapter also makes use of face-to-face, in-depth interviews with key experts in Denmark, the producers of solar collectors in Sweden, and relevant internet sites. Further, statistical economic data and energy price trends are also used. Moreover, using a life cycle single approach once again, the study identifies where in the process one could reduce the use of materials and simplify the process to make the whole system more cost-competitive. As the LEDs are implemented in the solution tested by this study, light is also shed on the improvement potential for this technology to reduce the total life cycle cost.

***Chapter 6 Assessing Consumer Aceptance***

Based on the Diffusion of Innovation theory (Rogers, 2003), this chapter discusses previous studies of the elements that need to be considered when implementing energy saving lamps, in relation to consumer demands. The second part of the chapter identifies consumers or focus users, including a discussion of their role and what possibilities there may be to improve communication channels to further development and implementation of new lighting technologies at the product-service system phase. Using the value concept suggested by Porter and user perception in relation to new technologies, also from Porter and Rogers, the study identifies the characteristics of innovation that can differentiate these products on the market and thereby assess their real value for consumers and users.
The intensive case study is used to understand the feasibility of LEDs and new applications in which LEDs might be incorporated (e.g. HFOLS). The final part of the chapter reports on and analyses a consumer-user test, which was conducted to establish the potential for product acceptance by consumers and users.

***Chapter 7. Components and Conditions Analysis***

This chapter is built on the theories of technological and innovation networks in relation to strategic actors and institutions (components) supporting the technological development and the qualitative conditions for innovation considering aspects, such as, knowledge development and diffusion, influence of the direction of search, legitimation and development of positive externalities, and, finally, the technological knowledge that drives current innovation in the illumination sector (Technological drivers).

Consequently, the first part of the chapter identifies and analyses the roles of the technological innovation system's main actors and networks. The second part analyses how the social relationships work with the qualitative relationships, and assesses current existing knowledge. The intensive case study reveals both the general conditions for LEDs and the technological development conditions for HFOLS.

***Chapter 8 Market Conditions and Policy/Regulatory Analysis***

This chapter builds on theories of functions or conditions for innovation, but will focus more on market formation (as Chapter 7 already discussed the technological development and the technological drivers). Consequently, the qualitative elements (functions) considered are: entrepreneurial experimentation, market formation and resource mobilisation, which are related to financial mechanisms that support both the technological and the market formation. To focus on product development feasibility, this chapter builds on the knowledge-based entrepreneurship theory and Valley of Death theory to underline the importance of the business feasibility dimension and to identify important actors and networks that are not revealed in the technological innovation network (for example, seed capital, entrepreneurial networks, etc.) that are necessary to support business capabilities. These capabilities are crucial to building the bridge that will allow the technological innovation to become a product that may be sold in the market. The objective of this is to make it possible to close the innovation life cycle more effectively. Putting together the three theories, the study will analyse the financial programmes supporting both the research on technological development and market formation. It will also analyse how the programmes available to support the transition from technology to products are structured, and how these might be supporting or setting a barrier for the development of the whole technological and innovation system. In other words, what is the effect of push-pull policy drivers on the illumination sector and on the development and commercialisation of more radical alternatives, such as, HFOLS.

***Conclusions***

Finally, in the conclusions, the author will take the main points from all the chapters to answer the general problem formulation. It will outline where, in the life cycle of the product system, changes will need to be made and what type of inputs and processes this sector should focus on. It will also discuss which types of technologies are more feasible to continue developing and will identify alternative technologies. This chapter also points out the possibilities to further design and implement the suggested technologies, stressing the added value that these technologies might contribute and the possibilities of dealing with price development. Institutional and network capacity are discussed, and suggestions are given for specific actions to improve knowledge generation and communication, as well as more inclusion for new innovation initiatives. Moreover, there is a discussion of market possibilities for this sector and the instruments and business models that can be utilised to support further innovations in this sector in Denmark.

Designing and innovating sustainable technologies is a complex issue which requires the understanding of material conditions, processes and contextual circumstances. This process requires an interdisciplinary and broad approach, which is difficult to find in only one theory. Consequently, the author will discuss the role and importance of the use of different theories, concepts and case study in relation to the overall research approach used for this study.

The theoretical considerations and empirical material in this chapter will also take discuss the criteria that a feasibility study should take into account when pursuing design and innovation through an eco-design perspective.

# Identification of the main environmental impacts in the product system

The environment poses the most important challenge for human beings at the beginning of the 21st century. If we hope to plan for strategic technologies that really contribute to environmental performance within the illumination sector we must look at the availability of resources, energy consumption and health risk potentials derived from such devices.

Thus, when discussing the planning of emerging alternatives which aim to reduce the $CO_2$ challenge within the illumination sector, the first relevant questions to ask are: What are the main environmental impacts of the illumination technologies and in which stages of the product system life cycle do the mayor impacts take place? The main objective should be to strategically direct actions towards reducing current and future environmental burdens, using the LCA as a basis for this. These actions should focus on materials, energy, chemicals, and the impact of the conditions necessary to recover resources or absorb waste during the extraction, production, use, consumption and waste or recycling process. Using a qualitative approach, the author has gathered information and participated at relevant events which have been organised to inform on and promote the phase-out process for incandescent lamps. Using the LCA perspective, a critical analysis will be conducted of the Preparatory Studies for Eco-design Requirements for Energy-using Products (EuPs) and the Danish report by COWI for the Environmental Danish Authority, which gives an assessment of the environmental impacts of illumination devices. Documents published by the Danish Environmental Authority on materials and hazardous substances that are part of the alternative illumination technologies will be referred to, along with the Waste Electric and Electronic Equipment (WEEE) guidance. There will be a critical review of the life cycle assessments made by OSRAM and DEFRA (2009) comparing the environmental impacts from incandescent, fluorescent and LED bulbs. Additionally, the reports from some of the most relevant institutions within this sector in Denmark, such as the Danish Centre for Light (Dansk Center for Lys) will also be referred to.

## 3.1 BACKGROUND TO THE ENVIRONMENTAL ASSESSMENT OF ENERGY-USING PRODUCTS IN THE LIGHTING SECTOR

The decision to make an environmental assessment of energy-using products (EuP) was taken under the framework of the commitment of European leaders to reduce $CO_2$ emissions by 20% compared to 1990 levels.

The technical briefing on phasing out incandescent lamps states that the Spring European Council of 2007 invited the Commission to 'submit proposals to enable increased energy efficiency requirements on incandescent lamps and other forms of lighting in private households by 2009'. In this document, the commitment is to reduce primary energy consumption by 20% compared *to projections for 2020,* taking the *business as usual* scenario as the point of reference (EU Technical Briefing, 2008-12-08).

With the Directive 2005/32/EC On waste electrical and electronic equipment, a framework was established setting requirements for energy-using products (EuPs). A major concern was that these products account for a *large proportion* of the consumption of natural resources and energy in the Community. Another important point within this directive is the preventive character of the Community strategy on Integrated Product Policy. It also establishes the priority for the reduction of greenhouse gases within a sustainable framework where health, social and economic aspects are considered in the alternatives. Another important element is the consideration of the entire life cycle of the product in order to avoid environmental impacts outside the use-phase. This is necessary because "…it is estimated that over 80% of all product-related environmental impacts are determined during the design phase of a product" (EU, 2009). In March 2009, the EU Member States Experts of the Eco-design Regulatory Committee agreed that, from 7 September 2009, less efficient light sources should be slowly phased out (Commission Regulation (EC) No 244/2009).

Since 2005, most of the public debate has revolved around alternatives for the incandescent lamp. In a parallel discussion, the media and the main institutions related to the energy sector were pointing to CFLs as the main alternative. However, the emergent development of white light emitting diodes has also entered the discussion. On the 24 October 2008 (for example) the Danish newspaper "Ingeniøren" published an interesting article entitled "What will replace the incandescent bulb?" The conclusion, in the words of Kenneth Munck, the director of Danish Center for light, was that, "without doubt, the winning technology will be Light Emitting Diodes (LEDs)". Generally, the focus on energy saving within the illumination sector has centered only on the lamp instead of focusing on the many other inputs necessary to deliver the service of illumination.

The Parliament's decision was formally adopted by the Commission in March 2009. The decision-making process as to which type of lamps should be phased out was the outcome of an assessment using the MEEUP method (Method for the Evaluation of Energy-using Products), which builds on the principles of environmental impacts for the entire life cycle of a product (www.eup4light.net). It must be said that light emitting diodes were considered in the report, but they were not included in the environmental assessment, since it was argued that the color rendering and luminance were not yet at a level to be considered as a real replacement for existing sources. However, in the study they are recognised as the "Best not yet available technology" (BNAT).

Although the main discussion tends to centre on what should replace the incandescent lamp, the European Commission for the eco-design directives has carried out three preparatory studies (www.eup4light.net) focusing on the lighting service and covering different sectors. These are:

- Domestic lighting
- Street lighting, and
- Office lighting

The studies are preparatory, in the sense that they set the basis for energy-using product directives and for eco-design directives in relation to the European strategy for phasing out less efficient lamps.

***Office lighting***

Office lighting is chosen as a representative example of the tertiary sector, because offices consume a substantial amount of electricity, and also because this sector is where the most reliable information is found. Therefore, this study will only discuss the alternatives proposed by the preparatory study of the European commission focusing on the office sector.

## 3.1.1 Environmental assessment in the office lighting sector

As mentioned above, office lighting was one of the sectors in the preparatory study that provided the basis for the Commission regulation ( (EC) N0 245/2009) with regard eco-design requirements for fluorescent lamps. Office lighting was defined in this document as, "…a fixed installation for office work intended to enable people to perform *visual tasks efficiently*". The study included lamps, ballast and luminaries.

When establishing the functional unit, the preparatory studies consider it important to focus not only on the lamp and the ballast, reducing the functional unit only to the light output of single devices, but on the entire system.

The functional unit in this study was defined as:

> *"The maximum maintained useful luminous flux (lumen) from the luminaire according to the performance requirements for the office lighting task as set out in EN12464-([1]).*
> *'Maintained' means that performance depreciation parameters are taken into account (e.g. the luminaire maintenance factor LMF, lamp lumen maintenance factor LLMF, ballast*
> *maintenance factor BMF, ...) and 'useful' means that only the luminous flux received by the office task area and immediate surrounding area is taken into account. 'Maximum' means that it is the luminous flux in non dimming conditions" (Van Tichelin P., et al., 2007).*

1 See appendix 5

***Base categories***
The preparatory study was designed considering four base categories:

- Base case Category A1-cellular office (single person office: ca 20m$^2$): luminaire with two 36 W T8 LFL lamps, having an aluminum reflector and two electromagnetic ballasts operating the two lamps.
- Base case Category A1-open plan office (from 10-30 workers: ca 60m$^2$): luminaire with the same characteristics as for A1, but with different Utilisation Factor (UF) value.
- Base case Category A2-cellular office: luminaire with one 54 W T5 LFL lamp, having a refractor and one electronic ballast.
- Base case Category A2-open office: luminaire with the same characteristics as for A2 cellular office, but with different UF value.

***Scenarios***
The assessment also considered three scenarios: Business as Usual, Worst Case Scenario, and implementing the Best Available Technology. It is remarkable that in the three scenarios, the technology dominating this sector is the fluorescent lamp. Fluorescent lamps are described in the preparatory study as "a low pressure gas-discharge lamp that uses electricity to excite mercury vapor in argon or neon gas, this results in a plasma that produces short-wave ultraviolet light. To convert this UV-radiation into visible light, a phosphorous layer is applied at the inside of the glass tube. Mercury is an essential ingredient in fluorescent lamps. Unlike incandescent lamps, fluorescent lamps always require a ballast to regulate the flow of power or current through the lamp" (Van Tichelen, *et al.,* 2007: page 160).

If compact fluorescent lamps are the favorite to replace incandescent lamps within the household sector, then, according to the EuPs Preparatory study for the office lighting sector (Van Tichelen, et al., 2007), in the tertiary sector, triphosphate will replace halophosphate linear fluorescent lamps and electronic ballasts will replace magnetic ballasts. In fact, one can say that in the tertiary sector, the expected savings will be achieved by changing fluorescent lamps for more effective fluorescent lamps.

## 3.2 ENVIRONMENTAL IMPACTS ALONG THE ENTIRE LIFE CYCLE

Considering the distribution of impacts along the whole life cycle, the EuPs Preparatory study for the office lighting sector (Van Tichelen, et al., 2007) carried out a life cycle assessment and established that *the use stage* is the most dominant of all phases. As can be seen in Table 3.1, the use stage represents the biggest burden to the environment in relation to resources, waste, emissions to air and emissions to water. Therefore, when making strategic suggestions for the reduction of environmental impacts within the illumination service for office lighting, it is important to concentrate on this phase of the life cycle. Nonetheless, there remains the question of what process is most relevant to target the effort.

In figure 3.1, when looking at the process with the biggest impact, one can clearly see that *electricity consumption represents the biggest impact*. This, as was stated in earlier chapters, is mostly because the production of electricity is based on coal.

***Table 3.1:*** *Distribution of impacts over life cycle phases. Source: Tichelen, et al., 2007:150)*

| | Production | Distribution | Use | End-of-life |
|---|---|---|---|---|
| **Other Resources & Waste** | | | | |
| Total Energy (GER) | 1% | 0% | 99% | 0% |
| of which, Electricity (in primary MJ) | 0% | 0% | 100% | 0% |
| Water (process) | 1% | 0% | 99% | 0% |
| Water (cooling) | 0% | 0% | 100% | 0% |
| Waste, non-hazardous/landfill | 21% | 0% | 78% | 1% |
| Waste, hazardous/incinerated | 5% | 0% | 93% | 2% |
| **Emissions (Air)** | | | | |
| Greenhouse Gases in GWP100 | 1% | 1% | 98% | ***0%*** |
| Acidification, Emissions | 1% | 0% | 98% | 0% |
| Volatile Organic Compounds (VOC) | 4% | 10% | 86% | 0% |
| Persistent Organic Pollutants (POP) | 31% | 0% | 68% | 1% |
| Heavy Metals | 7% | 1% | 91% | 1% |
| PAHs | 49% | 2% | 49% | 0% |
| Particulate Matter (PM, dust) | 9% | 13% | 69% | 9% |
| **Emissions (Water)** | | | | |
| Heavy Metals | 18% | 0% | 82% | 0% |
| Eutrophication | 25% | 0% | 69% | 5% |

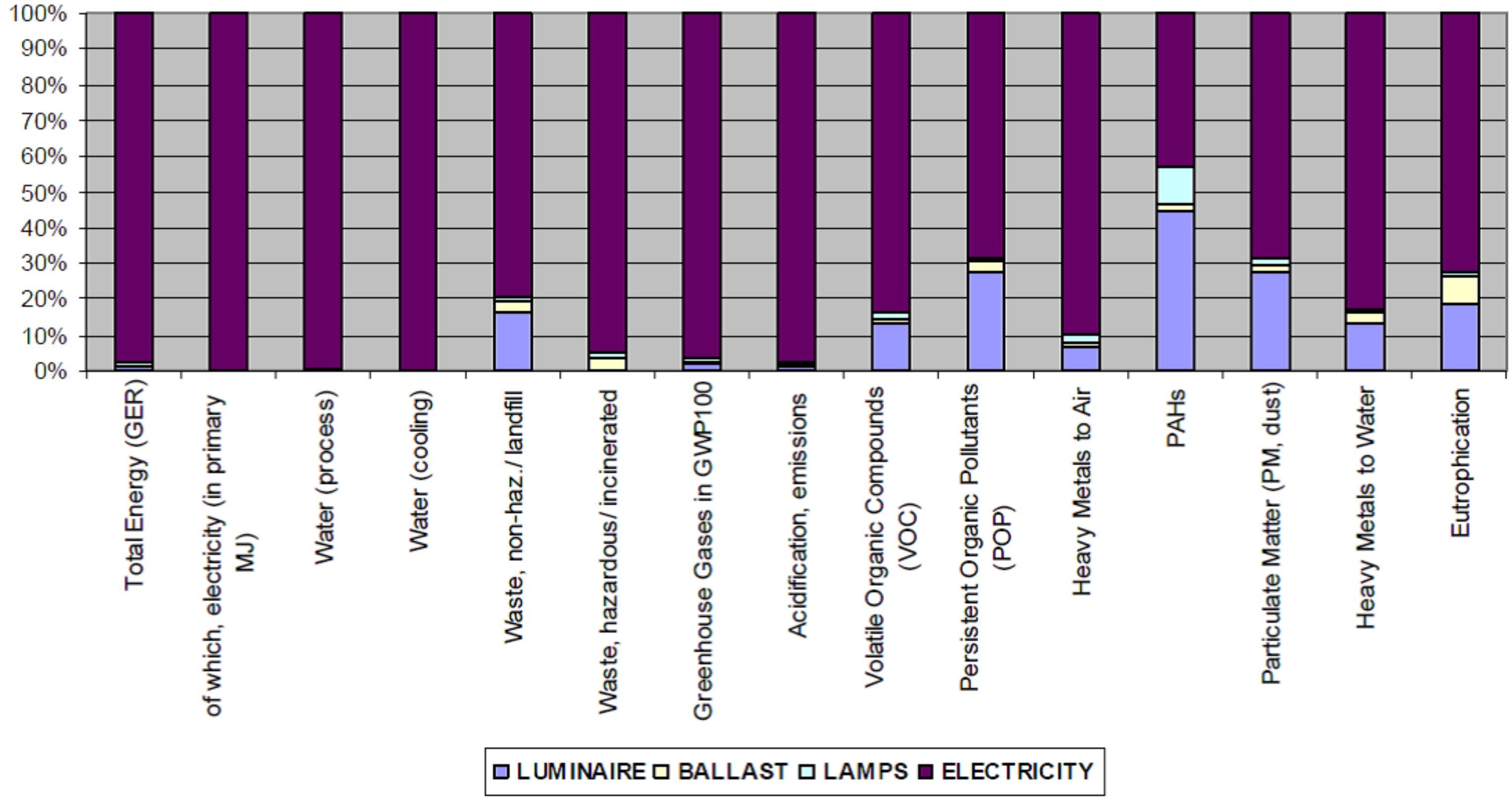



***Figure 3.1:*** *Distribution of impacts over luminaire, ballast use, lamp use and electricity consumption.*
*Source: Van Tichelen, et al., April 2007:149.*

The report from OSRAM (November 2009) has the same conclusions. However, this report is important, since it includes LEDs in the comparison (see Figure 3.2). Figure 3.2 shows that, in terms of primary energy demand, both types of compact flourescent lamps have similar environmental impact proportions to LEDs.

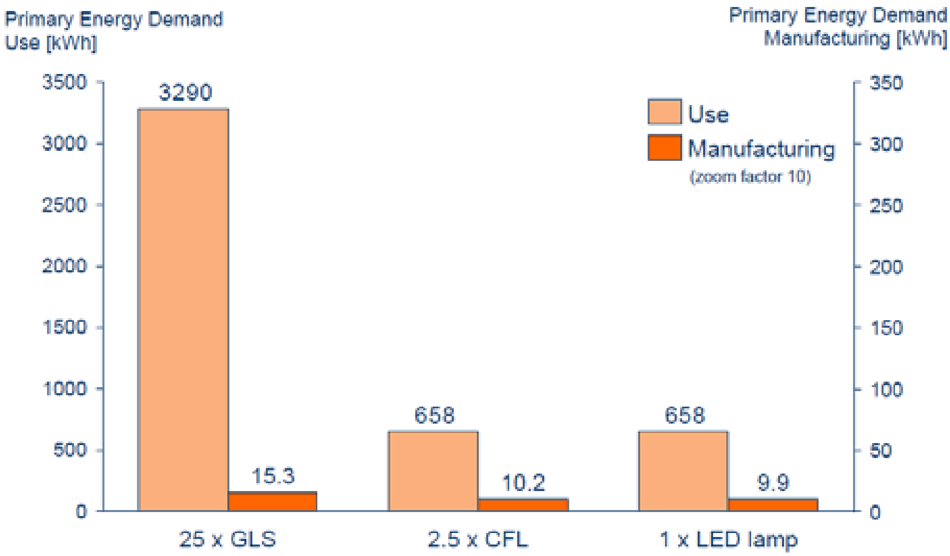



***Figure 3.2:*** *Primary Energy Demand for the manufacturing and use of all three lamps. Source: OSRAM, November 2009:15. (The following abbreviations are used: GLS - General Lighting Service, a designation of an incandescent lamp standard; CFL - Compact Fluorescent Light; LED - Light Emitting Diodes).*

## 3.2.1 Manufacturing and use phases

In the EuP Preparatory Study for the office lighting sector (Van Tichelen, et al., 2007), the environmental impact due to materials consumption (which is thought to be relatively small in comparison to the use phase) is mainly associated with the production phase of lamps, ballast and luminaries. As shown in Figure 3.1, some of the main results from the study indicate that the production of luminaires contributes to significant environmental impacts, such as, polycyclic aromatic hydrocarbons (PAHs, which are produced as by-products of *fuel burning* - some compounds are carcinogenic, mutagenic and teratogenic), non-hazardous waste, persistent organic pollutants (POPs, which can bio-accumulate) and heavy metals to air (for example, Hg), particulate matter dust (PM) and eutrophication (mainly the release of phosphate). Therefore, even when energy has the biggest environmental impact, the materials used to make the devices should not be neglected when providing illumination service.

From the OSRAM report (November, 2009) it can also be concluded that, when comparing the environmental impacts of only CFLs and LEDs,,the manufacturing phase is relatively smaller than the use phase. A strategic way of reducing the impact in this stage will give more consideration to the materials used. As can be observed in Figure 3.3, in most of the environmental impact categories LEDs seem to have a slightly higher environmental impact than the CFLs. This is due to the energy consumption for the production of aluminium heat sinks, ballast, and metals, such gold and copper.

DEFRA reports the following:
"The impacts for the incandescent lamp were driven almost exclusively by the energy in-use phase, which represented between 95% and 99.9% of the impacts across the fifteen life-cycle assessment categories. Looking at a few specific indicators of interest, it was found that:

- comparing the performance of an incandescent lamp to a T5 fluorescent lamp, the incandescent produces 5.7 times more carbon dioxide per unit of delivered light;
- the integrally ballasted CFL had a similar general profile to that of the integrally ballasted LED, although the LED had slightly higher impacts in all categories due to the aluminium content in the heat sink; and
- the incandescent lamp is the worst performing light source evaluated in this analysis due to its high energy consumption per unit of light produced.

The other life cycle process that makes a noticeable contribution to a number of the environmental indicators, particularly for the LED luminaire system, is the aluminium heat sink. For the LED systems, the largest contributor from the ballast components is the printed circuit board, while, for the T5 luminaire system, are the printed circuit board and the inductive coil. Creating a positive feedback loop, efficacy improvements for LED systems will not only reduce the energy consumption per lumen life cycle, but it will also enable manufacturers to reduce the size of the heat sink, and thus the environmental impacts associated with it" (DEFRA 2009).

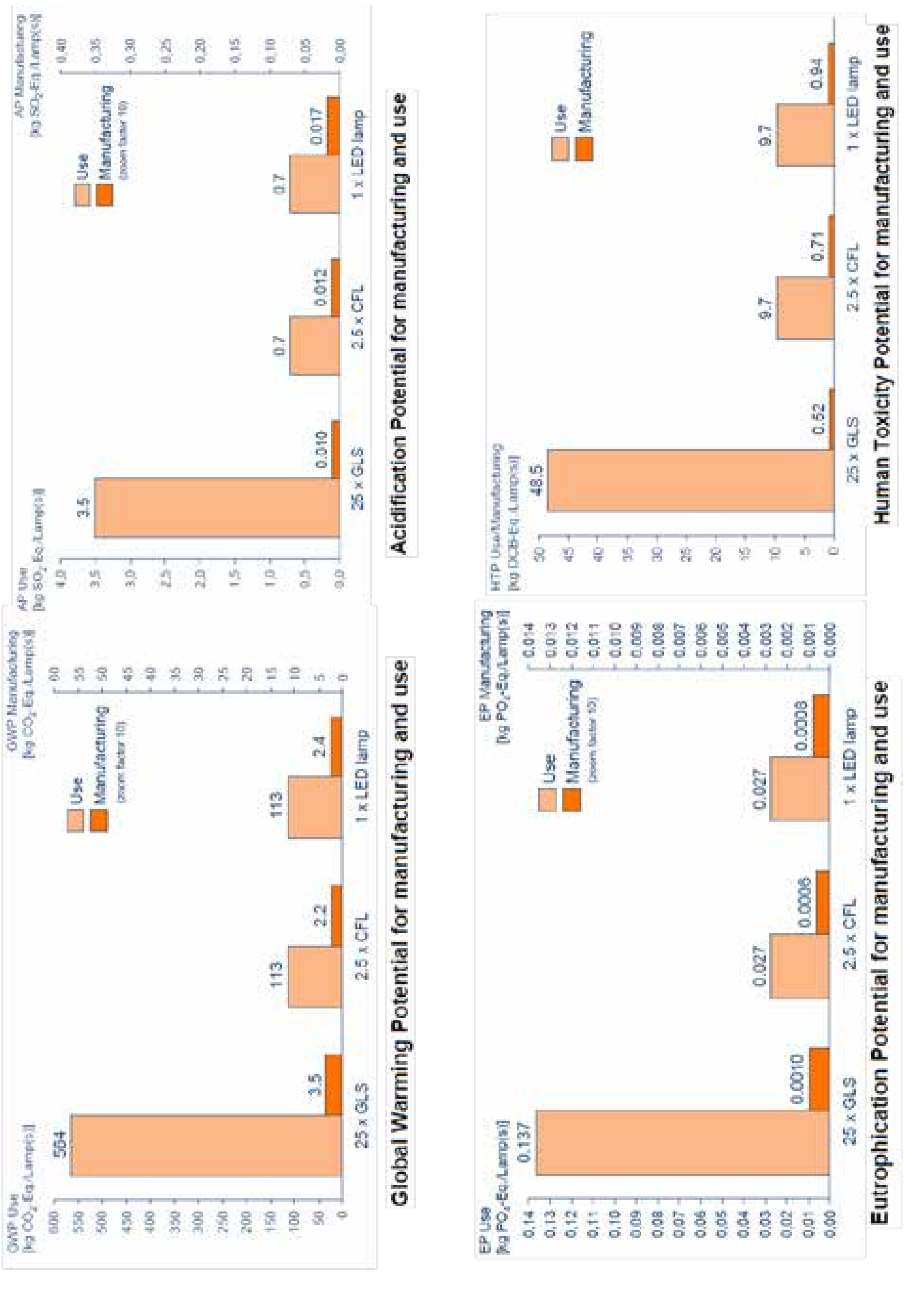



***Figure 3.3:*** *Selected main environmental impact categories for the three lamps. Source: OSRAM, November 2009.*

### 3.2.2 The consumption of electricity and the mercury issue

The total annual primary energy consumption of the office lighting stock in 2005 was 281 PJ, of which 271.73 Pj was due to electricity use. Office lighting generates 519 kt of non-hazardous (or landfill) waste and 7.2 kt of hazardous (or incinerated) waste, 12.5 MT $CO_2$-eq. of greenhouse gas emissions, and 73 kt $SO_2$-eq. of acidifying gases. It emits 5.7 ton Ni-eq. of heavy metals to air and 2.7 ton Hg/20 of heavy metals to water. It is estimated that 5 tons of mercury is contained in lamps that are disposed of each year (Van Tichelen, et al., 2007:153).

Although the mercury issue has centered on fluorescent lamps, one of the main results from the report stated that the major mercury releases are present in the production of electricity and that the amount of mercury saved by the reduction of electricity surpasses the risk of the mercury contained in the lamps.

The EuPs Preparatory Study for the office lighting sector (Van Tichelen, et al., 2007) considered that, in the waste phase, *only 10%* of the mercury contained in the lamps is not captured. It also established that no documentation was found to support this assumption, and therefore, it is assumed that “only” 0.5 ton of Hg is emitted to air and water. Consequently, the conclusions of the report are that the emissions from production and scrap recycling process are more substantial than the emission of mercury from the lamps in question.

However, the report *Cleaner products and better waste management for the illumination sector in Denmark* (COWI, 2006) states that an average of *85 kg* per year is used to cover the consumption of lamps containing mercury. The question is, how much of this mercury is really captured? The reality, in Denmark at least, seems to be different to that of the EU assumed average. According to empirical data, it can be established that up to *90% is not captured*. This figure was formulated by an electricity contractor when he was asked how many lamps from the tertiary sector are really disposed of appropriately.

> *“For all of those I sell… I think it is under 10% of what I get back to me. I have to charge those (clients) with ‘green taxes (which I have to fully pay to the state in form of taxes as well). I think it is a shame that the lamps do not get back to the right place... I, as installation contractor, need to receive the lamps back so I can send them to the municipality service “KARA”, which can then recycle them in a proper*

*manner. The responsibility of collecting this waste is actually on me, but if the users do not bring them back to me I can't do anything" (IBSEN, interviewed 2008).*

The emissions of mercury are serious because of the way in which electricity is produced in Denmark (see box 3.1). Therefore, while not neglecting the materials from the illumination services devices, the reduction of electricity consumption within the consumption phase constitutes one of the major challenges. A better strategy would be to focus on how to reduce electricity consumption, either by increasing the luminance efficacy, avoiding mercury in the lamps and using more renewable sources of energy, or by including more natural light in the building to reduce the use of artificial light.

Box 3.1

"Myth: The environmental benefits of energy saving bulbs are outweighed by the negative impact of the mercury in the bulbs
Fact: A-rated bulbs contain mercury, which incandescent bulbs do not; but mercury is also discharged into the environment during the production of electricity. To a large extent, Denmark uses coal to generate electricity, and burning coal leads to the discharge of mercury into the atmosphere, even if the smoke is cleaned.
Overall, less mercury is therefore discharged when we use energy saving bulbs because they use so little electricity and last for such a long time. Furthermore, many energy saving bulbs are taken to waste recycling centres where the mercury is processed in an environmentally correct way.
In all cases, choose an A-rated bulb containing the least mercury. You will often find the mercury content listed on the bulb's packaging".

Source:http://www.savingtrust.dk/consumer/products/lighting/lighting-myths/myths-about-a-rated-bulbs/index_html#negative impact

As was mentioned in Chapter 1, mercury is a heavy metal of special concern. It is toxic to humans and other living organisms, it bio-accumulates in food chains and is quickly absorbed by living organisms (including people). The Directive of the European Parliament and the Council on Waste Electrical and Electronic Equipment (WEEE) both state that the main concern is the environmental harm that arises when WEEE is treated in the EU without using proper procedures. Of particular importance are releases of heavy metals, like mercury, from compact fluorescent lamps (COM. SEC., 2008).

The document *Light Sources Environmental Labelling* (Danish Ministry of the Environment, , 2000), states that the Environment Secretariat also recognises the risk potential and urges for the introduction of an information campaign targeting those who buy lamps. However, as we will point out in Chapter 5, in the majority of cases within the workplace, the person who buys the lamps is not the same person who uses and eventually disposes of them.

In fact, when consumers and users become aware of the mercury contained in lamps, they view them as a significant potential health risk *inside their homes* and everyday working environment. Consequently, most users would prefer to avoid that risk sooner rather than later.

From the LCA perspective, one should constantly seek radical solutions (MacDonough and Braungart, 2002). That being said, any potential risk to human health should be radically avoided, as one of the criteria for the eco-directives is that its *implementation should not increase health risks* for consumers.

One of the exceptions, according to the RoHS Directive, is that there is no technology that can really replace flourescent lamps. However, with the latest LCA report on LEDs from OSRAM, it appears that this risk can be avoided. Therefore, one part of the strategy should look for devices that are mercury-free and avoid the use of any kind of hazardous materials right from the design phase. The other, should look at how to reduce the consumption of primary energy based on fossil fuels. Current legislation in Europe is also focusing on the mercury contained in the electronic devices, as indicated in the following statement:

> *"EU legislation to restrict the use of hazardous substances in electrical and electronic equipment and to promote the collection and recycling of such equipment has been in force since August 2004. More than four years later only about a third of electrical and electronic waste is reported to be treated in line with these laws and the other two thirds is going to landfill and potentially to sub-standard treatment sites in or outside the European Union". (Press release, IP/08/1878)*

Mercury should be avoided both in the production of energy and in the production of electronic devices. One cannot deny that there will always be some environmental impacts, since all product use energy or materials. However, from an LCA perspective, these impacts should always be investigated and *radically minimised*. It is obvious that if the electricity used for lighting increases, the mercury release will also increase if we continue to base our illumination systems only on fossil fuel sources. Therefore, the integration of illumination systems based on renewable energy could play a very important role.

### 3.2.3 Recommendations to reduce electricity consumption

One of the recommendations from the EuPs Preparatory Studies, Lot 8: Office Lighting is that, in order to reduce electricity consumption, service providers should consider using more daylight (Van Tichelen, et al., 2007). At the same time, this requires broadening the focus to other types of technologies, such as light controls, sensors, automatic dimmers, and technologies that enable the conduction of natural daylight into the buildings. However, the whole life cycle and environmental impact will need to be reconsidered when planning for any new system.

## 3.3 CONCLUSIONS

The life cycle stage in which environmental changes need to take place is the use phase of the illumination systems. If the options recommended in the eco-design directive for the office lighting sector, the Waste Electrical and Electronic Equipment (WEEE) (Directive 2002/96/EC) and the restrictions on the use of certain hazardous substances in electrical and electronic equipment (RoH) (Directive 2002/95/EC) are considered, mercury content continues to be a problem.

The main environmental impact is caused by the consumption of electricity, which in Denmark, is still highly dependent on fossil fuels (79.8 %). Therefore, designing systems that reduce the use of electricity, or finding ways of using direct sunlight more effectively would be of strategic importance.

In relation to energy consumption, Linear Fluorescent Light sources (LFLs) and Light Emitting Diodes (LEDs) have a similar impact. In the use stage, one of the main objectives would be to further increase the efficiency of LEDs and LFLs. Increasing efficiency, especially in LEDs, could contribute to a positive feedback loop in the reduction of heat sinks (which also have a significant negative contribution in several environmental categories).

In relation to the use of hazardous materials, mercury and lead should be avoided in the component parts. Other important impacts are caused by the ballast, both in LEDs and LFLs. Therefore, more research needs to be carried out to find more effective ballast, or to find ways to avoid its use (i.e. through local implementation of low-voltage systems). This will contribute to the reduction of the environmental impact of the whole system.

One of the main conclusions is that an increase of energy efficiency performance would be beneficial for the whole system. Therefore, it is important to establish the potential for LEDs or fluorescent lamps to increase their energy efficiency while providing a similar or an improved *level of service* for consumers, and what technological improvements would be needed to enhance the whole illumination system service and its environmental performance. Thus, the analysis in the next chapter will pay special attention to the possible technological improvement potential to provide more lumens when considering the positioning properties in relation to the whole product-service system.

Chapter 4

# Identifying Product System Technological Improvement Potentials

In the previous chapter it was established that the use phase is the stage where the main changes should be carried out and that electricity consumption is responsible for most of the environmental impacts related to the illumination service. In this chapter, the question to answer is: Which technologies have further potential to reduce CO2 emissions and continue developing technologically in relation to Life Cycle considerations?

As discussed in Chapter 3, when considering a replacement for the incandescent lamp, the environmental impact from different types of lamps, both fluorescent lamps and LEDs, appears to be quite similar.

As mentioned in Chapter 2, what is important in relation to increasing efficiency in this sector is the potential of the illumination devices to provide further luminous efficacy, which relates to the efficacy of the lamp, but it is also important to find ways to reduce the energy consumption, while providing the desired amount of luminous efficacy.

This chapter will start by analysing which of the current alternatives has more potential in continuing to provide higher luminous efficacy in the future. The second part of this chapter will assess the possibilities for the achievement of total electrical power reduction through a comparative analysis of the inputs and outputs of energy consumption. Because there are numerous producers of LED armatures and direct comparison of el-consumption and resulting light intensity is variable, in order to make a proportional energy evaluation, it was decided to compare CFL and LED bulbs. The rationale for this is that these devises have reached a higher degree of maturity. This is followed by a comparison of the inputs and outputs of a hybrid system using LED bulbs and a Solar Optical Fibre system. The result of these calculations is going to be used as the proportional saving potential in Chapter 5, where I will apply these factors on the specific office illumination system example outlined by IBSEN (an electrical firm). The data for this assessment has been gathered through an iterative communication process with PhD. Lara Scolari and Professor. Dr. Techn Anders Bjarklev from DTU-Fotonik.

## 4.1 LEDS OR LFLS... WHICH WAY SHOULD WE GO?

As discussed in Chapter 3, the Preparatory Studies for Eco-design Requirements of Energy Using Products (EuPs), using a life cycle assessment and a life cycle cost assessment, recommended the substitution of halophosphate lamps with triphosphor lamps using electronic ballast with daylight responsive dimming controls.

According to the AEA discussion paper (2009), future design of illumination systems should take into account the following issues:

- in-use energy efficiency of the lamp (or luminous efficacy)
- lamp lifetime
- maintenance of light output
- mercury content of lamp

### 4.1.1 Luminous efficacy

At the time that the Preparatory Studies were carried out, the luminous efficacy of LEDs was so low that this technology was not taken into consideration as a real alternative, arguing that the efficacies of warm white (WLEDs) with good colour rendering in 2006 was lower than 30 lm/W for LEDs, as opposed to 90 lm/W for fluorescent lamps.

Luminous efficacy has been one of the main limitations to LEDs becoming real alternatives, especially to office lighting. However, in September 2007 CREE announced its bulb, the Cree XLamp® with an efficacy of the cool-white LED of 72 lumens per watt and 52 lumens per watt from the warm-white device (Lovig, 2007). Through a press release, in May 2009, OSRAM announced that the typical efficiency of the Golden Dragon Oval Plus was about 90 lm/W in cold white (6500 K colour temperature), about 80 lm/W in neutral white version (5000 K), and for warm white 65 lm/W (4500 K). In 2009, OSRAM reported that "LEDs show efficiencies of up to 100 lumens per watt (lm/W), 160 lm/W have already been achieved in the laboratory" (OSRAM, November 2009).

At that time, the Preparatory Studies suggested that LEDs were the Best Not yet Available Technology (BNAT), but it was suggested that they would be the leading technology in the future, especially if LED prices dropped. The EuPs Preparatory Study, Lot 8: Office Lighting recommended further considerations to help reduce the environmental impact. These included: improving the reflectance of the walls, *increasing the utilisation of daylight,* utilisation of presence detection systems, and of course, awareness of energy consumption (Van Tichelen, et al., 2007).

According to Krames, et al., (2007), there are different LED attributes that make this technology one of the most promising illumination technologies for the future. Two of these attributes are their size and their capacity to direct light onto the desired surface. "The difference between this utilisation efficiency for LEDs versus conventional sources can be a factor of two, or even more in the case of task lighting" Krames, et al., 2007:171). With linear flourescent lamps, the light is emitted in all directions, and therefore, reflective parts inside the luminaire are necessary. According to Krames, et al, (2007), the luminous efficacy of LEDs is expected to reach 137 lm/W by 2015 (see Figure 4.1), while according to Paul Michael Petersen from DTU Fotonik (the leading institution on light research in Denmark) the LFL will hardly reach 120 lm/W.

Figure 4.2 shows the rapid development that LEDs have experienced over the last few years. From Figure 4.2 one can say that the development of the LFL has reached maturity, while according to Narukawa et al., (2010), there remains a possibility for further enhancement of the efficacy of white LEDs. In January 2012, LED professionals (2 January 2012) announced that EPISTAR had already been introduced to the market in 100, 120 and 150 lm/W LED chipsets.

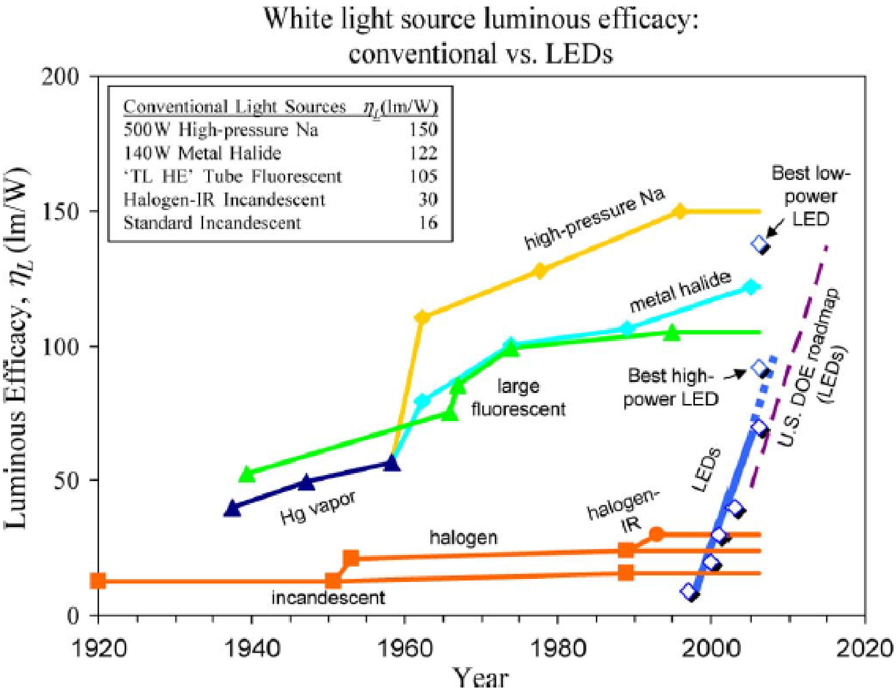



***Figure 4.1:*** *Development of luminous efficacy performance of white light sources. "Commercially available high-power LED performance is indicated by the points along the solid blue curve. Best documented high-power LED is 92 lm/W at 350-mA drive, while best low-current device is 138 lm/W (20 mA). The U.S. Department of Energy projections for commercially available high-CCT white LED performance is indicated by the dashed purple line." Figure and description source: Krames et al., 2008.*

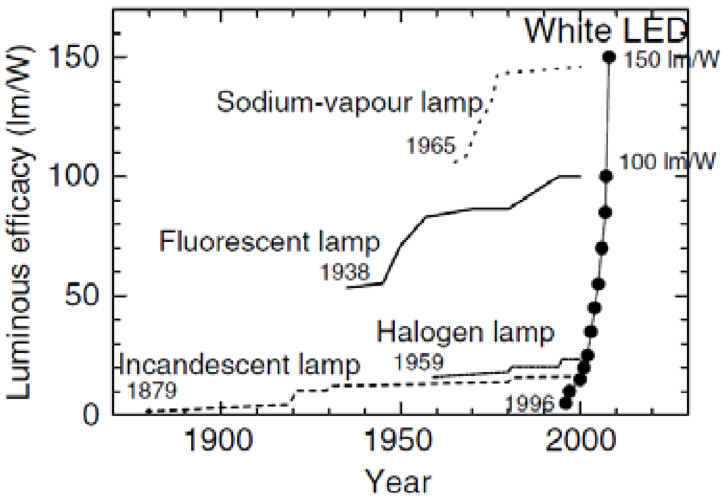



***Figure 4.2:*** *Historic developments of white LEDs in comparison to other conventional white light sources. Source: Narukawa et al 2010.*

### 4.1.2 Lifetime factor

Apart from having a high efficacy, it is important that illumination systems last as long as possible before requiring replacement, and that there is a high light output throughout their life. There is a general agreement that the lifetime of LEDs can be 3 to 4 times longer than that of linear fluorescent lamps (OSRAM, November 2009; and interviews with Paul Michael Petersen, and Carsten Dam-Hansen, 2009; Poul Erik Pedersen, 2009). Because of this, LEDs have more potential for development in the future.

### 4.1.3 Mercury content

Mercury content was discussed in the previous chapter. However, it necessary to stress that, the lifespan of an LFL depends on its mercury content. The best available technology known today for the LFL has already reached the limit on mercury established by the EuPs eco-label directive, which sets out that the normal life of an LFL has to be at least 12,500 hours, with a maximum of 5mg mercury. For long-life LFLs (with a minimum of 20,000 hours) the mercury content is a maximum of 8mg (AEA, 2009:17). Patterns of mercury use in the EU only anticipate further restrictions. Thus, there is little hope for future expansion of the lifetime of fluorescent lamps.

### 4.1.4 Product-service system-oriented potential

In relation to consumer preferences, LEDs have more potential than the LFL. The following are some of the most important characteristics of the LED:

- the robust presentation makes it safer than LFL for transportation and handling,
- there are no UV rays, so they are safe for humans and products,
- the potential for dimming and being directed to where light is most desired
- the colour of the light can be adjusted to meet consumer preferences and demands (Holm, 2005; and the LED- til belysning-nu og fremtiden – Conference, 2009).

### 4.1.5 Selection of the light transport system used in this assessment

As mentioned in Chapters 1 and 2, it is important to consider the luminous efficacy, but it is equally important to consider the total consumption of energy when delivering the service of illumination. Some of the recommendations from the EuPs Preparatory Studies, Lot 8 Office Lighting was that, in order to reduce electricity consumption, service providers should consider making greater use of daylight (Van Tichelen et al., 2007).

It is important to provide more lumens with less electricity consumption. As previously mentioned, this has to be done not only through the reduction of electricity, but also through the reduction of all resources. A technological way of achieving this goal could be by integrating systems that make use of renewable energy or that use the resource of daylight.

***Windows***

One of the methods to obtain more daylight is to add more windows to buildings. However, one of the disadvantages of this is that the level of insulation in the buildings is affected and the use of air-conditioning has to compensate for temperature variations, again making use of more energy. Another problem is the placement of windows, which are usually only possible at the sides of buildings (especially in buildings with more than two levels) providing illumination at eye level. The provision of light from side windows is often so uncomfortable that, even on sunny days, people use blinds and switch on the electric light in offices and classrooms. For large commercial centres, illumination by daylight is also complicated due to the number of levels and the size of buildings.

In addition, recent studies show that when more windows are included in buildings, the heating or cooling load increases the overall energy demand of the building's heating and air-conditioning systems. Asdrubali et al, (March 2010) state:

> *"The increase of the transparent surfaces decreases the need of electrical lighting and the corresponding environmental impact but, at least in the Italian climate, it enhances the energy needed for space air conditioning, so that the overall impact is increased. Also the choice of materials is very important, since an increase in the transparent surfaces may result in a higher environmental impact during the construction phase" (Asdrubali et al. March 2010:260).*

In practice, the use of windows for lighting results in additional electricity use, because the users place blinds on the windows and turn on electrical light (see Pictures 4.1, 4.2, and 4.3 below).

***Pictures 4.1, 4.2 and 4.3:*** *From left to right the pictures show a classroom at a university, an office in a research institution, and a meeting room in a county building. The three pictures were taken during the summer of 2009 in different public spaces when there was full sunshine outdoors. Note that in all three cases, the lights are switched on.*

Furthermore, the impact of constructing new buildings is relative small, as the number of new buildings represents a very small percentage of the whole building mass in Denmark. Although it is very important to construct new buildings in a more sustainable way, one of the biggest challenges in this sector is how to include more daylight in existing private and public office buildings in the service sector, without glaring or increasing the heating or cooling loads inside the buildings.

***Solar cells***

The European Union defines energy efficiency as the use of less energy input to provide the same level of energy service. In this respect, the illumination system that provides the highest potential to contribute to the increased energy efficiency (highest reduction of net electricity consumption) will be the most feasible in the future.  Because of this, solar panels are at a disadvantage when compared to systems that transport light directly, such as, solar fibre optical collectors. Solar cells need to first convert solar light energy into electrical energy, transport it, and then convert this energy into light again. Although technological development is advancing at a fast pace, the energy efficiency of a solar cell is calculated at being between 18 - 20% (Sun et al., 2010), while for a solar fibre optical system it is calculated between 60 to 80% (Feuermann and Gordon, 1998; Muhs, 2003; and Mayhoub and Carter, 2010).

***Solar optic fibre systems as a potential technologic alternative***

Considering the challenges mentioned above and the possibilities provided by sunlight, optical solar systems have become an interesting option. The reason for analysing the potential of such technologies is their ability to transport solar light directly, and therefore, save electricity in the use phase if an automatic switch on/off system is designed. Until today, optical fibre systems have only been considered as fittings or fixtures but, not as lamps. The reason is that they operate, as in the case of the Roblon systems (Picture4.4), with a central electric light source (high powered lamp). However, the Parans systems (Picture 4.5) are producing and selling systems that collect direct sunlight, which is then transported into buildings using optic fibres. The idea is not new, it dates back to the 1980s, and there are at least three companies in the world already working on this technology. Parans systems, however, are installed as a parallel system to existing artificial light systems and, even when the sun is shining, the artificial light is always on. Consequently, there are no real savings. If these systems are to be considered for work places, it is important that they have, and maintain, a certain level of illumination so the users do not have to stop doing their work to turn the lights on or off when the sun goes down or when it gets cloudy. Therefore, in order to provide the same level of service, it is necessary to design a reliable and stable hybrid system.

***Picture 4.4:*** *(left) Optical fibre illumination.*

***Picture 4.5:*** *(right) Solar optical fiber collector system*

As mentioned in the considerations for the LCA, the materials and area ($m^2$) required to produce a unit of energy also has to be taken into account. Therefore, even when one can argue that sunlight is unlimited and that installing more solar cells will be cheaper than using HFOLS, the constraints posed by use of materials and area required should not be ignored.

Based on the above, in order to assess the possibilities of integrating LED technology and Solar Optical Fibre system to provide an illumination service for offices in Denmark, an interdisciplinary collaboration project was proposed. Consequently, the aims, scope of the study, functional unit and system boundaries have been set as part of an interaction process within the working group for the project "Hybrid illumination systems directed towards reducing the illumination ecological footprint".

## 4.2 ASSESSING ENERGY CONSUMPTION

### 4.2.1Goal of the study:

To assess how much energy could be saved in the use phase by integrating a current solar fibre optical illumination system into an illumination system comprising LFL or LEDs.

## 4.2.2 Scope

While focusing on lighting and its energy consumption in Denmark, it was noted that a strategic sector to direct our efforts towards was trade, service, and the public sector (see Bjarklev et al., 2009). When examining the hours in which electricity is consumed for the purpose of illumination, it was noticed that almost 40% of this is consumed when daylight is "available" naturally.

It was also observed that new regulations concerning energy consumption in buildings increased the number of lumens necessary for working environments and made innovative solutions necessary that use less energy while providing satisfactory light (200 lux for general illumination/ 500 lux for reading-working illumination). Consequently, this study focuses on office lighting.

***Functional unit***

In order to define the functional unit, the obligatory and positioning properties of the service are specified in Table (4.1).

***Table 4.1:*** *Obligatory and positioning properties of the illumination system*

| Obligatory properties | Positioning properties |
|---|---|
| Supplying 500 lux to a working area in a typical Danish office | It should be possible to read and write |
| | It should be possible to work on a computer without having light reflections |
| | It should be possible to see peoples' faces while holding meetings |
| | The light has to be as close to daylight as possible (indirect sunlight) both in color and intensity |
| | It should avoid overheating |
| | The light should come from a comfortable angle (no blinding) |
| | The lamps should be aesthetically pleasing |
| | It should have flexibility (regulation of intensity) |
| | It should reduce $CO_2$ emissions |
| | It should not contain mercury |
| | There should be a feel-good factor when one is using daylight (indication of "green responsibility") |

In optimum conditions, the lifespan of an LED is calculated to be about 45,000 hours (OSRAM, 2010). To calculate the LED lifespan in relation to our functional unit, two different office working times were considered: 8 hours, when all users start work at the same time, and 10 hours if there is no fixed starting time, plus an additional hour for cleaning, making a total of 8 and 11 hours respectively. It was also assumed that the illumination service would generally be used 5 days per week. Estimated annual use was for 220 days, taking into consideration vacations and holidays in Denmark (www.workindenmark.dk and IBSEN –El ANLÆG A/S, personal communication). In this situation, the lifespan of an LED is calculated to be between 20 to 25 years if the lamp is designed under perfect conditions to allow the best heat dissipation produced by the LEDs. If the system was based solely on LEDs, the estimated optimal utilisation time would be approximately 20 years.

Additionally, the lifespan of the *fibre optical system* is about 20-25 years, according to the interview with Parans representatives. Therefore, the lifespan for this system (LEDs+solar optical system) is set at **25 years**.

**The functional unit** was defined based on the above-mentioned criteria as:

**The Illumination of a work station in a typical Danish office (1.5 m x 1 m) = 1.5 m$^2$, in an office space of 6.5 m$^2$ during a period of 25 years.**

### 4.2.3 System boundaries

In order to make a comparison of energy consumption based on three different technologies, consideration was given to:

1. a system based on LFL
2. a system based on LEDs
3. a system based on LEDs combined with a solar fibre optical system

All the systems considered include lamps, luminaires and ballast, see Box 4.1.

Box 4.1

1. A "*lamp*" is a "source made in order to produce an optical radiation, usually visible"
2. A "*ballast*" is "a device connected between the supply and one or more discharge lamps, which serves mainly to limit the current of the lamp(s) to the required value"

Note that a ballast may also include the means for transforming the supply voltage, correcting the power factor and, either alone or in combination with a starting device, provides the necessary conditions for starting the lamp(s)

3. A "*luminaire*" is "an apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes, except the lamps themselves, all parts necessary for fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting the lamps to the electric supply" (Van Tichelen et al., 2007)

As mentioned in Chapter 3, the phase in which the major impact is detected is the use phase, and this is due to the consumption of energy. Therefore, this study will only assess energy consumption, and the boundaries of the analysis will be set to include the use phase only (see the dashed blue box in Figure 4.3). Consequently, the system was depicted similarly for all the three systems. As the use phase is where more energy is consumed, the boundaries were set around this stage with its respective inputs/outputs, as shown in Figure 4.4.

In order to further explore the energy savings that would be made if a solar fibre optical system was added, the following system is depicted in Figure 4.3:

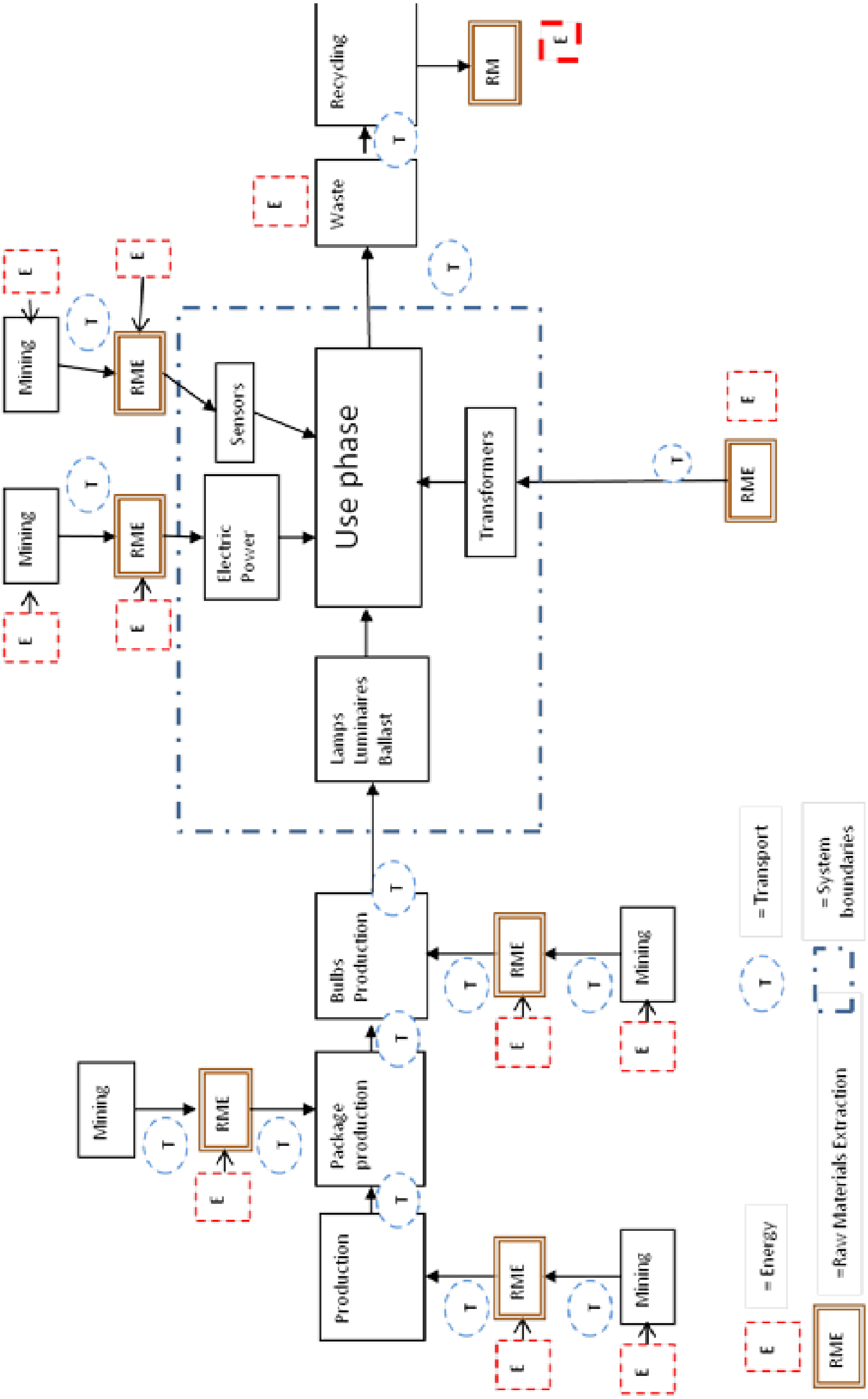



***Figure 4.3:*** *System boundaries of the illumination service for LFL and LEDs.*

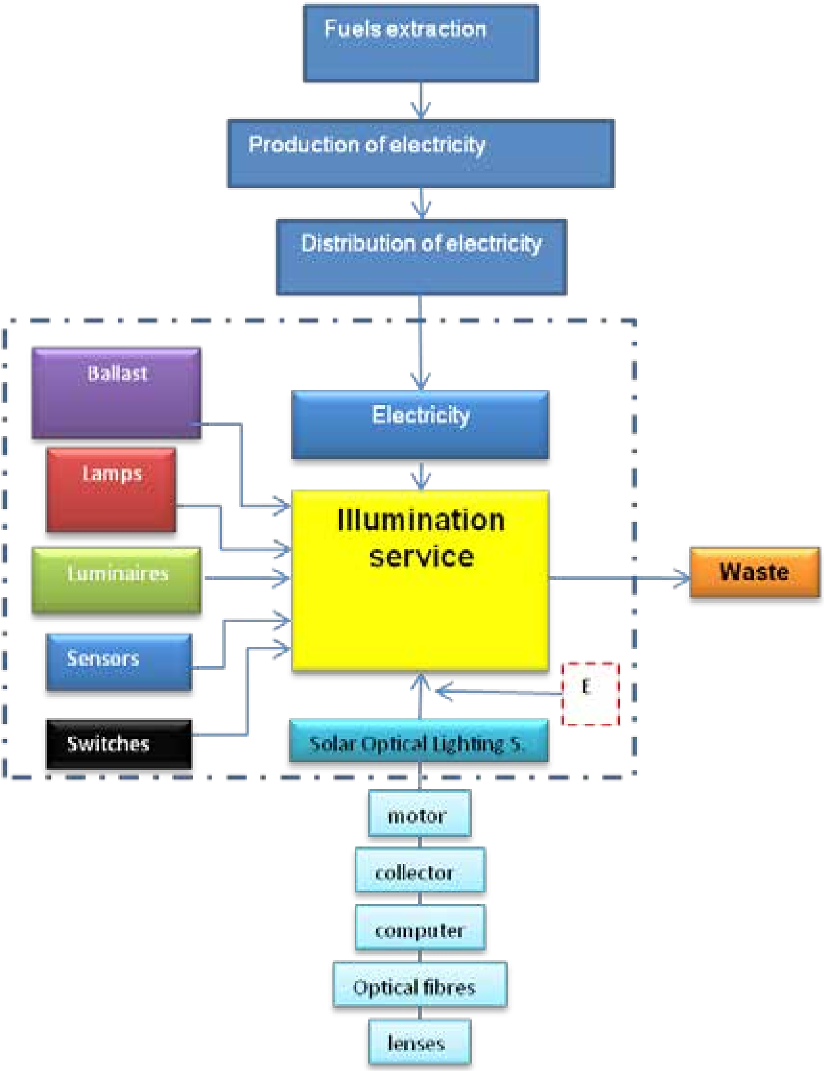



***Figure 4.4*** *System boundaries for a hybrid illumination system.*

## 4.3 ENERGY INPUT VS. LUMEN OUTPUT IN A SOLAR FIBRE OPTICAL SYSTEM

To calculate the functional office working time when there is bright sunshine, a working day of 7.5 hours plus a half hour for cleaning was assumed, making a total of 8 hours. This modality was named "single-user's office". Further consideration was given to the time when users arrive at the office, as this might vary, particularly if the office accommodates more than one employee. For example, instead of starting at 9.00am, people might start at 8.00am or 10.00am, thereby extending the time when the office is used. For this situation, 10 hours + 1 hour cleaning have been assumed, making the functional office working time a total of 11 hours. This modality was named the "multiple-users' office".

From February to October working hours are located where there is full daylight. The number of hours with bright sunshine is estimated as a simple ratio between the number of work hours with daylight and total number of daylight hours. For the single-user scenario, this is done by correcting the number of working hours with daylight for the months of November, December and January by reducing the number of hours according to the number of working hours without daylight. For the multiple-user scenario, the correction is done during the months of January, February, March, October and November (see Tables 4.2.a and 4.2.b, and Figure 4.5).

***Table 4.2 a:*** *Office functional working time with bright sunshine in Denmark. *Almanac for Denmark, (Almanak for Danmark).*

| Month | Sunrise* | Sunset* | No. of daylight hrs. | No. of minutes with daylight | No. of days | Approx. daylight hours | No. of working days |
|---|---|---|---|---|---|---|---|
| January | 08:31 | 16:10 | 07:39 | 459 | 31 | 237 | 20 |
| February | 07:36 | 17:15 | 09:39 | 579 | 28 | 270 | 20 |
| March | 06:27 | 18:14 | 11:47 | 707 | 31 | 365 | 23 |
| April | 06:06 | 20:17 | 14:11 | 851 | 30 | 426 | 18 |
| May | 05:00 | 21:16 | 16:16 | 976 | 31 | 504 | 19 |
| June | 04:26 | 21:57 | 17:31 | 1051 | 30 | 526 | 22 |
| July | 04:47 | 21:45 | 16:58 | 1018 | 31 | 526 | 22 |
| August | 05:42 | 20:47 | 15:05 | 905 | 31 | 468 | 22 |
| September | 06:42 | 19:29 | 12:47 | 767 | 30 | 384 | 22 |
| October | 07:41 | 18:11 | 10:30 | 630 | 31 | 326 | 21 |
| November | 07:46 | 16:04 | 08:18 | 498 | 30 | 249 | 22 |
| December | 08:34 | 15:38 | 07:04 | 424 | 31 | 219 | 23 |
| Total numbers | | | | 8865 | 365 | 4499 | 254 |

*Table 4.2b: Functional office working time with bright sunshine in Denmark.*

| Month | Work daylight hrs. (single-user case) | Hrs. of bright sunshine** | Estimated functional office working hours with bright sunshine (single-user) | Work daylight hrs. (multi-user case) | Estimated functional office working hours with bright sunshine (multi-user case) |
|---|---|---|---|---|---|
| January | 143 | 43 | 26 | 183 | 33 |
| February | 160 | 68 | 40 | 206 | 52 |
| March | 184 | 117 | 59 | 247 | 79 |
| April | 144 | 185 | 63 | 198 | 86 |
| May | 152 | 249 | 75 | 209 | 103 |
| June | 176 | 259 | 87 | 242 | 119 |
| July | 176 | 244 | 82 | 242 | 112 |
| August | 176 | 233 | 88 | 242 | 121 |
| September | 176 | 158 | 73 | 242 | 100 |
| October | 168 | 103 | 53 | 223 | 71 |
| November | 156 | 57 | 36 | 219 | 50 |
| December | 153 | 38 | 27 | 222 | 39 |
| Total numbers | 1964 | 1754 | 707 | 2675 | 964 |

*In the single-user case, the calculation provides the total number of functional office working hours* **with bright sunshine = 707** *(office hours between 9.00am and 5.00pm)***.** *In the multi-user case, the calculation provides the total number of functional office working hours* **with bright sunshine = 964** *(office hours between 8.00am and 7.00pm)***.** *All sunrise and sunset times are for the 15th day of each month. ** Observed Hours of Bright Sunshine in Denmark, København station 30340 (Vaarby, , Laursen and Cappelen, 1998).*

In order to estimate the number of hours with bright sunshine during working hours, it is assumed that there is the same probability at a given hour during day-light to have bright sunshine. Further, the number of bright sunshine hours was calculated with the Danish Almanac (2010 www.Almanak for Danmark). One of the objectives is to deliver a certain amount of lumens with the use of as little energy based on fossil fuel as possible. Therefore, it is important to consider the number of lumens that current optical fibre systems can deliver.

In order to understand the possibilities of hybrid solar illumination systems in Denmark, it is important to look at the number of estimated working hours over the year. Figure 4.5 makes it is evident that, during midwinter, one cannot expect more than 25 hours of bright sunshine over a full month, whereas this number is almost four times as high at midsummer.

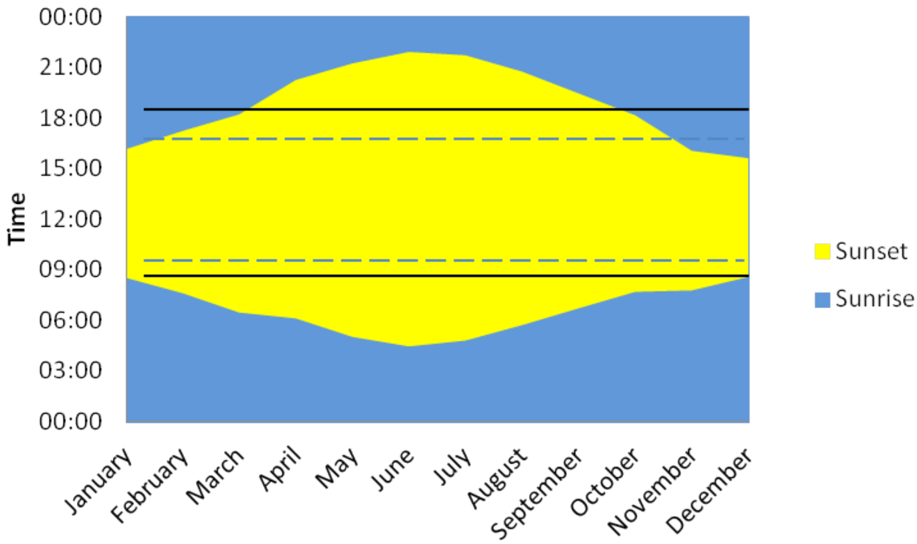



***Figure 4.5:*** *Distribution of sunshine hours during the year in Denmark. The yellow section shows how many hours Denmark has daylight. The dashed area indicates the single-user functional office hours in Denmark. The solid black line indicates the multiple-user functional office hours.*

The following assumptions have been made:

1. There is an average of 1,754 sunshine hours per year in Denmark, although not all will coincide with working hours (see comments in Table 4.2)
2. The optical fibre system used for this analysis has an output in lumens of 3,300 lm (measured value under Danish conditions) when the sun is shining brightly (the producer states 3000 +/- 300 lm.)
3. To provide 500 Lux to a surface, such as a work station, of 1.5 $m^2$ will require 750 lm.
4. Estimating the minimum office space to be 6.5 $m^2$, excluding the work station, the provision of 200 Lux is required for an area of 5 $m^2$, and from these 1,000 Lumens are required.
5. Out of the 1,754 hours of sunlight, a proportion of these hours will occur when the systems are not being used (this energy could be collected with a photo-voltaic system). This implies that for the single-user office there would be *an estimated **707** hours of sunlight during work hours, and for a multiple-user office, an estimated **964** hours of sunlight during work hours*. Some additional hours of sunlight occur during the evening or early morning, but these hours

may be used for cleaning, for night security staff, or for the collection of solar energy (these additional hours are not included in the following calculations).

6. The number of working days was estimated to be 254. This figure was reached by subtracting weekends and official/national holidays. It should be noted that the actual number of working days is closer to 220 days, as 25 days need to be subtracted for personal vacation leave and few additional days for travel, illness, etc. (a further estimated 9 days). Therefore, the final estimate is 220 days, and this figure will be used in the following chapter. However, when calculating the relative energy reduction below, it was noted that the correction factor of 220/254 should be multiplied by both the number of sunshine hours and the number of working hours. When the reduced energy consumption is estimated by looking at the number of sunshine hours compared to the total number of working hours, it would be both these numbers that should be multiplied by the vacation reduction factor (220/254) and, therefore their ratio will be unchanged. Consequently, the correct energy reduction will be estimated by using the figures from Table 4.2.

As there is a great deal of variation in the way that offices are used, the following scenarios were created to consider their functional time:

***Single-user offices***

- The light is on when an office is being used, and cleaning also takes place within this time.
- An office is occupied for only 8 hours during working days, giving an estimated 707 hours (see Table 4.2) of useful sunshine per year in Denmark.
- An estimated 1.964 work daylight hours in total (see Table 4.2).
- Assuming that all collected sunlight is used (and distributed to two offices, 3,300 lumens from the system for offices needing 1.750 lm each) this gives a relative energy reduction of 707/1,964 = ***36%***.

***Multiple-user offices***

- In multiple-user offices, the lights remain on even if some of the users are on vacation. The office will use more light than in the single-user case, because different users will be in the office at different times. In this case, there are estimated 964 hours of sunshine.

- The office is used for 10 hours, with an additional hour for maintenance/ cleaning, giving a total of 11 hours.
- An estimated 2,675 work daylight hours in total (see Table 4.2).
- Assuming that all collected sunlight is used, there will be 1,500 hours,available to distribute between two offices, (3,300 lumens from the system for offices needing 1,750 lm each). This gives a relative energy reduction of 964÷2,675= **36%**.
- The reason why the savings in the two scenarios above are proportional is due to the fact that single-user offices save energy when the users are not in the office, but at the same time, the total available resource of sunshine hours is not used. In the multiple-user scenarios, the users consume more energy, but the full use of total sunshine hours compensates for this.

## 4.3.1 Energy consumption in the use phase

Lamps of the types that OSRAM describe in their report were positioned so that the right distribution of light could be obtained (one LED Lamp Parathom A55 with Golden Dragon LEDs 8 W, Lifetime: 25,000 h and 2.5 Compact Fluorescent Lamps CFL DULUX Superstar Classic A 8 W, Lifetime: 10,000 h).

The European average electricity mix was taken into consideration in order to produce 1kWh of electricity. According to the assumptions made by the OSRAM report (November 2009), approximately 3.3 kWh of primary energy are needed. The number

$$LED\ and\ CFL: \frac{1{,}750\ \text{lm}}{420\ \text{lm}} = 4.2$$

$$LED\ and\ CFL: \frac{1{,}750\ \text{lm}}{345\ \text{lm}} = 5.07$$

of lamps required to obtain the necessary light intensity is estimated as follows:
For ease of comparison, the lamps would need to have a light output between 345 to 420 lm during their whole lifetime. As the number of lamps needed was between 4.2 and 5.07, it was decided to use 5 lamps.

With each lamp using 8 W, this provided a total power consumption of 40 W to illuminate the office.

***Using the single-user scenario:***
As the system will last for 25 years and will be in use for 1,840 hours per year, the total electrical energy needed will be: 40 W × 1964/year × 25 years = 1964000 Wh = 1964 MWh.

***Using the multi-user office scenario:***
As the system will last 25 years and will be in use for 2,860 hours per year, the total electrical energy needed will be: 40W × 2675/year × 25 years = 2675000Wh = 2675 MWh.

The total amount of energy is not affected by the number of lamps that have to be changed, but by the level of consumption. It does, however, affect the resources needed to produce and dispose of materials.

## 4.4 HYBRID SYSTEM (LEDS + SOLAR FIBRE OPTICAL SYSTEM) ENERGY ASSESSMENT

In the case of the hybrid system, if one assumes that the electric power needed can be reduced in proportion to the amount of available sunlight, the energy saved can be estimated according to the percentages mentioned above.

The power consumption of the electric parts of the hybrid system was 0.5 W, which has to be considered in relation to the total energy account.

***For the single-user office***

- The hybrid system will use 1964 *MWh* × 64% = 1256 *MWh*.
- Additionally, one needs to include 0.5 W × 1.964 h/ year × 25 years = 0.025 *MWh*.
- Therefore, total electricity consumption will be 1,281MWh for the 6.4 $m^2$ office space (the functional unit).

***For the multi-user office***

- The hybrid system will use 2675 *MWh* × 64% = 1712 *MWh.*

- Additionally, one needs to include 0.5 W × 2675 h/year × 25 years = 0.033 *MWh*.
- Therefore, the total electricity consumption will be 1,745 *MWh* for the 6.4 $m^2$ office space (the functional unit).

The electricity saving in the single-user scenario is (1964 *MWh* -1281 *MWh*) = 0.683 *MWh* for the hybrid system compared to the CFL or LED systems.

For the multi-user office scenario, the electricity saving is (2675 *MWh* – 1745 *MWh*) = 0.93 *MWh* when using a hybrid system compared to the CFL or LED systems.

## 4.5 SOLAR OPTICAL FIBRE PRODUCT-SERVICE SYSTEM POTENTIALS ASSESSMENT

In relation to the obligatory properties, introducing a solar fibre optical system could contribute a saving of 36% to our functional unit.

From the positioning properties or from a product-service system perspective, the addition of a solar fibre optical systems could contribute to:

- reducing overheating, thereby reducing the need for air conditioning in summer, and
- effectively reducing $CO_2$ emissions, thereby contributing to primary energy reduction.

### 4.5.1 Flexibility potential (having the light where it is needed)

When providing a product-service system for illumination, one of the characteristics to consider is that it has to provide more flexibility than windows. To "measure" this, colleagues from Designskolen Kolding (working with the project "Hybrid illumination systems - towards reducing the illumination footprint") installed a solar fibre optical system in their institution. They reported that one of the main challenges is that the fibres cannot be installed in the same manner as normal electric wires , as the fibres cannot not be bent as much as electric cables.

## 4.5.2 Optimal spectral composition of light for a working space (colour of light)

Within the same collaboration project, colleagues from the Department of Photonics at the Technical University of Denmark measured the composition of light assessing fibre loss (see Box 4.2) using a commercially available fibre illumination system consisting of a 20 metre length of (polymer) fibre bundles to transport the collected sunlight.

> Box 4.2
>
> "Fibre loss is the ratio between input power and output power of the fibre" Anders Bjarklev , 2010

*"Measurements were performed outside during sunny summer days in Denmark. Results are illustrated in the chromaticity diagram, shown in Figure 4.6, where the reference point (Ref) corresponds to the light coming from the sun and the point "Test" corresponds to the light coming from the fibre bundle output. The chromatic distance (DC) of the light coming from the fibres is $31 \cdot 10^{-3}$, which is far above the limit of $5.4 \cdot 10^{-3}$ given by the International Commission on Illumination (CIE). This observed 'decolouration' is one of the challenges that future fibre illumination systems have to find solutions to" (Scolari, 2009 and Bjarklev, 2010, personal communication).*

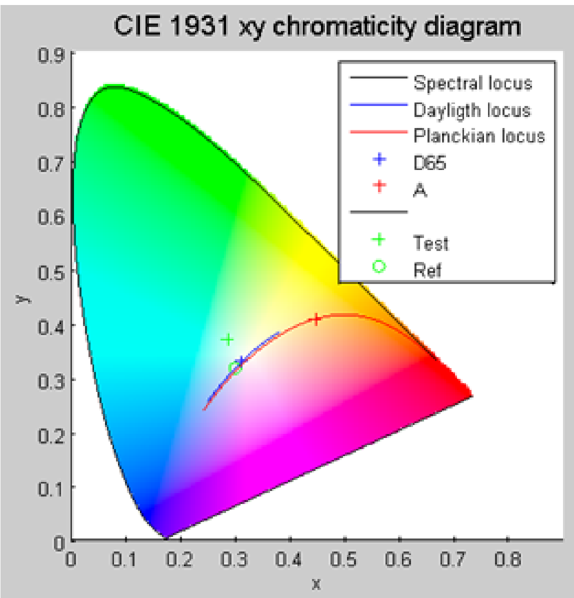



***Figure 4.6:*** *Chromaticity diagram measured on a commercially available fibre illumination system (Figure provided by Lara Scolary)*

As stated by senior researcher Carsten Dam-Hansen, who is perhaps one of the most highly-regarded experts in Denmark regarding colour characterisation of illumination sources, when commenting the characterization of fibre solar collector systems: "you cannot even say that the light is blue, I would say it is green" (Carsten Dam-Hansen, 2011 personal communication). Therefore, in order to provide a high- level service for office lighting, losses have to be reduced so the colour of the light can be improved.

Alternatively, although the system transports sunlight into the building, one of the advantages is that the UV rays are filtered out. This advantage provides the benefit of the natural light without having dangerous radiation inside the building and, therefore, offers a consumer-friendly illumination service. Furthermore, the heat from sunlight is also filtered, which reduces the need for air-conditioning. Providing natural light (sunlight) can also improve the user's wellbeing and productivity (CEC, 2003; Edwards & Torcellini 2003; Heschong Mahone Group, 1999). Thus, utilising the benefits of daylight could represent a positive potential to developing hybrid illumination systems for work spaces.

## 4.6 MATERIALS AND CHEMICALS IN OTHER PHASES OF THE SFOS LIFE CYCLE

As mentioned above, the manufacture phase and materials used are not within the scope of this thesis. However, during the transportation and installation phases of the system, colleagues from DTU and from the School of Design Kolding found the system heavy and bulky to deal with. The materials used for the SFOS in the manufacture phase are mainly polymers and aluminium that, in principle, can be reused or recycled and most of these materials have a lifespan of approximately 20 years. An overview of the materials and their weight can be seen in the materials list in Tables 4.3 and 4.4.

Despite not considering the manufacture phase as the major environmental load in the scope of this analysis, it is clear that reducing the amount of materials during this phase would be a positive step in making the system more practical, easy to handle and, at the same time, it would reduce the energy and cost of transportation and installation.

***Table 4.3 and 4.4:*** *Specifications and materials list for the Parans systems. Source: http://www.parans.com/*

| Specifications | |
|---|---|
| Dimensions | 980 x 980 x 180 mm |
| Weight solar panel | 30 kg |
| Weight optical cable | 273 g / m |
| Power Supply | AC 100 - 250 V |
| Power Consumption | 0 - 6 W |
| Operating Temperature | -20°C – 40°C |
| Luminous Output | 3 000 +/- 300 lm* |

| Materials, Components | Weight (g) |
|---|---|
| Aluminum EN AW-5754 H22 | 16 220 |
| Toughened safty glass (EN12150). Antireflective Centro Solar HiTC+ | 5 120 |
| Zink (alloy ZL 0410) | 3 660 |
| Stepping motor Type 16PM-M009-02, MINABEA CO LTD, Thailand | 822 |
| Plastic (PMMA) | 341 |
| Stainless Steel | 148 |
| Electrogalvanized Steel | 128 |
| PA6 | < 100g |
| POM - Delrin 500AL NC010 | < 100g |
| Ertalyte TX (PET-P w/ solid lubricant) | < 100g |
| Silicone, Loctite 5140 | < 100g |
| UV curing glue, Loctite 3103 | < 100g |
| EPDM rubber | < 100g |
| Nickleplated brass | < 100g |

## 4.7 CONCLUSIONS

Although the environmental performance of Light Emitting Diodes (LEDs) and Linear Fluorescent Light sources (LFLs) are similar, the product-service system advantages of LEDs are superior to those of LFLs. These advantages offer more possibilities for the development of energy efficiency, as well as an improved and more flexible service to fulfil consumer demands in the future. Consequently, this study recommends focusing on LED technology.

The proposal for adding a Solar Fibre Optical System with automatic switch on/off controls, would have the benefit of energy efficiency savings of approximately 36% of the primary energy when compared to LED systems. However, considering the opinion of the DTU Fotonik experts, the design of the systems has to focus on reducing the fibre losses and designing improved light characterisation so that it will be accepted by the users.

However, for successful implementation, consumers should also be part of the decision-making process. It is important to consult directly with users in order to establish how far these technologies (LEDs and HFOLS) go in fulfilling consumer demands. Using sunlight can become an extremely positive potential in terms of green responsibility, since renewable sources are used. Furthermore, additional use of more natural light can enhance the level of service providing a higher quality of life and, at the same time, enhancing wellbeing and productivity in work areas. Therefore, a user test becomes very relevant (this will be discussed further in Chapter 6).

In a number of situations, the peak consumption hours of electricity could be reduced, particularly during the summer months. However, the power system should still be able to deliver full effective power during days where no bright sunlight is present (mainly during winter or on cloudy days), in this case, contributing positively to the heating system. Likewise, these savings could reduce the need for extra energy for air-conditioning, since the heat generated by the LEDs will be reduced in the same proportions, particularly during summer.

It would also be beneficial to focus on the size of the components, material consumption and flexibility of the materials, so as to further extend the working life of the existing building mass and increase the potential for utilisation.

The consumption of materials can influence the total cost and become a barrier to consumer acceptance of this new technology. Consequently, these aspects will be assessed in the next chapter.

A real-life example (iterative communication with Ibsen APS Electrician Company) will be used in the next chapter to calculate the energy saving potential, the $CO_2$ emissions savings and the life cycle cost of an LED system and hybrid fibre optical system using LFL T5 as the base for comparison of the three scenarios.

Chapter 5

# Assessing the life cycle cost of the chosen alternatives

In the previous chapter, the proportional energy saving potentials for hybrid illumination systems was calculated to be 36%. In this chapter, this factor is applied to calculate the life cycle cost of the hybrid lighting system. A comparison will be made between the three systems in relation to energy consumption and $CO_2$ emissions using the DEEP's LCC tool (Isaac, et al., 2007). This tool is chosen for its simplicity and is used to assess total energy consumption for the initial future cost. It takes into account the costs, such as materials and installation, and evaluates them in terms of net present value. Future benefits are seen as alternative(s) that will consume less energy and will emit less $CO_2$ throughout their life cycle.

The aim of this chapter is to establish the *total cost* for the use phase by comparing the best available technologies for a linear fluorescent system, and to identify potential improvements from a cost benefit perspective for the chosen technologies (LEDs and hybrid fibre optic lighting systems). As was stated above, even if there are energy savings, if the new alternatives are not cost competitive, they will face a substantial barrier when entering the market. Therefore, it is important to ascertain if the hybrid illumination systems are more expensive for the consumer or if there is potential to make them more accessible, whilst taking the life cycle cost of the service into account. These considerations go beyond the initial investment outlay for the illumination devices, and include the material and labour costs of replacement, and the energy cost during the lifetime of the product-service. This is relevant because there is a societal need to make changes in the trade and service sector. The service sector, in particular, is dominated by public buildings that are currently in the EU's focus of attention due to their high-energy consumption and substantial $CO_2$ emissions. European policies encourage the managers of public buildings to make use of the Green Public Procurement Strategy. This strategy seeks to support public authorities to become more conscious consumers and actors of change when procuring goods, services or work. The aim of the strategy is to make public authorities consider, not only the initial cost of procurement, but to take into account all the life cycle costs of the product-service. Accordingly, when their life cycle is considered, competitively priced product-services with a lower environmental impact are more likely to be purchased by public authorities.

## 5.1 COST INVENTORY OF THE SELECTED TECHNOLOGIES

The data for this assessment has been gathered through an iterative communication process with the research partners: Poul Ibsen (IBSEN EL-ANLÆG A/S), Lara Scolari and Anders Bjarklev from DTU Fotonik. The data was gathered during May to July 2010. The prices used are those given to the research team by Parans at the end of 2009, when one of its systems was purchased for the Elforsk funded project which was carried out in cooperation with the Design School Kolding, DTU Fotonik, Roskilde University - ENSPAC and IBSEN EL-Anlæg A/S.

The following prices were specified for providing an illumination service to an area of 100m$^2$ during 220 days per year for a functional office time of 8 hours (7.30 working hours + 30 minutes cleaning time) and a functional office time for a multi-user office of 11 hours (10 working hours + 1 hour cleaning time).  From this data, the cost of providing illumination service to a single-user office and a multiple-user office can be calculated.

The illumination service will be provided for a period of 25 years, which is the estimated lifetime of the hybrid system being considered.

In addition, there will be 500 lux provided to a work station of approximately 1.5 m$^2$. For that purpose, one working (lamp) luminaire will be provided for each work station.

In order to obtain the total cost for our functional unit the following will be considered:  the total cost to supply an illumination service to an office of 6.5m$^2$ with a 1.5 m$^2$ work station during a 25 year period; the energy consumption for the general illumination of a larger office of 100 m$^2$, the illumination of the work station, material costs (luminaires + lamps) and installation costs. The total cost will then be divided by 100m$^2$ and then multiplied by 6.5 m$^2$.

### 5.1.1 Use phase life cycle cost for the BAT within fluorescent lamps

***In the first case (base case), a system based on fluorescent technology is considered:***

- Standard Fagerhult Loop Light 2x35w with T5 fluorescent lamps (see Picture 5.1)
- One electronic ballast coil loss < 2%
- Lamps: 2 pcs. 1x35 w T5 35-0183 HG free Ballast lifetime >50.000 hours
- Fluorescent luminaires:  15-20, 000 hours
- Number of luminaires per 100m2 with 200 lux: 16 luminaires

***Picture 5.1;*** *Fagerhult Loop Light luminaire*

***Multiple user offices***
*General Illumination*

Electricity consumption: 70W, using two lamps per luminaire (+ - 2%) 0.07 kW in a multi-user office (11 hours functional office time) = 0,77kWh per functional day X 2DKK/kWh (cost of electricity) = 1.54DKK per day. The 1.54 DKK X 220 functional days X 16 luminaires = 5,420 DKK. Over a period of 25 years this gives an energy cost of 135,500 DKK for the total electricity consumption for general illumination.

Price per luminaire, including the installation price is approximately 900 DKK, which multiplied by the number of luminaires (16) gives the total cost of 14,400 DKK per 100m$^2$.

The lifetime of the lamps requires them to be replaced after the 6th or 7th year. Over a 25-year period, this means that 4 sets of fluorescent lamps are needed, including the initial set. The cost per lamp at current prices is 69 DKK. There are two lamps per luminaire which makes 32 lamps in total, consequently this represents a cost of 69 DKK X 32= 2,208 DKK. The lamps have to be installed/changed 4 times, consequently 2,208 X 4 = 8,832.00 DKK. Furthermore, the labour price for replacing the lamps will be approximately 800 DKK per two hours plus 25% tax. Since the lamps have to be changed three times, the labour cost is 3,000.00 DKK. The total cost of replacing the fluorescent lamps will therefore be 26,232.00 DKK.

The total cost for the use phase of an illumination system providing general illumination based on LFL BAT in a multiple user office will be 161,732.00 DKK for an illumination service period of 25 years providing 200 lux to an area of $100m^2$.

*Focus task illumination*

Considering our functional unit, the minimum workspace for an office is 6.5 $m^2$. This means that in an area of $100m^2$ there will be space for 15 workspaces. There needs to be 500 lux for each work station (1.5 $m^2$) within each workspace/office, therefore, one table luminaire (working lamp) is used in order to provide each work station with the right level of illumination. The current cost for an LFL working luminaire is 700 DKK and the office will be using 15 working luminaires, for which the total price is 10,500 DKK. The lifetime of the LFL is 6-7 years, therefore, they will need to be replaced 4 times during the 25 year period. The cost of each lamp is 60 DKK X 4 = 240 DKK x 15 lamps = 3,600.00DKK. The total cost of materials is 14,100.00 DKK. These lamps can be replaced by the user so no extra labour costs are included for this task.

The energy consumption for a working lamp/luminaire is 18 W or 0.018 kW X 11 h (functional time for a multi-user office) = 0.198Wh X 220 functional days = 43.56 kWh X 2DKK/kWh = 87.12 DKK. For 15 units, this becomes a total of 1,307 .00 DKK, which during 25 years, gives a total of = 32,675.00 DKK.

To calculate the total cost of supplying an illumination service to an office with an area of 6.5m$^2$ and a 1.5 m$^2$ desk over a period of 25 years, the cost of our functional unit needs to be obtained by adding the general illumination energy consumption and the illumination of a work station + material costs (luminaires and lamps) + installation costs. The total cost is then divided by 100 m$^2$ and multiplied by 6.5 m$^2$ to obtain the total cost for our functional unit.

This calculation gives the following result:

208,507.00 DKK X (6.5/100) = **13,553.00 DKK.**

***Single-user offices***
*General Illumination*

Electricity consumption: 70 W using two lamps per luminaire (+ - 2%) 0.07 kWh in a single-user office (8 hours functional office time) = 0,56kW per functional day X 2 DKK/kWh (electricity price) = 1.12 DKK per day. The 1.12 DKK X 220 functional days X 16 luminaires = 3,942 DKK x 25 years = 98,550.00DKK of total electricity consumption for general illumination.

Price per luminaire including the installation price is approximately 900 DKK. When multiplied by the number of luminaires (16), this gives the total initial installation cost 14,400 DKK per 100m$^2$.

Due to the lifetime of the lamps, these have to be replaced after the 6th or 7th year. Over a 25-year period this means that 3 sets of the fluorescent lamps are replaced. The price per lamp at current prices is 69 DKK. There are two lamps per luminaire which makes 32 lamps in total, consequently this represents a cost of 69 DKK X 32 X 4 = 8,832.00 DKK. Furthermore, the labour cost to replace the lamps will be approximately 800 DKK per two hours plus 25% tax. Since the lamps have to be changed three times, the total labour costs are = 3,000 DKK. The total cost of replacing the fluorescent lamps will therefore be 11,832.00 DKK. The total cost for the use phase of an illumination system providing general illumination of 200 lux based on LFL BAT in a large office of 100m$^2$ will be 110,381.00 DKK for a period of 25 years.

*Focus task illumination*

In this functional unit, the minimum space for an office workspace is 6.5 $m^2$. An area of 100$m^2$ divided by 6.5$m^2$ provides 15 workspaces. Furthermore, 500 lux needs to be provided for each work station (1.5 $m^2$) within each workspace/office, therefore, in order to provide the work station with the required level of illumination one table luminaire (working lamp) is used in most cases. The current cost for an LFL working luminaire is 700 DKK and the office will be using 15 working luminaires. This gives a total price of 10,500 DKK.

The lifetime of the LFL is 6-7 years, so they will need to be replaced three times during the 25 year period. The cost of each lamp is 60 DKK X 4 = 240 DKK. Each lamp x 15 luminaires = 3,600 DKK. Therefore the cost of materials is 3,600.00 DKK.

These lamps can be replaced by the user, so extra labour costs do not need to be included for this.

Energy consumption for a working lamp/luminaire is 18W or 0.018 kW X 8 h of functional office time X 220 functional days is = 31.68 KWh X 2DKK/KWh (energy cost) = 63 DKK. Considering a total of 15 luminaires this gives a cost of 945.00 DKK. For the 25 year period the total cost is 23,625.00DKK.

To calculate the total cost of supplying an illumination service to an office of 6.5 $m^2$ with a 1.5 $m^2$ work station over a period of 25 years. the total cost for our functional unit needs to be obtained by adding the general illumination energy consumption and the illumination of a work station + the material costs (luminaires + lamps) + installation cost and dividing by 100 $m^2$ and then multiplied by 6.5 $m^2$

This gives the following result:

**162,507.00DKK** X (6.5/100) = **10,563.00DKK.**

## 5.1.2 Use phase life cycle cost for the BAT within LEDs lamps

***The second case considers a system based only on Light Emitting Diodes.***

- Sourced from the Fingerhut gaudi LED range.
- One electronic ballast coil loss <2%
- Luminaire: 7 LEDs of 3w each =21 W
- Ballast lifetime > 50-100.000 timer
- LEDs lifetime < 50.000 timer
- Number of luminaires per 100m$^2$ with 200 lux: 35 luminaires


**Picture 5.2;** *Fingerhut gaudi LED*

***Multiple user offices***
*General Illumination*

Electricity consumption 21 W (+ - 2%) 0.021 kW in a *multi-user office (11 hours functional office time)* = 0.231 kWh per functional day X 2DKK/Kwh (electricity price) = 0.46 DKK per day. The daily figure of 0.46 DKK is multiplied by 220 functional days X 35 luminaires = 3,557. Over a period of 25 years this becomes 88,925 DKK of total electricity consumption.

The price per luminaire is around 3.500 kr. including installation, multiplied by the number of luminaires this gives a total cost of 122,500.00 DKK per 100m2. Due to the LEDs lifetime, the luminaires need to be replaced within the 20 years of service. As the functional unit is 25 years, the installation of new lamps needs to be considered. The replacement cost will include the luminaire and the lamp, as is not possible to only change the lamp. Therefore, 122,500.00 DKK × 2 = 245,000.00 DKK. The total cost for the use phase of an illumination system providing general illumination for a period of 25 years based on LEDs BAT in a 100 m2 large office will be 193,648 DKK.

*Focus task illumination*

Within the functional unit, the minimum space for an office is 6.5 $m^2$. An area of $100m^2$ divided into $6.5m^2$ workspaces = 15 workspaces. Furthermore, each work station needs to be provided with 500 lux per $1.5m^2$ workspace, and therefore, in order to provide appropriate illumination usually one table luminaire (working lamp) is used. The current cost for an LED working luminaire is 4,100 DKK. This case will use 15 working luminaires = 61,500 DKK. The lifespan of such lamps is calculated to be 20 years, and as our functional unit is set for 25 years these luminaires should be also replaced once. Consequently, 61,500 DKK X 2 gives a total of 123,000.00 DKK.

Energy consumption for a working lamp/luminaire is 10 W or 0.010 kW X 11 h = 0.11 kWh of functional office time X 220 functional days is 24.2 KWh X 2DKK/Kwh = 48 DKK. During 25 years = 1,200.00 DKK per lamp. For the total number of 15 lamps required this gives a total of 18,000.00 DKK.

> To calculate the total cost of supplying an illumination service to an office of $6.5m^2$ with a 1.5 $m^2$ work station during 25 years the total cost for the functional unit needs to be obtained by adding the general illumination energy consumption and the illumination of a work station + the material costs (luminaires + lamps) + installation cost, then dividing the total cost by 100 $m^2$ and then multiplying the result by 6.5 $m^2$.
>
> This gives the following result:
>
> 474,925.00DKK/100 × 6.5 = **30,870.00 DKK**.

***Single-user offices***

*General Illumination*

Electricity consumption 21 W (+ - 2%) 0.021 kW in a single-user office (8 hours functional office time) = 0.168 kWh per functional day X 2 DKK/kWh (electricity price) = 0.34 DKK per day. The daily figure of 0.34 DKK is multiplied by 220 functional days X 35 luminaires = 2,587 DKK. Over a 25 year period this becomes 64,675.00DKK of total electricity consumption for general illumination.

The price per luminaire is approximately 3.500 DKK, including installation, multiplied by the number of luminaires. This gives a total cost of 122,500.00 DKK per 100m$^2$.

Due to the lifetime of the LEDs, there is no need to replace the luminaires within the 20 years of service. The lifespan of such lamps is calculated to be 20 years. As our functional unit is set for 25 years, these luminaires should be also replaced once. Consequently, 122,500.00 DKK X 2 = 245,000.00 DKK.

The total cost for the use phase of an illumination system providing general illumination based on LEDs BAT in a 100 m$^2$ large office will be 309,675.00DKK for an illumination service period of 25 years.

*Focus task illumination*

For this functional unit, the minimum space for an office workspace is 6.5 m$^2$. An area of 100m$^2$ divided by 6,5m$^2$ provides 15 work places. Furthermore, 500 lux needs to be provided for each work station (1.5 m$^2$) within each workspace/office included in the functional unit, therefore, in order to provide the work station with the required level of illumination, one table luminaire (working lamp) is used in most cases. The current cost for an LED working luminaire is 4,100 DKK and 15 working luminaires will be used. This gives a total price of 61,500 DKK. The lifespan of such lamps is calculated to be 20 years. As the functional unit is being calculated for 25 year period, these luminaires should be also replaced once. Consequently, 61,500 DKK X 2 = 123,000.00 DKK.

Energy consumption for a working lamp/luminaire is 10 W or 0.010 kW X 8 h X 220 functional office time is = 17.6 kWh X 2DKK/kWh =35.2 DKK. During the 25 years, for 15 luminaires, the total cost will be 13,200.00 DKK.

> To calculate the total cost of supplying an illumination service to an office of 6.5m$^2$ with a 1.5 m$^2$ work station during a period of 25 years, the total cost for the functional unit needs to be obtained by adding the general illumination energy consumption and the illumination of a work station + the material costs (luminaires + lamps) + installation cost, then dividing the total cost by 100 m$^2$ and then multiplying the result by 6.5 m$^2$ .
>
> This gives the following result: 445,875.00/ 100 × 6.5 = **28,982.00 DKK**

### 5.1.3 Use phase life cycle cost for a hybrid system

The third case is calculated including a system base on LEDs in combination with a solar optical illumination system.

The assumption here is that requirements for the number of lux of artificial lighting will be the same as if the service was only being provided by LEDs, and therefore, the same number of luminaires will be used.

- Luminaire: 7 LEDs of 3W each = 21W
- Ballast life time > 50-100.000 timer
- LEDs life time < 50.000 timer
- Number of luminaires per 100m$^2$ providing 200 lux: 35 lamps

***Multiple-user offices***
*General Illumination*
Electricity consumption 21W (+/- 2%) 0.021 kW in a multiuser office (11 hours functional office time) = 0.231 kW per functional day X 2 DKK/kWh (current electricity price) = 0.46 DKK per day. The daily figure of 0.46 DKK is multiplied by 220 functional days X 35 luminaires = 3,557 x 25 years = 88,925 DKK of electricity consumption.

As the hybrid system is designed using LED lamps, it is calculated that the same number of lamps will be required to illuminate the 100 m$^2$ area with 200 lux. If the system was not hybrid, the lamps would use the same energy to illuminate the same area as the multiple-user offices using only LED systems. Consequently, when the solar system is added, it can harvest energy equivalent to a saving of 36%. This saving is subtracted when considering a multiple-user office (see Chapter 4). This gives: 88,925 – (36% of 88,925) = 56,992.00 DKK for the total energy consumption for general lighting. This will proportionally increase the lifespan of the LEDs, as they will be used for less hours and therefore they will not need to be replaced during the 25 year period.

The installation price for a hybrid system is approximately 7,500 DKK per lamp. Thus, 35 luminaires X 7,500 DKK= 262,500 DKK per 100m$^2$. This amount includes the price per luminaire.

To this amount is added the cost of the solar systems, which require 7 systems per 100m$^2$ and the cost of installation per unit: 5,487DKK + 1,372 DKK taxes = 6,859 DKK per unit. The cost of installation for the 7 collector units = 48,013 DKK per 100 m$^2$.

Further calculations indicate that 7 solar collectors (Parans system) will be needed to illuminate 100 m$^2$. The price for the systems in 2010 (with special discount) is as shown in Table 5.1

***Table 5.1:*** *Price of a solar fibre optical system from Parans in 2010*

| | Unit price | Net price | Discount |
|---|---|---|---|
| Parans SP1 Kollektor | 10,900.00 Euros | 7,040 Euros | 40% off = 54,208 Kr |
| Parans L1 (s) Luminaire | 590 Euros | 413 Euros | 30% off = 3,180 Kr |

The total cost of seven solar optical fibre systems for an area of 100 m$^2$ without the luminaire is 379,456 DKK, at the discounted price, making a subtotal of material + labour costs of 689,969.00DKK.

The total cost for the use phase of an illumination system providing general illumination for an illumination service period of 25 years based on Hybrid Solar Lighting System BAT is 746,961 DDK.

*Focus task illumination*

For this functional unit, the minimum space for an office needs to be 6.5 m2. This is 100m2 / 6,5m2 = 15 workspaces. Further, 500 lux needs to be provided to a work station (1.5 m$^2$) for each workspace/office included in our functional unit. Therefore, in order to provide the work station with the required level of illumination one table luminaire (working lamp) is used in most cases. The current cost for a LED working luminaire is 4,100 DKK and 15 working luminaires will be used, making the total cost 61,500 DKK.

Energy consumption for a working lamp/luminaire is 10 W or 0.010 kW X 11 h of functional office time × 220 functional days = 24.2 kWh X 2 DKK/kWh = 48.4 DKK. X 15 luminaires = 726 DKK. During the 25 years = 18,150 DKK. This basic figure is the same as was determined for the full LED system, but it is assumed that when the sun is shining, a significant part of the work station luminaires may be switched off. The specific situation will probably need practical experiments, but for simplicity, the 36% saving harvested by integrating the solar optical fibre illumination systems is subtracted. The total electricity cost becomes = 18,150 DKK – 6,534 = 11,616.00 DKK. The lifetime of the LEDs is 25 years, and therefore it will not be necessary to change the lamps.

> To calculate the total cost of supplying an illumination service to an office of 6.5 $m^2$ with a 1.5 $m^2$ work station for a period of 25 years, the total cost for the functional unit needs to be obtained by adding the general illumination energy consumption and the illumination of a work station + the material costs (luminaires + lamps) + installation cost, then dividing the total cost by 100 $m^2$ and then multiplying the result by 6.5 $m^2$ .
>
> This gives the following result:
>
> **820,077.00 DKK** (6.5/100) = **53,305.00 DKK**.

***Single-user offices***

The life cycle cost for single user offices with hybrid system is calculated considering the functional office time to be 8 hours, and the expectation of achieving a ***36%*** saving in energy.

*General Illumination*

As the hybrid system is designed using LED lamps it was calculated that the same number of lamps would be required to illuminate the 100 $m^2$ office area with 200 lux. If the system was not hybrid, the lamps would use the same energy to illuminate the same area as the multiple-user offices using only the LED systems. Electricity consumption of 21 W (+ - 2%) 0.021 kW in a *multi-user office (8 hours functional office time)* = 0.168 kWh per functional day X 2 DKK/kWh (electricity price) = 0.336 DKK per day. The daily figure of 0.336 DKK is multiplied by 220 functional days X 35 luminaires = 2,587 DKK x 25 years = 64, 675.00 DKK of total electricity consumption. Consequently, when the solar system is included in this calculation, the **36%** savings made by the solar system (see Chapter 4) **are subtracted.** The result of this is 64, 675.00 DKK – (36% of 64, 675.00) = 41,392.00 DKK.

The costs for the installation, the luminaires and the solar optical systems is the same as that calculated for the multiple-user offices, making a total of 689,969DKK.

*Focus task illumination*

For this functional unit, the minimum space for an office needs to be 6.5 $m^2$. This is 100 $m^2$ / 6.5 $m^2$ = 15 work places. Further, 500 lux needs to be provided to a work station (1.5 $m^2$) for each workspace/office included in our functional unit. Therefore, in order to provide the work station with the required level of illumination one table luminaire (working lamp) is used in most cases. The current cost for an LED working luminaire is 4,100 DKK 15 working luminaires will be used, making the total cost 61,500 DKK.

Energy consumption for a hybrid working lamp/luminaire is 10 W or 0.010 kW X 8 h of functional office time X 220 functional days = 17.6 kWh X 2 DKK/kWh (energy price). For 15 luminaires = 528 × 25 years = 13,200.00DKK – 36% of the working lamp total energy consumption price = 8,448.00 DKK.

The lifetime of the LEDs will cover the 25 year period (as they will be used less hours); therefore it will not be necessary to include a cost for changing the lamps.

| |
|---|
| To calculate the total cost of supplying an illumination service to an office of 6.5 $m^2$ with a 1.5 $m^2$ work station during 25 years, the total cost for the functional unit needs to be obtained by adding the general illumination energy consumption and the illumination of a work station + the material costs (luminaires + lamps) + installation cost, then dividing the total cost by 100 $m^2$ and then multiplying the result by 6.5 $m^2$.<br>This gives the following result:<br>01,309.00.00DKK ÷ 100 × 6.5= **52,085.09 DKK** |

## 5.2 USE PHASE COST ASSESSMENT COMPARING THE THREE CASES

To summarise the results, the cost is compared over the use phase (25 years) of the three different technologies for this analysis (see Table 5.2). The different costs are given in DKK to 2010 values.

***Table 5.2**: Cost assessment for the illumination use phase of LFLs, LEDs and Hybrid illumination systems.*

| Type of technology | LFL BAT based system | | LEDs BAT based system | | Hybrid illumination system | |
|---|---|---|---|---|---|---|
| Type of office | Multiple-user office | Single-user office | Multiple-user office | Single-user office | Multiple-user office | Single-user office |
| General lighting electricity | 135500 | 98550 | 88925 | 64675 | 56992 | 41392 |
| General lighting luminaires + inst. cost | 14400 | 14400 | 122500 | 122500 | 262500 | 262500 |
| General lamps | 8832 | 8832 | 0 | 0 | 0 | 0 |
| Labour replacement for general lighting | 3000 | 3000 | 122500 | 122500 | 0 | 0 |
| Task luminaire electricity consumption | 32675 | 23625 | 18000 | 13200 | 11616 | 8448 |
| Task (lamp) luminaire | 10500 | 10500 | 61500 | 61500 | 61500 | 61500 |
| Task luminaire replacement | 3600 | 3600 | 61500 | 61500 | 0 | 0 |
| Solar collectors cost | | | | | 379456 | 379456 |
| Solar collectors installation cost | | | | | 48013 | 48013 |
| Total cost 100m$^2$ | 208507 | 162507 | 474925 | 445875 | 820077 | 801309 |
| Total cost per Functional Unit | 13553 | 10563 | 308701 | 289818 | 553050 | 528850 |

The total costs for the entire use phase of the three different systems are shown in Figure 5.1. The multiple-users office scenarios (MU) are used to provide an example, and the Energy Efficient Procurement (LCC) DEEP Tool kit (Issac, et al. 2007)) is used to carry out this assessment.

As can be seen in Figure 5.1 and Table 5.3, installing a system based only on LEDs will contribute an energy saving of *36%* when compared to the energy consumption of a system using only LFLs. Using a hybrid system combining a solar fibre optic collector and making a hybrid lamp will *save 59%* of energy when compared to the energy consumption of an LFL system. Yet the most costly solution today is the hybrid illumination system, although, as shown in Figures 5.2 and 5.3, it is the solution that uses the least energy and produces the least $CO_2$ emissions.

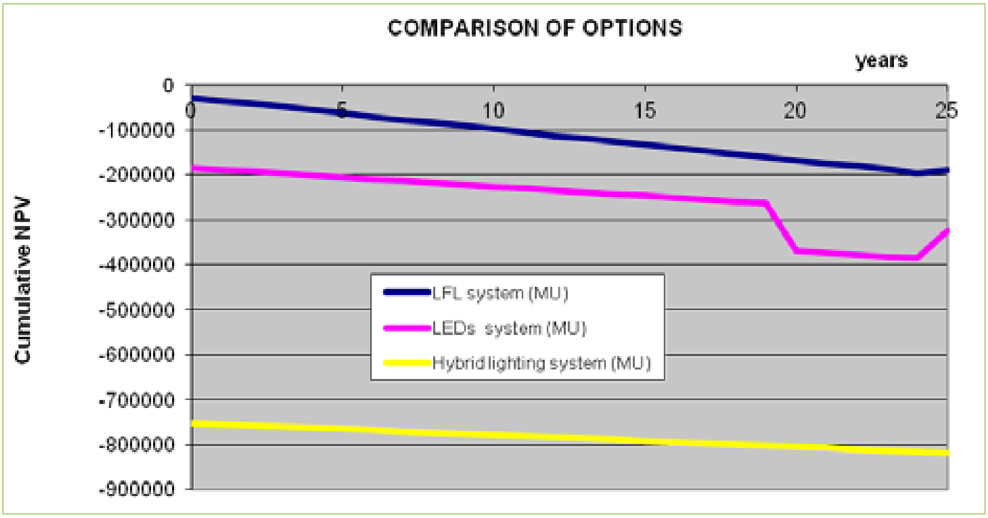



***Figure 5.1:*** *Comparison of options in terms of Net Present Value. A current discount rate of 3% (Denmark National Bank, 25 Marc. 2010, ref 2010-14E), an "On - peak electric tariff price escalator" of 3% as an average value for the different energy sources (Bolt J., 2009, "Fremtidige priser på biomasse til energiformål") and a carbon factor of 0.801 kg*$CO_2$*/kWh (DONG energy., 2008, ASNÆSVÆRKET- Grønt Regnskab 2008) are all assumed. The emission factor reported by the EU Commission is 0.041 kg*$CO_2$*/kWh, and the Danish General Declaration (DONG 2010) is 0.473 kg*$CO_2$*/kWh; However, these valuesare not considered representative of an average of all types of energy sources (renewable and non-renewable). The figure of 0.801kg*$CO_2$*/kWh was chosen, since it is more representative of the marginal energy produced by non-renewable sources. The logic behind this choice is that when net energy is saved, one can actually counteract the consumption of electricity based on fossil fuels. The life time for the hybrid system is estimated to be 25 years, as the LEDs will be less used in combination with sunlight.*

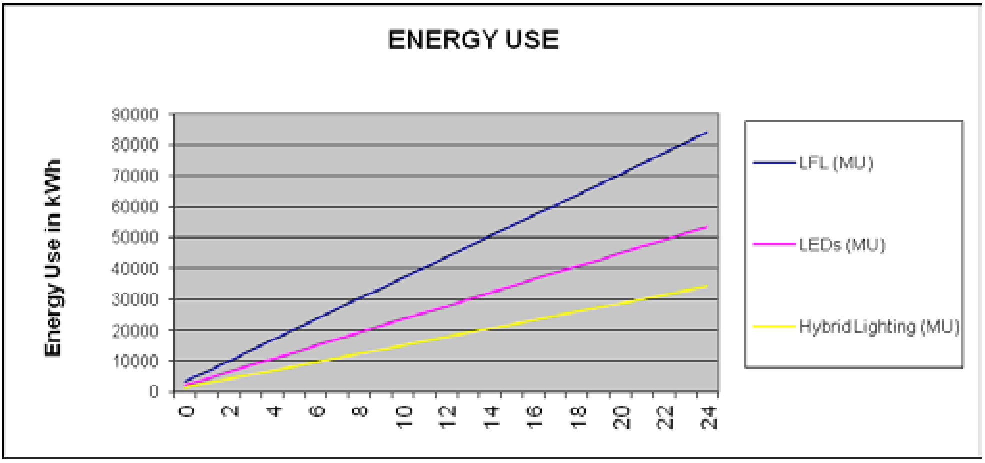



***Figure 5.2:*** *Energy use for the three options for Multiple User offices (MU)*

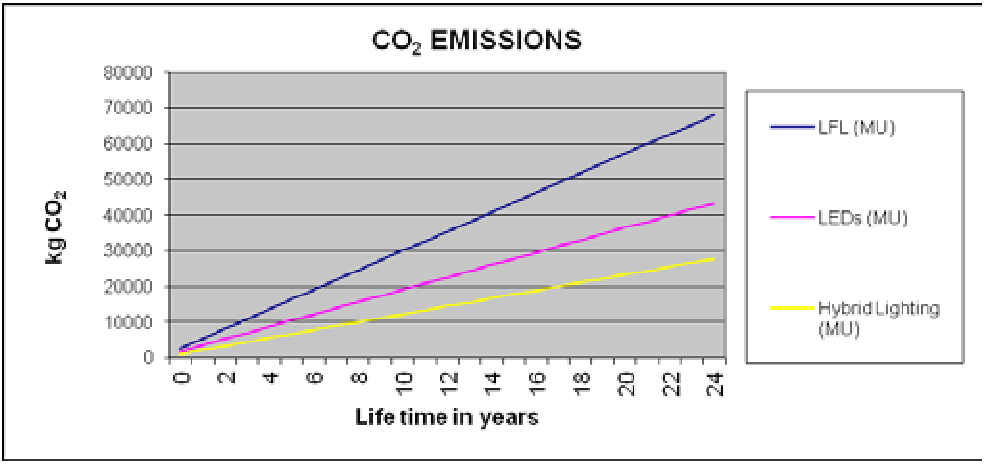



***Figure 5.3:*** *$CO_2$ emissions for the three options for Multiple User offices (MU).*

*A remarkable cost saving can be seen in the total energy consumption of the use phase (see Figure 5.4). Hybrid systems provide the facility to economise should energy prices continue to rise.*

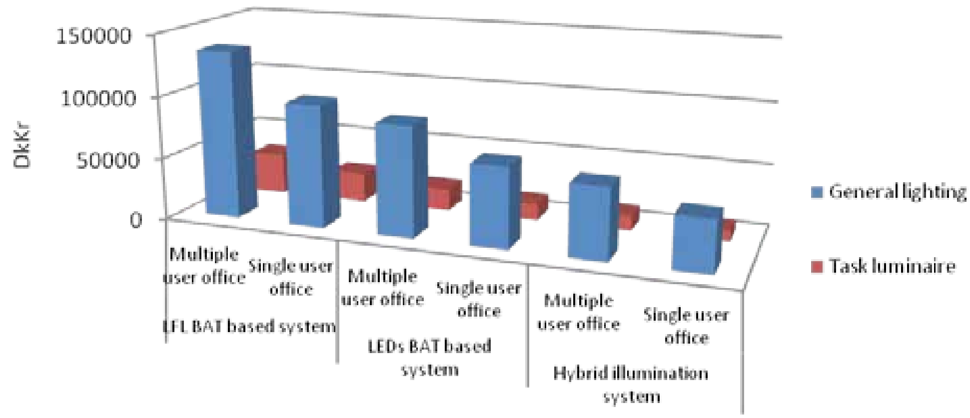



***Figure 5.4***: *Total costs of electricity consumption per functional unit for LFLs, LEDs and Solar hybrid systems. The prices are given in DKK of 2010.*

Another important parameter in relation to energy prices is that the cost of producing and consuming electricity based on fossil fuel has, until now, not reflected the *real* environmental effect of the so called $CO_2$- tax ($CO_2$-afgift). If the true environmental cost to society were to be reflected in the price, the cost of energy would increase considerably.

***Table 5.3***: *Total cost over life cycle current scenario.*

| | LFL System | LED System | Hybrid Fibre System |
|---|---|---|---|
| Total undiscounted cost over life cycle | -262 415 DKR | -386 191 DKR | -851 440 DKR |
| NPV at end of life | -188 336 DKR | -323 947 DKR | -818 022 DKR |
| Total energy use over life cycle | 84 100 kWh | 53 550 kWh | 34 275 kWh |
| Total $CO_2$ emissions over life cycle | 68 121 Kg $CO_2$ | 43 376 Kg $CO_2$ | 27 763 Kg $CO_2$ |

As can be appreciated from Figures 5.5.a and 5.5.b, the main issues in relation to LEDs appear to be the prices of the luminaries and the installation costs. This is due to the fact that many new LED luminaries are designed integrating the luminary to the lamp and the converter. The reason why it is argued that this is necessary is because the LEDs actually produce a lot of heat, and if it is not channelled properly, it can drastically reduce the lifespan of the LEDs. The current solution to this problem is making whole new luminaries that work as heat sinks at the same time. Although this solves the problem of the heat, it creates a cost barrier, as the whole system has to be replaced (luminaires, lamps and converters, plus the de-installation and re- installation costs).

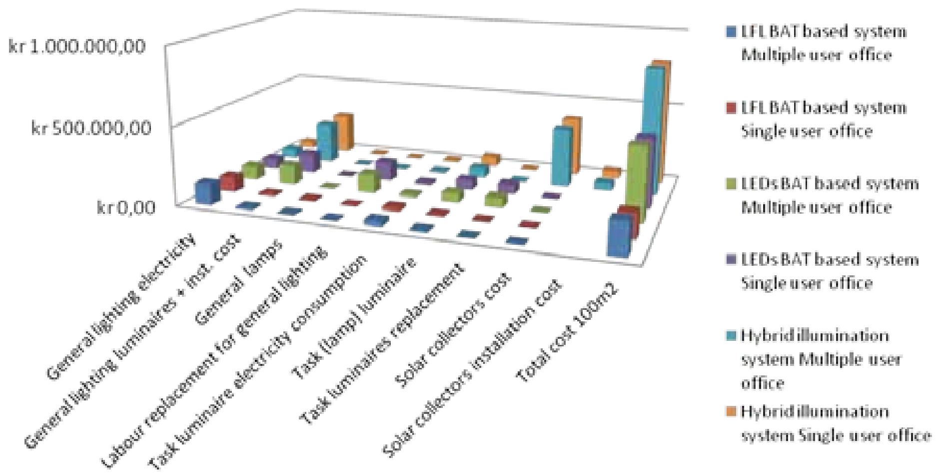



*Figure 5.5.a: Graphic distribution of total costs in the illumination service use phase. The prices are given in DKK of 2010.*

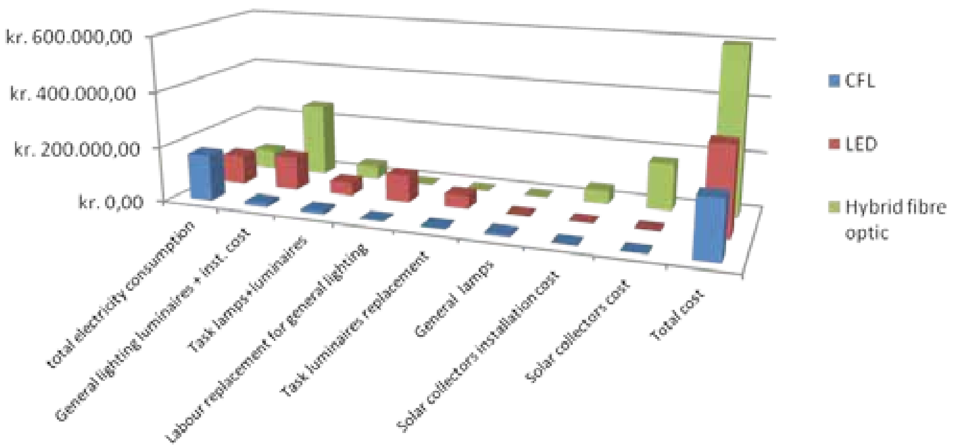



*Figure 5.5.b: Graphic distribution of total costs in the illumination service use phase. Prices of solar collectors adjusted in 2012.*

One way of avoiding this situation is to create solutions that can better adapt to currently installed luminaries. As Rogers (2003) points out, making the systems more *compatible* will reduce the uncertainty in potential adopters. If nothing is done it will set a very considerable barrier for the rapid implementation of LEDs and the achievement of approximately 36% energy savings. Making the lamps more compatible for the office sector will allow easier updating of this rapidly developing technology and will avoid the necessity of recycling the luminaire (heat sink) and the convertors. There are already some solutions of this type on the market (lamps that are compatible with previous LFL systems); however, in the opinion of the actors in the value chain, who have been contacted during this research, there is no EU standard on how long the LED might last. There are some American efforts for standardisation on the way (The National Institute of Standards and technology-NIST). In order to ensure a long LED lifetime, most of the research has been based on how to make LEDs dissipate heat. The fact is that while the lifespan of the LEDs and their efficacy is safeguarded, the use and cost of materials (heat sinks) has been compromised. As mentioned in Chapter 3, heat sinks make a considerable contribution to a number of environmental indicators. Although research on how to improve the luminous efficacy of the LEDs is being conducted, this needs to be be strengthened and more focus has to be put on this part of the development process. This could help reducing materials and installation costs, making this option more economically attractive.

In relation to HFOLS, the cost of materials (lamps + solar collector) and the installation represent the highest cost barriers for the hybrid illumination systems. This is in part due to the excessive price of the Parans solar optical systems, the still very high prices of LED luminaires, and the installation cost. As can be appreciated from the prices provided by Parans, the cost of a solar optical luminaire is 3,180 DKK, while a working LED luminaire costs 4,100 DKK. According to Poul Ibsen, the price is also relative to the design of the luminaires. Consequently, in order to become a real alternative, the material and labour costs of these systems have to be reviewed. The problem of adaptability and its solution is the same as for LEDs. Sensitivity analysis for HFOLs

The USA Department of Energy pointed out that some of the main problems in relation to the high costs for the Oak Ridge Laboratory's solar system are related to the tracking system:

> *"The main drawback compared to skylights is that HSL requires motors, electronics, and sophisticated control algorithms to continually align the solar collector with the sun" (*The National Renewable Energy Laboratory, 2004*).*

This might very well also be the case for the Parans' system, since the evaluation of the material used (lenses + fibres + aluminium) should not be so expensive. Making a passive system can considerably reduce the total cost, however, it could also reduce the efficiency of the system. Nevertheless, the passive solutions could make the hybrid systems more accessible, and perhaps make it more realistic to obtain energy and $CO_2$ reductions from these systems.

The prices of hybrid systems are expected to be reduced in the future. One of the cost projections from the USA Federal Energy Management Program indicates that the commercial price estimated for the year 2006 (20,000 USD) could be reduced by 85% by 2012. This goal was expected to be achieved even using a tracking system (see Table 5.4). The goal of reducing installation costs in 2006 was set at 75%. (Kintner-Meyer, 2007).

***Table 5.4:*** *Timeline for price reductions in hybrid solar lighting (Kintner-Meyer, 2007)*

| Cost element | 2006 | 2007 | 2012 |
|---|---|---|---|
| System cost | $20,000 | $16,000 | $3,000 |
| Installation cost | $ 4,000 | $ 3,00 | $1,000 |

This technology is currently on the early stage on the innovation curve, and this makes it possible to see that there is great potential for product development and possibilities for technological improvements both in terms of cost and energy efficiency.

In order to make a sensitivity analysis for HFOLS, the Energy efficient procurement (LCCC) DEEP Tool kit (Issac, et al. 2007) is used. The reduction rate is assumed to be the same as for the base scenario (3%). An on-peak electric tariff price escalator of 5% is estimated, based on the net present value at the end of life of the three options, as it is evident that reserves of fossil fuels will decrease and demand will increase.

***Scenario 1***

In this scenario it is assumed that the Hybrid systems are the same price as the LED systems in 2010, indicating a reduction in price of 24% (see Figure 5.6). In this case, the Hybrid systems become a better option than LEDs from year 2 or 3 and, in terms of Net Present Value, they will be cheaper than an LED-only system (see Table 5.5). However, the hybrid systems will be more expensive than LFLs, although Hybrid fibre systems will still be the option that achieves greater $CO_2$ reductions.

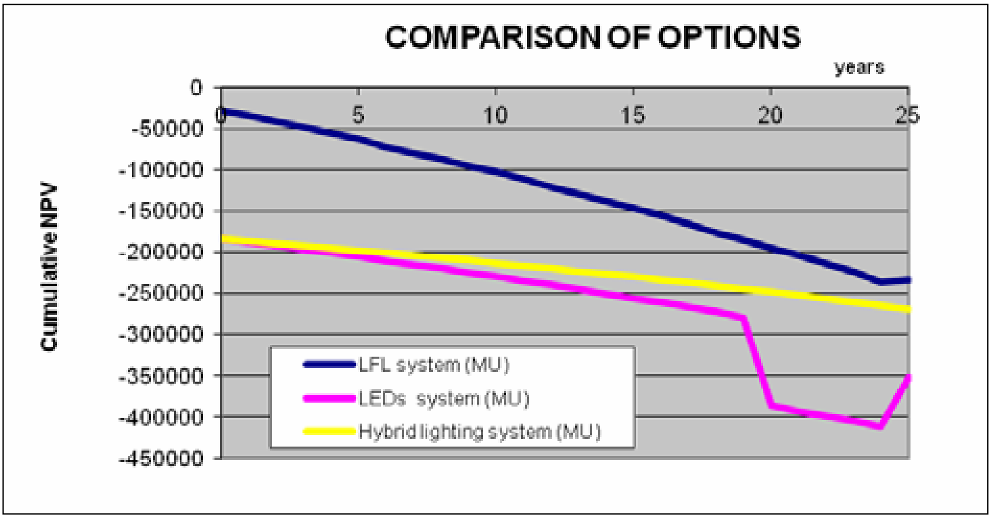



***Figure 5.6:*** *Scenario 1. A discount rate of 3% and a 5% electric tariff price escalator are used. An additional consideration is that the systems and installation prices can be reduced by 24%. Curves pointing up at the end indicate the residual value, for example, if the investment was sold off at the end of its life cycle. However, this will not be the case, since these systems are disposed of, and not sold on. The kinks in the graph occur, when there is significant expenditure. These are associated with the lifetime of the systems, occurring at various intervals, such as, when equipment is replaced.*

***Table 5.5:*** *Total cost over life cycle in Scenario 1*

| | LFL System | LEDs System | Hybrid Fibre System |
|---|---|---|---|
| Total undiscounted cost over life cycle | -338 225 DKR | -434 463 DKR | -314 868 DKR |
| **NPV at end of life** | -232 708 DKR | -352 201 DKR | -268 638 DKR |
| **Total energy use over life cycle** | 84 100 kWh | 53 550 kWh | 34 275 kWh |
| **Total $CO_2$ emissions over life cycle** | 68 121 Kg $CO_2$ | 43 376 Kg $CO_2$ | 27 763 Kg $CO_2$ |

### *Scenario 2*

In this scenario, the question is whether there is a high enough energy saving in relation to size. Price is one of the most important parameters that will have an effect on these savings, and therefore needs to be set accordingly.

In order to be competitive and take account their life cycle costs, hybrid lighting systems should be approximately the same price as LFL systems. Calculations indicate that, to achieve this goal, the whole hybrid system needs to reduce its price by 80% (see Figure 5.7 and Table 5.6).

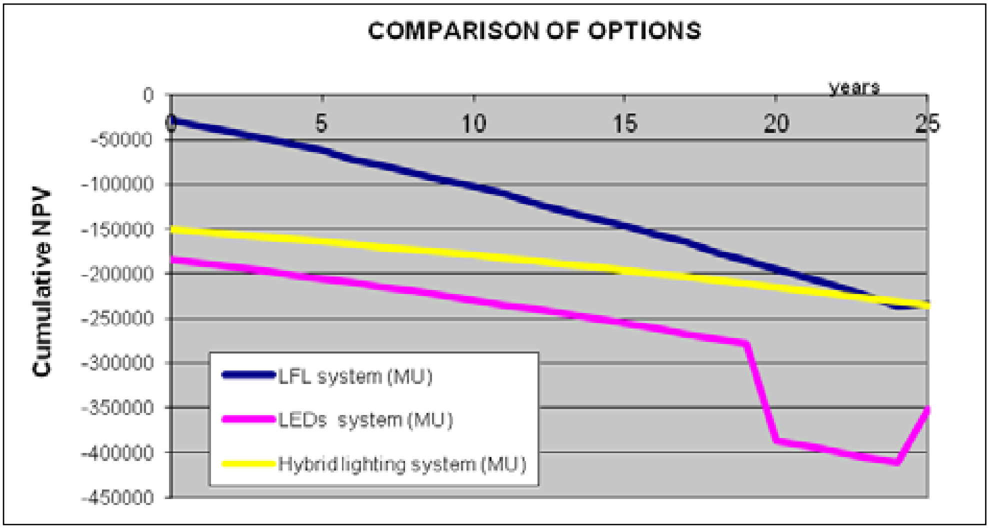



***Figure 5.7:*** *Comparison of options Scenario 2. A 3% discount rate and a 5% electric tariff price escalator are used, considering that the systems and installation prices can be reduced by 80%. Curves pointing up at the end indicate the residual value, for example, if the investment was sold off at the end of its life cycle. However, this will not be the case, since these systems are disposed of, and not sold on. The kinks in the graph occur when there is a significant expenditure. These are associated with the lifetime of the systems occurring at various intervals, such as when equipment is replaced.*

***Table 5.6:*** *Total cost over life cycle in Scenario 2*

| | LFL System | LEDs System | Hybrid Fibre System |
|---|---|---|---|
| Total undiscounted cost over life cycle | -338 225DKR | -434 463 DKR | -281 162 DKR |
| NPV at end of life | -23 2708DKR | -352 201DKR | -234 932DKR |
| Total energy use over life cycle | 84 100kWh | 53 550kWh | 34 275kWh |
| Total $CO_2$ emissions over life cycle | 68 121Kg $CO_2$ | 43 376 Kg $CO_2$ | 27 763 Kg $CO_2$ |

With the above price reduction in mind, for the 25 year period, the whole illumination service including materials, installation and energy prices should be around 25, 000.00 DKK, considering the Net Present Value of this study.

Reducing the price of the HLS system by 80% is not unrealistic for emerging lighting technologies. For example, LED roadmaps (Tsao, 2003) were suggesting a reduction of 100% for LEDs in 2010 in relation to their introduction price in 2003. This goal has almost been achieved, and the prices of LEDs continue falling.

Hybrid technologies are at a very early stage of development, and the small number of producers in the current market points to the fact that there is still a huge potential for the further development of hybrid systems.  A good example of how prices for these systems continue to fall can be seen by comparing the Parans price of 80,000 DKK quoted for a solar collector in 2009 (the year when this thesis project was started). When the research team purchased the systems for this study in 2010 the price was 54,208 DKK per system.  Parans system prices were further reduced in May 2011 to 24,000.00 DKK. This shows that prices fell 55% in just one year and 70% in relation to prices in 2009. Another example of the continuing growth of this technology can be seen when, at the beginning of this research in 2009, even after carrying out intensive research, it was not possible to find a source from which to purchase a hybrid lamp, as there were no lamps of this type on the market. Therefore, cooperation with Kolding School of Design was essential to this research.

In relation to the project financed by Elforsk, several lamps were designed with the aim of using materials that could be re-used or recycled. The project showed that when included in the aims, the costs of the materials can be reduced considerably without diminishing the aesthetic requirements of the product-service (see Picture 5.3)


***Picture 5.3,*** *LED lamp designed by Kriista Neergaard student at Kolding School of Design in the spring semester of 2010.*

## 5.3 IMPROVEMENT POTENTIALS FOR LEDS

It is very important to increase efforts to make LEDs more efficient at the same time as creating solutions that are compatible with current systems, particularly within the service sector. This could considerably reduce the price of materials and the installation costs, making the LED systems easier and cheaper, and therefore a more attractive solution for decision makers. According to the experience of IBSEN APS (a Danish electrical company), consumers do not think in terms of life cycle costs, they think in terms of a cost recovery time of three years maximum. If the solution offered does not fall within this time frame, they will adopt other solutions that do.

Life cycle cost is a very useful tool to show where further improvements can be made in the design phase. However, its main limitation appears to be that consumers operate with a completely different rationality in relation to what motivates them to adopt new solutions.

## 5.4 IMPROVEMENT POTENTIALS FOR HFOL SYSTEMS

A potential way to make the HFOL system more attractive to consumers is to find ways of reducing the price of materials and installation costs, making the system less complicated, and making better use of materials and design so they fit in with current lighting solutions. Particular focus should be placed on simplifying the heliostat, and avoiding complicated electronics for the collector system that can shorten the lifetime of the whole system. The project partners from Kolding School of Design reported that during the winter of 2010, when temperatures fell to -25°C, one of the systems purchased for this research became frozen and the tracking system failed, making the system inoperable.

Passive systems can be another option, but little research has been done in this area. Ways of simplifying the installation process need to be found for the system as a whole. This could be achieved by reducing the number of optical fibres, providing improved training for installation staff, and/or by improving the installation process system.

The Swedish company, Parans, launched a new design of their solar fibre optic collector in 2011. They have reduced some of the material used and have reduced the price by 70% compared with the version purchased at the beginning of this research in 2009. This indicates that further research could make this technology even cheaper.

## 5.5 DISCUSSION AND RESULTS

Installing a system based only on LEDs will contribute by saving 36% of energy when compared with the energy consumption of a system using only LFLs. Even though the price of LEDs of being reduced, the prices for luminaires where LEDs are implemented have not shown the same trend. The fact that most solutions integrate the luminaire, the lamp, and the converter, means that they will require the replacement of the whole illumination system. This makes the up-front investment very expensive and the life cycle cost more expensive than systems based on LFLT5. The recommendation made on the basis of this assessment is to place greater focus increasing the LEDs' luminous efficacy, and improve their design so that they can better adapt to current systems. In this way it will be possible to make use of the energy savings that LEDs can contribute.

By using a Hybrid system combining solar fibre optic collectors and making hybrid lamps, there is the possibility of a 59% energy saving when compared with the energy consumption of the LFL T5 system. Yet the most costly solution today is the hybrid illumination system, even though it is the solution that uses less energy and produces less $CO_2$ emissions.

Scenario 2 showed that, in order to be competitive in terms of price with the Linear Fluorescent Lamps (base case), the hybrid fibre system service tested in this assessment should cost at least 80% less than it did in the Net Present Value of 2010. This anticipation is not unrealistic, as Parans has already achieved a reduction of 70% compared to prices of 2009. However, in terms of adaptability, the same barriers that are present for LEDs are also present for HFOLS.

If electricity is produced entirely by renewable energy, there would be a reduction in $CO_2$ emissions, although this does not imply that the price of electricity will be cheaper. As can be seen in Table 5.7, electricity prices vary according to the

***Table 5.7:*** *Electricity prices by type of production plant (Levelized Cost of New Generation Resources 2016). Source: EIA, 2010 (original source Annual Energy Outlook 2010).*

| Plant Type | Capacity Factor (%) | U.S. Average Levelized Costs (2009 $/megawatthour) for Plants Entering Service in 2016 | | | | |
|---|---|---|---|---|---|---|
| | | Levelized Capital Cost | Fixed O&M | Variable O&M (including fuel) | Transmission Investment | Total System Levelized Cost |
| Conventional Coal | 85 | 65.3 | 3.9 | 24.3 | 1.2 | 94.8 |
| Advanced Coal | 85 | 74.6 | 7.9 | 25.7 | 1.2 | 109.4 |
| Advanced Coal with CCS | 85 | 92.7 | 9.2 | 33.1 | 1.2 | 136.2 |
| Natural Gas-fired | | | | | | |
| Conventional Combined Cycle | 87 | 17.5 | 1.9 | 45.6 | 1.2 | 66.1 |
| Advanced Combined Cycle | 87 | 17.9 | 1.9 | 42.1 | 1.2 | 63.1 |
| Advanced CC with CCS | 87 | 34.6 | 3.9 | 49.6 | 1.2 | 89.3 |
| Conventional Combustion Turbine | 30 | 45.8 | 3.7 | 71.5 | 3.5 | 124.5 |
| Advanced Combustion Turbine | 30 | 31.6 | 5.5 | 62.9 | 3.5 | 103.5 |
| Advanced Nuclear | 90 | 90.1 | 11.1 | 11.7 | 1.0 | 113.9 |
| Wind | 34 | 83.9 | 9.6 | 0.0 | 3.5 | 97.0 |
| Wind – Offshore | 34 | 209.3 | 28.1 | 0.0 | 5.9 | 243.2 |
| Solar PV[1] | 25 | 194.6 | 12.1 | 0.0 | 4.0 | 210.7 |
| Solar Thermal | 18 | 259.4 | 46.6 | 0.0 | 5.8 | 311.8 |
| Geothermal | 92 | 79.3 | 11.9 | 9.5 | 1.0 | 101.7 |
| Biomass | 83 | 55.3 | 13.7 | 42.3 | 1.3 | 112.5 |
| Hydro | 52 | 74.5 | 3.8 | 6.3 | 1.9 | 86.4 |

[1] Costs are expressed in terms of net AC power available to the grid for the installed capacity.

Source: Energy Information Administration, Annual Energy Outlook 2011, December 2010, DOE/EIA-0383(2010)

plant type. Additionally, if the demand for electricity increases prices will also increase. Consequently, savings in electricity consumption may have an impact on the future implementation of LEDs and increase the use of HFOL systems. This last option might still make sense in Denmark, as the target to phase out energy based on fossil fuels is set to be achieved, by 2050.

Hybrid illumination systems have a substantial potential for achieving net energy savings, and consequently real $CO_2$ emissions. However, since the use of artificial light is still necessary, the total cost of the HFOLS will have difficulty in competing with LED systems, as they are also becoming cheaper. Further, LED systems can stand alone while, in order to be reliable, Hybrid systems always need to include a device that provides artificial light when there is not enough sunlight.

In terms of implementation, the hybrid fibre systems would have difficulty in being chosen by decision makers today, particularly within the public sector and especially if their choice is based only on economic considerations, even though prices were reviewed in 2010. Nevertheless, if the cost of electricity increases considerably, hybrid systems could have a relevant part to play.

Porter (1990) and Rogers (2003) agree that competitive advantage in term of prices can be achieved by the overall cost leadership of the product or by differentiation. Porter also states that *focus* is a third strategy approach to outperform other firms or industry.

According to Porter *overall cost leadership* requires aggressive construction of efficient-scale facilities, vigorous pursuit of cost reduction from experience, tight cost and overhead control, avoidance of marginal customer accounts, and cost minimisation in areas like R&D, service, sales force, advertising, and so on. Whereas *differentiation* is about creating something that is perceived by the consumer as something unique. The differentiation might be due to, among other things, brand, design, comfort, service, or ethical issues. *Focus strategy* refers to focusing on a particular group or geographic market with a specific need (Porter 1990).

From this perspective, one can say that riding bicycles is more environmentally friendly and a cheaper method of transportation, yet most people prefer to drive automobiles. In relation to focus strategy, one can say that one needs to see if there is a group of costumers with a specific need. Focus strategy differentiates itself from the two first strategies in that, instead of pursuing an industry-wide objective, the firms concentrate on delivering the service more efficiently, or effectively narrowing the focus to target a specific sector or group of consumers.
Consequently, it is important to see if LED and hybrid lighting systems could offer additional service quality for the consumer, and if there is a specific group of consumers that currently needs to reduce their energy consumption of energy. This will be discussed in the following chapters.

Considering that HFOLS is an emerging technology and that there is still room for improvement, it is not unrealistic to forecast that this system will become cheaper, particularly considering the entire life cycle of the illumination service and the future development of energy prices.

There are two ways to make hybrid systems cheaper: the first is to make them more effective using fewer materials, and through increased efficiency in collecting solar light per $m^2$, which will also require the second option, which is the improvement and use of sun tracking systems. More research needs to be done into sun tracking systems to see how the cost and technology develops.

Other ways of reducing the cost of the systems is to avoid expensive sun tracking systems using more optic engineering and streamlining the efficiency of the system in order to obtain a faster implementation. To facilitate system development, there is also need for more research into passive and active systems.

## 5.6 CONCLUSIONS

In this chapter, a life cycle cost assessment was conducted comparing three illumination systems. The objective was to establish if LEDs and HFOLs could be cost-competitive in comparison with the best available solution suggested by the EU Preparatory Studies for the office sector. The comparison cases were:

A. an illumination system based on T5 linear fluorescent lamps;
B. an illumination system based on LEDs, and
C. an illumination system combining a solar fibres, solar collectors and LEDs using an automatic switch on/off function. The baseline case was the system based on LFLT5.

Further a calculation of energy and $CO_2$ emissions savings was also carried out through the use phase of the illumination service life cycle. The illumination service was calculated for an office space where both general light and focus task illumination were both taken into account. The illumination calculations made were based on two scenarios: a single- user office and a multiple-user office.

From the study it can be concluded that, for the cases hereby considered:

The least favourable option in terms of energy consumption and $CO_2$ emissions was the illumination system based on linear florescent lamps T5.

Using a system based on LED lamps could *save 36%* of energy and thereby the same proportion of $CO_2$ emissions, as the type of energy saved is primary energy in comparison to the least favourable option (LFL T5).

The cost of materials and installation are some of the main barriers for LED systems to be economically competitive with the best available technology (LFLT5).

The recommendations are to increase focus and research to make the LED more efficient, and concurrently, it is very important to design solutions that are compatible with current systems (particularly within the service sector).

Using a hybrid lighting system (solar fibre collector/LED lamps and an automatic switch on/off function) could *save 59%* of primary energy, and thereby 59% of $CO_2$ emissions. This option is the best solution in terms of energy and $CO_2$ emissions savings, yet it is currently the most costly solution.

There are two ways to make the hybrid systems cheaper: one is to make them more effective using less materials and collecting solar light per $m^2$ more efficiently.

Other ways of reducing the cost of the systems would be to avoid expensive sun tracking systems that use more optic engineering and streamlining the efficiency of the system to obtain a faster implementation. To facilitate the development of the technology more research is needed into passive and active systems. The improvement of the installation process would also be of substantial benefit. This system could become highly attractive in terms of achieving important energy reductions and thereby real $CO_2$ emissions savings.
Life cycle cost is a very useful tool to establish where further improvements can be made in the design phase. However, its main limitation in relation to this study was that it operates without taking account of other rationalities that might motivate decision makers to adopt new technologies in relation to price.

In terms of eco-design feasibility assessment the conclusion is that the overall cost leadership cannot be used on its own to evaluate the competitiveness of products in the market. Consumer perceptions of the innovation, the identification of added values and of targets groups must be assessed to determine the real commercial potential of the system. These issues will be discussed in the following chapters.

Chapter 6

# Assessing consumer acceptance

As discussed in Chapter 5, cost is an important factor for successful implementation. According to Porter (1985 and 1998), there are three different strategies to be cost competitive in the market, namely: overall cost leadership of the product, by differentiation or by focusing on a particular buyer group. From the conclusion reached in Chapter 5, both LEDs and HFOLS have difficulty in competing with LFL T5 in terms of overall cost leadership at the present time. Therefore, it is important to establish if that competiveness can be achieved through a differentiation strategy, or by focusing on a particular buyer group. Thus, it is necessary to find out what would be the added value that consumers consider as unique (Porter, 1998) or as a relative advantage (Rogers, 2003) and to identify the focus group.

To achieve these objectives, Rogers (2003), believes that it is important to predict the reactions of people to an innovation, not only making a differentiation of the type of adopters, but also taking into account the beliefs and past experiences of potential adopters. For this, it is important to establish a means of communication and a mutual learning process. The question for analysis and discussion in this section is: What can be improved in the product-service system so that alternatives can provide a more satisfactory service for the consumer and what can be the added value?

In relation to the user practice inclusive eco-design and innovation life cycle framework (see Figure 2.3) discussed in Chapter 2, it is important to identify the decision units and their role in influencing the implementation or adoption of innovations.

Drawing from Rogers' innovation—decision process, it is important to find out what types of characteristics the decision units perceive as advantageous. According to Porter (1985) using this knowledge one can identify where the innovation can be differentiated from other products to be more competitive in terms of value, or in other words, if the technology has the potential to be consumer acceptable. According to Porter, "Value is what buyers are willing to pay, and superior value stems from offering lower prices than competitors for equivalent benefits or providing unique benefits that more than offset a higher price" (Porter, 1985:3). The innovation decision process, according to Rogers, "is the process through which an individual (or other decision-making unit) passes from gaining initial knowledge of an innovation, to forming an attitude toward the innovation, to making a decision to adopt or reject, to implementation of the new idea, and to confirmation of this decision. This process consists of a series of choices and actions over time through which an individual or a system evaluates a new idea and decides whether or not to incorporate the innovation into ongoing practice. This behaviour consists essentially of dealing with the uncertainty that it is inherently involved in deciding about a new alternative to an idea previously in existence. The perceived newness of an innovation, and the uncertainty associated with this newness, is a distinctive aspect of innovation decision making (compared to other types of decision making)" (Rogers, 2003:168).

The communication and subsequent learning process provided by consumer or user feedback can be used by the designers or the innovation managers to improve product design, including user engagement to help create a more consumer-oriented product-service. According to Rogers this inclusion can take place in the research and development process for new technologies or products, and will help to reduce uncertainties from the early stages of the innovation process. It is important to stress that this process assumes that inventions *are variant* and can undergo not only one, but several re-invention actions. This may not be a linear process, as the studies' eco-design and innovation framework tries to demonstrate (see Figure 2.3). Furthermore, this learning process has double benefits, as the consumers also learn about the new technologies and how to adapt to them.

This two-sided information and learning process (designer-consumer) helps to identify any additional benefits of the new technology and what could be included in the design or specification to satisfy consumer needs. Additionally, this learning and communication process can help to make a clear-cut differentiation when comparing a product with other alternatives. The innovation decision process for an eco-design strategy under a product service perspective helps the designer to improve the design and, at the same time, reduces consumer uncertainty about the new technology. Based on the author's experience, this process speeds up the evaluation process to establish if a new technology has the potential to be acceptable to the consumer and to identify the specific criteria a consumer might consider acceptable if the product price is higher than other available alternatives. This chapter will begin by analysing previous studies of the elements that need to be considered, in relation to consumer demands, when implementing energy saving lamps in the office sector. The second part of the chapter identifies consumers or focus users, including a discussion of their role and what possibilities there may be for the development and implementation of new lighting technologies. The intensive study case is used to understand the feasibility of LEDs and new applications in which LEDs might be incorporated (e.g. HFOL). The final part of the analysis is a consumer-user test which was conducted in order to establish the potential for product acceptance by consumers and users.

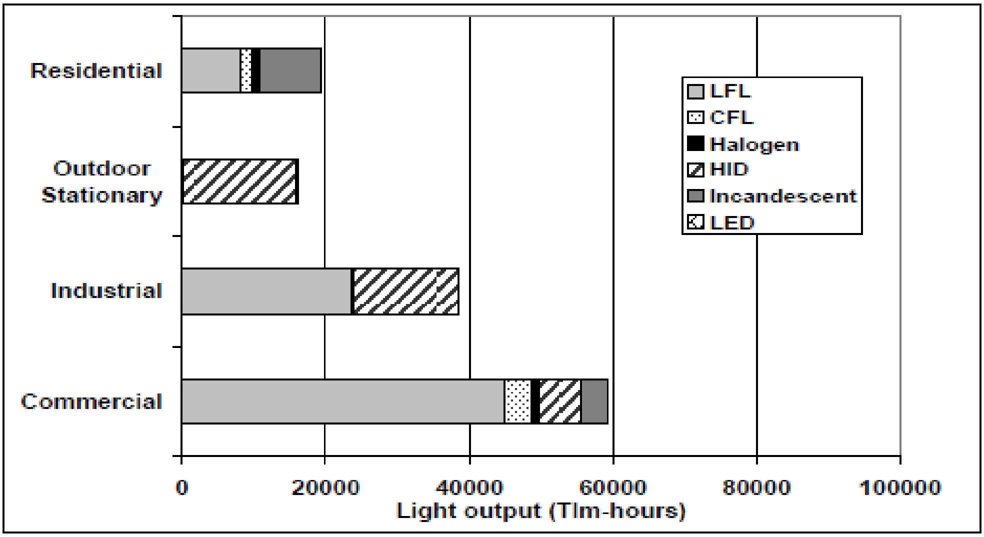
Ten face-to-face qualitative (semi-structured) interviews were conducted with office users (staff at Roskilde University) to establish the specific quality criteria for office lighting in general. This information was put through a "minimal statistical analysis" (O'Leary, 2007) containing these general criteria in order to support the study's qualitative data evaluating HFOLS in relation to consumers acceptance. The population was composed of university staffs who are office users. To encourage a wider range of participants to take part in the test, and thereby avoid recruiting only those that were interested in lighting, a couple of bottles of French wine were raffled. The invitation was sent out using the intranet e-mail system at Roskilde University. Thirty-two persons were interviewed and answered the questionnaire.

A more in-depth qualitative interview about this system was carried out when representatives of Stevns Municipality, as a particular sector of the consumers' group, visited the exhibition to see how this system functioned.

As the HFOL systems include LEDs, the assessment would also be useful for evaluating the performance of LEDs in relation to consumer demands when talking about the artificial light within the study case. Consequently, the intensive study provides knowledge in relation to design and implementation issues for both LED and HFOL systems.

## 6.1 PAST EXPERIENCES OF POTENTIAL ADOPTERS

One of the most relevant examples examining the experiences of potential adopters is the case of fluorescent lamps. These lamps were first invented in the late 19th century and were in the development stage until the beginning of the 20th century. They were introduced to the market in the 1930s. During the history of these lamps one can see that they were, and still are, more used in the commercial and industrial sector than they are in the domestic sector (see Figure 6.1).




Note: LFL = Linear Fluorescent Lamps; HID = High-Intensity Discharge Lamps; LED = Light-Emitting Diodes. Source: IEA (2006).

***Figure 6.1:*** *Estimated light production by application sector and type of lamps (Lefévre et al., 2006).*

According to Lefévre et al. (2006) and Sandahl et al. (2006), the market introduction of LFLs in the domestic sector is recorded as having started from the 1970s, although their implantation strategy was not very successful and took until the 1990s to really develop momentum.

In the studies carried out by Lefévre et al. (2006) and Sandahl et al. (2006) on compact fluorescent lamps, one is aware that in relation to direct users (those who pay and use the service) in the commercial sector, several barriers were identified to explain the slow implementation. In terms of consumer perception of the service, we can identify that the most important factors are:

- High level of uncertainty. This issue was linked to lack of awareness and mis-information about the lamp's clear-cut benefits
- Negative experiences when testing the products
- No real incentives to change, related to very stable and low energy prices
- Current trends, for example, associations with personal experiences from the light used in working places that gave this technology a negative image
- Lack of complete understanding of costs, in terms of service life cycle
- Colour of light
- Light output (intensity)
- Flickering and humming problems
- Design of the lamps and luminaires

From these central factors, both studies conclude that technological and performance issues go hand and hand with consumer perceptions and diffusion barriers. As Sandahl et al. (2006) explained:

> *"As we have seen in our discussion of barriers, technology improvements alone do not guarantee market acceptance. Getting the word out about the new product, showing consumers its value, educating retailers on how to market it, working with manufacturers to leverage promotion efforts – all of these are critical pieces of the consumer acceptance pie" (Sandahl et al., 2006: 42).*

The illumination sector in Denmark has learned some important lesson from these past experiences, however, as discussed in Chapter 1, much of the information and public campaigns in Denmark continue to be directed towards the domestic sector, while the biggest potential  for energy savings are in the trade, commercial and service sectors. If the intention is increased strategic differentiation and focus on its strategy, it is important to identify the main decision makers and establish what can be done so that they have a better perception of the innovations within the illumination sector. Consequently, targeting the real actors of change more directly will have better results.

## 6.2 WHO DECIDES WHAT ILLUMINATION SERVICE SHOULD BE BOUGHT FOR PUBLIC BUILDINGS?

Several main stakeholders were indentified upon the intensive study case:

- *Regulators: s*etting the standards for the minimum lumens to be used in workplaces, and currently setting the efficiency demands for lamps and luminaries
- *Services providers*: such as, illumination designers, illumination consultants and electric installation firms
- *Consumers:* such as, building developers, building associations and finance departments responsible for purchasing in municipality building. The main driver for this group is to find the most competitive price combined, in some cases, with their *aesthetic requirements* and, more recently, fulfilling public regulations and policies
- *Users:* such as, employees in all types of organisations, businesses and institutions.

### 6.2.1 Regulators

*Regulators,* in the form of EU directives or Danish standards, have had an important, although indirect role within the programs. Their objective is to phase out inefficient lamps, including the most inefficient linear fluorescent lamps. These regulators are currently influencing purchasing decisions in the public sector. The first initiative was the substitution of incandescent lamps which, in general, have not had a substantial effect on either public or services buildings, since these mainly use fluorescent lamps. However, Regulation (EC) No 245/2009 under the EU Directive 2005/32/EC, will have a more direct effect since it relates to phasing out current most inefficient fluorescent lamps. Other important actions include the Building Regulations BR08, which established the energy marks for already existing buildings (through energy categories, from A-F), and another from Danish Standards 700 which encourages a differentiation of illuminated areas with different degrees of illumination intensity (lumens) in buildings.

### 6.2.2 Service providers

Some of the main discussions, especially among architects, describe their reasons for choosing one light source over another. These include the colour of the light, the ability of the different light sources to spread the light and the light intensity. The role of these stakeholders is important, as they are the main advisors to the target consumer group. Further, these groups are made up of professional people, such as architects and engineers, who due to their professional status and expertise, can have a powerful influence over the consumer. Observations made in this sector by means of the intensive study case, reveal that OSRAM, Philips and CREE have made a considerable effort to inform this group, in cooperation with Danish Centre for light. Elsparefonden also targets information campaigns towards this group (see Picture 6.1).

However, this information is focussed more on the lamps than on the product-service. It appears that there is less information on control systems, sensors, dimmers and case studies describing solutions that integrate not only more natural light, but an intelligent combination of natural and artificial light. The discourse about cost is only relates to current prices. There is no discussion about the life-cycle cost development. Moreover, it was observed that service providers still consider the light intensity and light distribution from the LEDs deficient in relation to other artificial light sources. In contrast to this situation, the three industry representatives mentioned above continue to pursue an active information campaign about development performance, which has helped to maintain the interest of many service providers on the LED technology future performance but not as a current solution. As service


***Picture 6.1:*** *Information directed to service providers (consultants). Source:http://www.goenergi.dk/publikationer/brochurer/nyt-lys-paa-fremtiden*

providers advise consumers, the recommended solution uses to be LFL T5 or other conventional solution but not solutions based on LEDs. Thus, LED technology will not be widely implemented unless consumers are directly involved, fully informed, and have had an opportunity to test the options available by themselves.

### 6.2.3 Decision makers in public buildings

The European Commission has launched a European initiative called the Covenant of Mayors (www.eumayors.eu/). Under this initiative, local governments voluntarily agree to submit their Sustainable Energy Action Plans (SEAPs) describing how the local government will reach its $CO_2$ reduction target by 2020. Municipal infrastructure, such as, district heating, public lighting and smart grids, is one of the sectors where strategic changes should be implemented. Taking the Danish Municipalities into account as actors of change is important, as according to the vision of the EU initiative, they will have an important role as:

- Consumer and service provider;
- Planner, developer and regulator;
- Advisor, motivator and model; and
- Producer and supplier.

In the dialogue with the Stevns Municipality representatives, they expressed a great deal of interest in finding solutions to reduce energy consumption in their public buildings. As illumination is one of the sectors with the highest electricity consumption, this point is quite relevant for this target group.

The dialogue with the representatives of these municipalities established that little information is being received about the benefits that new illumination technologies can provide, and that most of their information comes through energy advisors or service providers. Consequently, it would be advisable to hold information meetings with these actors, or to create a specific campaign about the new technological possibilities and targeted at this sector. Apart from reducing the representative's uncertainties about this new LED technology, such information could give them a firmer foundation from which to voice their requirements when talking to services providers. Observations in the field in relation to the intensive study case have shown that some successful cases of LED implementation have been presented at information meetings. However, in most cases, the audience at these meetings is made up of service providers and not other municipality representatives.

The dialogue with the Stevns municipality representative when demonstrating and testing the intensive case (HFOLS) pointed out that price is important, but even more important for them is a good lighting service with a better light quality and with higher potential to save electricity, so that these savings can contribute helping them reach their $CO_2$ emissions saving goals. This municipality representative is further aware that implementing cleaner and more efficient technologies can also contribute to enhancing business possibilities in her region. Consequently, targeting the dialogue more towards these stakeholders is fundamental in establishing the clear-cut differences between LFL and LEDs, as well as creating a more focused strategy to encourage these stakeholders to be first movers in implementing the new technologies within the illumination sector.

### 6.2.4 Users

The qualitative interviews with office users showed that these actors are seldom consulted in relation to the type of illumination used. They also find their own strategies to achieve the type of lighting service that they require on an individual basis. These individual additional solutions are additions to the service provided, as shown in Pictures 6.2 (a) and 6.2 (b).

***Picture 6.2 (a) and 6.2 (b):*** *Researchers at Roskilde University adding personalised solutions to the one provided by their workplace.*

To cross check information employees from shops (boutiques) in Roskilde City were interviewed, their responses stated that they have not been informed about energy savings in their workplaces; they had not though about illumination before, and; they did not consider that they have any influence in the decision making process. These employees expressed that, in the majority of cases, the shop owners hire an illumination designer to do this job. In these types of businesses chains spots dominate the lighting systems (see Pictures 6.3.a, and b).

During the interview with the Telia representative (see Picture 6.3.b) about the heat produced by the lamps and its possible effect on customers' comfort while shopping, he stated that they normally compensate for the heat by turning on the air-conditioning. When it was explained to him that they could save air-conditioning by switching to a more efficient illumination system he agree that this would be a better option. A few months after the interview, when passing by the same shop (shown in Picture 6.3.b), it was evident that the spots had been replaced by more efficient lamps.


***Picture 6.3:*** *Different solutions depending on the actor who makes the decision. Picture 6.3.a) and b) show shops where the employees do not have the decision, they also stated that they have never questioned the illumination in the working places*

This example demonstrates that these actors lack information, and that providing them with more information is important. They do not consider themselves able to influence the decision making process, but if they acknowledge the problem, they can influence change. Yet the illumination campaigns in Denmark are mostly directed towards households. The implementation of direct campaigns for shops and owners of service buildings emphasising the additional benefits in energy savings due to reduced costs for lighting and air conditioning/heating, and a more comfortable environment for their customers might make these actors take active decisions toward more efficient systems. The current business decision process is quite top-down and there is little or no feedback about the end users (see Figure 6.2). A more dynamic and knowledge-based model can be achieved if consumers and users are placed at the centre of the model (as suggested in Figure 6.3).

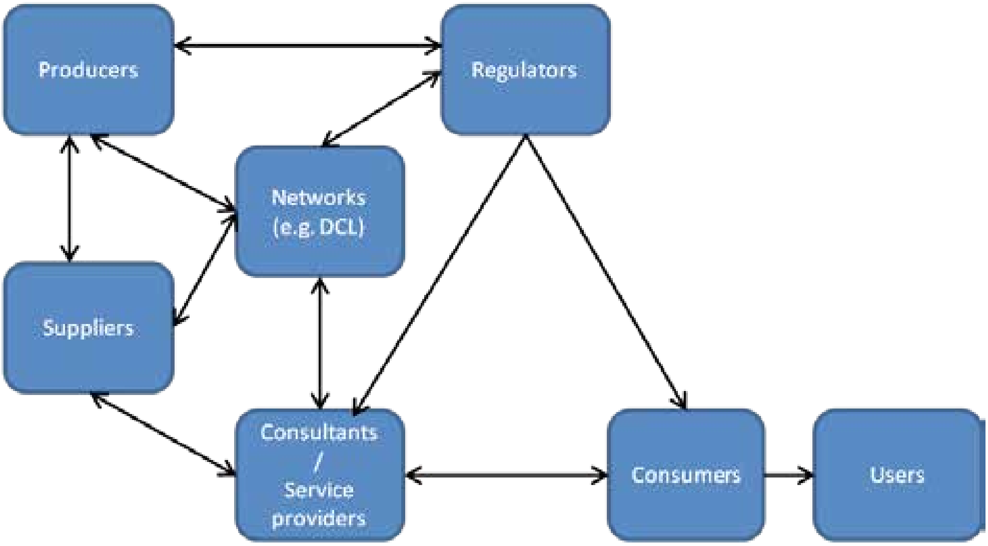



***Figure 6.2:*** *An illustration of the current model of the decision and communication process when purchasing illumination systems in the service system. In this model users' demands are hardly heard.*

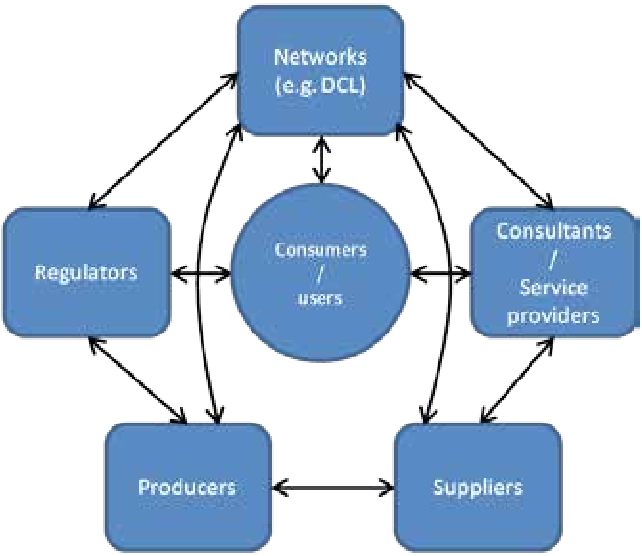



***Figure 6.3:*** *This is a suggestion for a model where the consumer/user are at the centre. The arrows show both the communication and the decision direction. Producers get consumer/user feedback indirectly from suppliers and consultants, and also from the networks.*

According to Rogers (2003), the more information the less uncertainty there is to adopt an innovation. This relates to consumers and to the whole technological system, therefore feedback from consumers is important at all levels.

## 6.3 HYBRID LIGHTING CONSUMER-USER TEST

Rogers (2003) believes that the diffusion of innovation, or the rate at which consumers will accept or reject an innovation, will depend on the communication channels used to communicate the benefits of the product or service. Although Rogers describes several types of communication channels, the interpersonal ones are of interest to this research. He argues that, often, the most successful methods for the diffusion of innovation take place when an innovation has been conveyed to people by other individuals like themselves who have already tested or adopted that innovation. Therefore, including potential consumers/users that will adopt this innovation is of central importance.

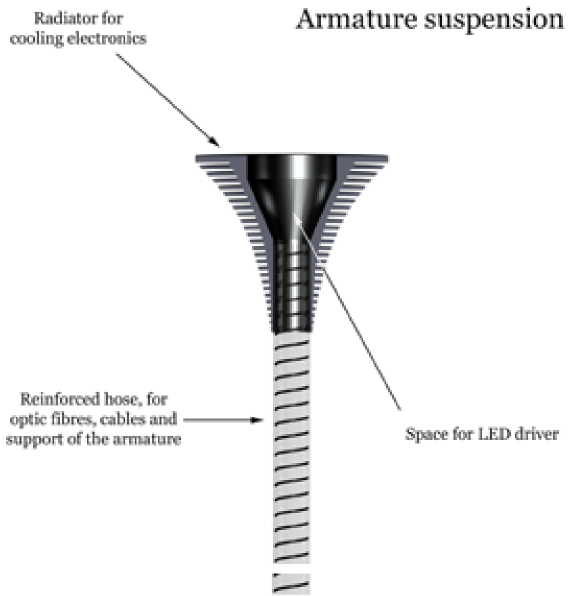
Identifying and evaluating consumers' perceptions in relation to the design in this research required looking at subjective preferences or properties in relation to its function. During the development of the project entitled "Hybrid fibre lighting directed towards a minor ecological footprint", in which a hybrid lamp was designed, the research group set the preliminary criteria for the design from the previously described criterion which is shown in Table 6.1 below.

***Table 6.1:*** *Functional unit defined by the design group working in the project "Hybrid fibre lighting directed towards a minor ecological footprint".*

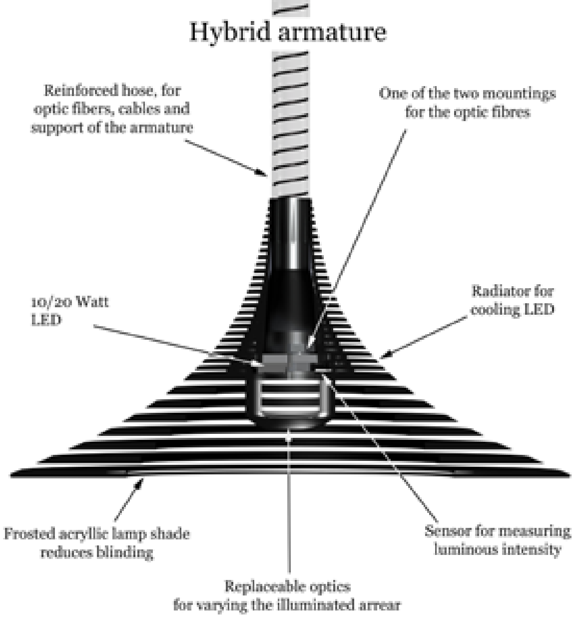
| **Obligatory properties** | **Positioning properties** |
|---|---|
| Supplying 500 lux to a working area and 200 lux for general illumination in a typical Danish office | - Non-blinding effect<br>- Avoiding overheating<br>- Optimal spectral composition of light for a working space (colour and warmth of light)<br>- Aesthetic components of the room<br>- Reducing $CO_2$ emissions |

## 6.3.1 Designing a hybrid lamp

The collaboration in this project resulted in the design and construction of two hybrid luminaire prototypes. One of these is an integrated, ready-to-install end solution (see Picture 6.4a and 6.4b, showing a Hybrid Fibre Optic luminaire designed under the project "Hybrid fibre optic lighting- towards a minor ecological-footprint", financed by the ElForsk programme).




***Picture 6.4.a:***
*Armature suspension*

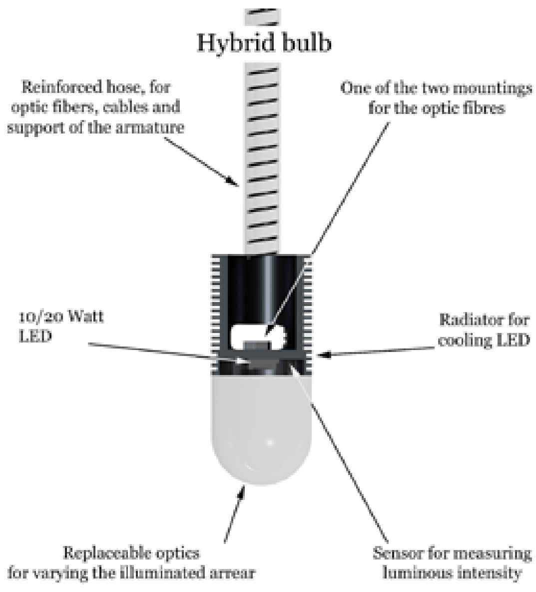



***Picture 6.4.b:***
*Hybrid Luminaire (armature)*

Within the same project, a lamp-luminary was also designed. This is an adaptable solution designed with the intention of giving consumers the option of bulb replacement in existing luminaires. This option offers the possibility of conserving classical luminaires that consumers value highly, such as, the famous Danish designed luminaires (see Picture 6.5). Light emitting diodes (LEDs) were selected in the design of both luminaires because these devices do not contain mercury and have a longer life span.

From a technological point of view, LEDs are more flexible for use together with on/off switches when interacting with solar lighting, thereby achieving real energy savings. They have the potential to become more effective in the future. Their intensity and colour of light is flexible, so they can be designed to fulfil consumer expectations.

From an aesthetic point of view, their size and flexibility allows for many new forms and expressions. The lamps were designed with an automatic intelligent on/off switch that allows the change from natural light to artificial light by making use of two fibre optic bundles to provide the direct solar light. In this way, even when it is overcast, the lamps can deliver a constant and reliable light source at all times of the day. Besides these two lamps, design students from Kolding School of Design were invited to participate and to learn more about this technology, as they will be key stakeholders in the lighting sector in the future.




***Picture 6.5:***
*Hybrid fibre optic lamp-luminaire designed under the project "Hybrid fibre optic lighting- towards a minor ecological footprint", financed by the ElForsk programme.*

## 6.3.2 User test

When the criteria based on the previous experiences and the 10 focus interviews (including costumer and user criteria) was included to define a good service, a more complete and user oriented definition of the illumination service in the office sector was obtained (see Table 6.2). These criteria were then used to create a simple questionnaire and user test.

***Table 6.2:*** *Functional unit defined by users in the office lighting sector.*

| **Obligatory properties** | **Positioning properties** |
|---|---|
| Supplying 500 lux to a working area and 200 lux for general illumination in a typical Danish office | - It should be possible to read and write comfortably<br>- It should be possible to work at a computer without being affected by reflected light<br>- It should be possible to see peoples' faces while holding meetings<br>- The light should be as close to daylight as possible (indirect sun light) both in colour and intensity<br>- It should avoid overheating<br>- The direction of the light should be at a comfortable angle (no blinding)<br>- The lighting should be aesthetically pleasing<br>- It should be flexible (regulation of intensity)<br>- It should reduce $CO_2$ emissions<br>- It should not contain mercury<br>- It should provide an indication of daylight usage ('green responsibility') |

## 6.3.3 Installing HFOLS prototype at Roskilde University

The fibre optic solar collector system from PARANS and the hybrid luminaires that were designed during this project, including those designed by the students were installed in one of the main buildings (Building 01) at Roskilde University. A questionnaire was created, which was based on the explorative qualitative interviews with users in the office sector. The questionnaire worked as the document test for reading and writing tasks, and we provided a laptop computer for the use of respondents. The test group was composed of staff and student volunteers at Roskilde University who agreed to test the system. The system was set up in one of the rooms near the central cafeteria of Roskilde

University (see Pictures 6.6. a, b, c, and d). Thirty-two volunteers tested the hybrid illumination system.

The test was conducted during April 28th to the 4th of May. The weather conditions were variable during the tests (sometimes overcast and sometimes full bright sunshine).

It must be stressed that the test was designed to explore further considerations to support our design decisions rather than making a scientific statistical research. Thus, the results of the test have been used to further point to issues that can be re-designed to further develop new hybrid lighting systems and also to evaluate the performance of LEDs when included in hybrid systems.

***Pictures 6.6 (a), (b), (c) and (d):*** *from left to right: installation of the sunlight collector; installation of the optical fibres; installation of the luminaires; and layout of the room.*

## 6.3.4 Assessing user perceptions

***Light dynamics***

Results from the test show that 91% of respondents experienced lighting variations when testing the systems. This occurred when the sky was overcast and when the sun started to shine again, or vice versa. Nine percent of respondents did not experience lighting variations. This might be because there was sunshine or an overcast sky during the entire period of the test.

There are some losses from the red part of the spectrum in relation to fibre optic lighting and this was observable in the test, since the designers used warm white LEDs. As indicated in the qualitative interviews, light dynamics were within the parameters that the focus group considered important. On further enquiry into whether they liked the light emitted by the system, the responses given indicated that they found the light pleasant, that there is an indication of daylight, and that the light appears natural.

Most people liked the light dynamics of the test system because they found it pleasant and because it demonstrated use of daylight. This was a positive indicator, as one of the positioning properties listed by the users suggested that light should have this value. From this, it can be concluded that even when the light emitted by the optical fibres is a bit greenish, it is not a big limitation for the user to accept or like the system as it was tested. In order to have a fuller and broader acceptance from all types of user, the system should be as close to the natural light (daylight) spectrum as possible, considering the information heard in the qualitative interviews, and this should be as important for the LED colour selection as for the light coming from the optical fibres.

***Temperature, colour and quality of light***

These criteria are important, as they are some of the past experiences that have created a barrier for the implementation of other light sources. The same factors were also pointed out to describe a good illumination service according to the qualitative interviews with the focus group.

*Light Temperature*

When the users were asked if they experienced warm or cold light, 71% of the interviewees answered that they had experienced more cold light. This might be due to the fact that the system was operating in full sunshine for most of the time and the LED light for only part of the time. As indicated above (in the section on the design of the lamps), a warm white LED was selected to supply the artificial light. This fact, contrasted with light dynamics perceptions, indicates that even when the dominating light was coming from the optic fibres (cold light) consumers considered it pleasant and an indication of using daylight.

*Colour of light*
In relation to the colour of the light, surprisingly 67% of the users indicated that they experienced blue light. As mentioned before, one of the characteristics of the PARANS solar system assessed by DTU-Fotonik project partners is that the spectrum of light is dominated by the green part. However, it is interesting to see that what users perceived as cold light is related to the colour blue.

*Blinding effect*
The respondents were allowed to mark more than one option in relation to the quality of light. When the respondents marked more than one option, all responses were given the same weight. 70.9% of respondents answered that the light did not blind them. This was a positive answer. However, the design needs to be improved so that all the users are satisfied.

***Even distribution of light in the room***
It is important to remember that some of the lamps were prototypes developed in a five week project by students of Kolding School of Design and were not commercial examples. These lamps were fragile, and although we asked the users not to touch them, many of the test users wanted to see the interior of the lamp, the LEDs, the optical fibres and the automatic switch. This showed that there is great excitement from consumers when using new types of lighting that emit natural light and which they are therefore unaccustomed to. Due to this, some of the lamps' electrical systems (LED) stopped working and were operating with only natural light, so when it was overcast only the remaining lamps worked and the room was only partially lit. It is not surprising that only 40.6% of the users thought that the light was distributed evenly within the room. This experience emphasised that any new prototypes have to be quite robust to be able to satisfy users' curiosity. Consumers indicated that this is something they consider as new and different from other products.

A drawback of the test was that it was difficult to replace the LED, as this was welded to the entire lamp.

***Influence of the armature design***
Both women (50%) and men (75%) stated that they had been influenced by the luminaire's design when considering their acceptance of this innovation. This means that work needs to continue on this area.

***Overall suitability of HFOLS for the performance of office work***
From consumer feedback it was concluded that there was broad acceptance that the service fulfilled user criteria. It was also realised that users required greater light intensity in order to read printed material, both from the LEDs and for the optical fibres. Reading and writing using a computer seemed to be an improvement, even considering that the computer has its own light source. In relation to holding meetings, the lighting provided by the hybrid system was satisfactory, since this activity does not necessarily require too much reading and writing. From these responses it was concluded that, for general lighting purposes, the light intensity is acceptable. Nonetheless, according to the user's physiological demands both from the optical fibre system and from the LED system, the system should provide the possibility of increasing light intensity in work task areas.

***Consumer opinions on locations for potential implementation***
Throughout this project, the focus has been to develop this system for office lighting as the primary market. However, in order to get users opinions on which other sectors may be relevant in the future, users were also asked to list the places where they thought this system may be implemented. Surprisingly, the "offices" option was not the highest preference (see Figure 6.4). This might be because the system did not fulfil user expectations in the test: to perform the task of reading and writing with 100% efficiency. As previously stated, users accepted the system more for general lighting or for orientation. Because of the users' experience with the test, it is not surprising that they would only use the system for places such as corridors, shops, cinemas and sports facilities, where only general lighting or orientation lighting is needed. Hospitals, clinics, schools and libraries are places where it is important to have focused light on work task areas, and these places were given a lower ranking when it comes to using the lighting systems in this study. Increasing the number of lumens at the work task areas would be fundamental for the service sector and for additional sectors.

However, it was positive to see that most users would prefer to have the system installed in their homes. This is because the properties of the light (as it is currently) appeals to users, who view it as pleasant lighting and therefore attractive for homes, although not necessarily for performing work tasks. Despite this positive feedback, the household sector requires a research on its own, as the functional unit for the domestic sector will be quite different to that of the office lighting sector which is being considered here.

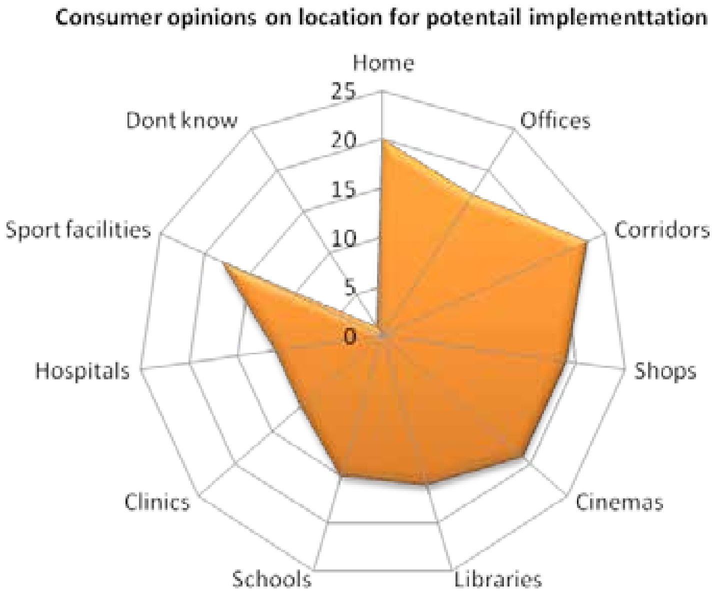



***Figure 6.4:*** *Acceptance of the hybrid system for the office sector and other potential markets*

## 6.4 DISCUSSION OF RESULTS

Purchasing new goods has some relation to previous experiences, habits and to previous experience of a product. However, one should not underestimate user perceptions of new artefacts. Taking account of consumer and user purchasing practices is important in helping to identify other strategies than those based on the overall cost leadership of a product. Carrying out tests at the early stages of the design phase can help to ensure that dominant actors do not have the wrong perceptions of a product and are more willing to accept new or less traditional products. Context and demands change with time, therefore, even when a solution was not previously accepted, a similar idea may not be rejected in the future, if presented in different way, combined with extra values, communicated effectively, and targeted at the right audience. Based on the intensive study case experience, representatives from the counties are looking for solutions that can help them to reach their $CO_2$ emission reduction goals, and which at the same time can supply a service that provides a more comfortable working environment for users.

A recommendation from this analysis is to create a focused strategy directed towards the trade and service sector building owners and users that will provide them with a greater level of information regarding the different attributes that LEDs, or other emerging energy saving technologies, can contribute now and in the future.

### 6.4.1 Assessing LEDs performance

According to the user test of the intensive study case, warm light LEDs in this sector are associated with relaxation, and not with work. Consequently, if LEDs are to be successfully implemented in this sector they have to provide a service with a colour of light which is similar to daylight. This could also work as a differentiation strategy, and be cost competitive, even though the price is higher when compared to LFLs. The LED's flexibility in regulating the colour of light has great potential as a unique characteristic within the market.

However, the LEDs' luminance emittance (light coming from a source = lux) is still low, according to consumer and user expectations when assessing artificial light. Because of this, the recommendation is to carry out further research in order to enhance this parameter.

### 6.4.2 Assessing LEDs in combination with solar fibre optical lighting (HFOLS)

The added value gained by combining LEDs and a fibre optic lighting system is related to the use of natural light. Natural light was important for users because it gives an indication of using renewable energy, which can be translated into a symbolic value of green responsibility, or using something even more environmentally friendly. One of the differentiation strategies could be the indication that these systems actually transport direct natural light into workspaces that would otherwise not have access to direct sunlight, such as, places at a distance from windows (corridors and stairs) and that this is a greener solution compared to those already on the market.

The test indicated that both LEDs and fibre optic lighting systems have to further increase their light intensity (luminous emittance) if they are going to be implemented in office lighting systems, particularly for work or study areas.

In terms of general lighting, HFOLS (and thereby LEDs) seem to be widely accepted, therefore, the demonstration projects should start with the illumination of corridors or areas where general lighting is required. The variation of light in HFOLS due to the integration of two different technologies represents a minor barrier, since the change of light temperature is associated with an indication of when the user experiences natural light and when the system is providing artificial light.

Despite this situation, the light coming both from the LEDs and optical fibre system should be as close to the daylight spectrum as possible, as this is actually an as important added value for this group in the service and trade sectors as saving energy and $CO_2$ emissions.

As with any other electric or partially electric device, LED systems have to be easy to maintain. The testing and use of LEDs in different applications would be easier if the LEDs could simply be screwed in or inserted instead of being soldered. The alternative situation requires that the whole luminaire is de-installed and disassembled. Consequently, the recommendation is to pursue further product development in this area.

The result of this research indicated that, currently, LEDs are positively accepted in places where only *general lighting* is needed, and that the quality of light is considered as pleasant. More specifically for HFOLS, even when the red spectrum has some losses the different colour indicates the use of daylight which may be a good strategy for differentiation.

An explorative consumer (user) test provided a relevant and useful insight into the challenges and design potential to make both technologies more acceptable to consumers and to see their potential to provide users with a better light quality. At the same time the project partners foresee the potential for a great variety of aesthetic applications.

### 6.4.3 Assessing feasibility perspective in the PSS

In relation to feasibility, it is important to emphasise the value of the practical approach suggested by Rogers in acquiring communication and knowledge of the artefacts and subjects of the adoption decision process. Questions, such as: if and how the artefact will be used in order to achieve energy savings; how both subject and objects will adapt to each other; what elements in the design and in the communication process can be changed so that the artefact can be used and the planned energy saving achieved can only answered if one focus on the Product-Service System. The Product Service System contribution helps to identify the relevant stakeholders to interact in this market system (actors related to the value chain). It also creates a broader perspective, as usually participatory approaches concentrate only on users. Using the PSS perspective one can see that users are a central part of the process (though not the only actors), as they act both in relation to other types of relationships (consumer in relation to other stakeholders and consumer in relation to objects). These relationships should therefore not be neglected. On the other hand, this transformative process, both of the object (in the process of continued development) and the subject (in the process of continued adjustment to the artefact and vice versa), require different levels and stages of involvement and an iterative pragmatic process. These levels and stages of testing and re-designing will be deeper and more complicated depending on the complexity and the level of technological development.

For the level of knowledge that this section of the research required, a simple pragmatic approach was enough to establish if the LEDs worked in combination with a fibre optical illumination system (HFOLS). However, companies (with more resources and time) might make use of different types of test strategies. The possibilities (feasibility dimension) that this approach gives to the design and innovation of low-carbon technologies studies is its iterative character to achieve an awareness of the market and societal challenges at an early stage of the innovation process so that the design can move forward with more effective and faster implementation. It further contributes with a business feasibility perspective as the added value of the alternative products comes forward complementing a more holistic sustainable (social, economic and environmental) evaluation.

## 6.5 CONCLUSIONS

LEDs have great potential to be acceptable to consumers, particularly because of their ability to provide different types of colour spectrum, their adaptability for different areas or uses as required, their potential to become more effective, and their contribution to reducing $CO_2$ emissions. Their ability to adjust the colour of light makes them very flexible for implementation in different types of consumer spaces, a fact which makes them unique. Consequently, this argument should be used for a differentiation strategy. In order to lower their currently higher prices, compared to those of LFL T5, the study recommends pursuing a strategy combining differentiation and focus aimed at consumers in the public sector, such as, municipalities and trade and services building owners. Currently, more of the focus is on the residential sector and most of the information is provided to consultants or services providers. It is important to target the tertiary sector more directly and ensure the information reaches consumers who, in this case, are the municipality representatives and trade and service building owners. This strategy needs to be pursued while technological development continues to reduce the overall cost of the product.

In terms of user demands within the test, the LED light intensity (luminous emittance) still has to be improved and, in order to provide this service effectively in the focused sector, the selected colour of light has to be as close as possible to the daylight spectrum. It is important to maintain a good dialogue with consumers and users to ensure that the right solution is provided and the consumer is not disappointed.

It is important to work towards LEDs that can be easily replaced. This will reduce uncertainty about the duration of the whole system and, at the same time (as was pointed out in Chapter 5), it will reduce the life cycle cost considerably, thereby making their implementation more attractive.

The intensive study indicated that the ability to combine both natural and artificial light in the same light source have great potential to be accepted by consumers.

This quality is perceived as something new for consumers, and therefore, also as a unique property. Their implementation, however, needs to start at locations where general lighting is needed. The intensive study case also indicated that their development depends both on the improvement of the intensity capacity of LEDs, on the colour of light, and on the improvement of the solar collectors. Their unique characteristics of indicating a greener technology and providing real natural sunlight can be used to make a differentiation of these products (both for LEDs and HFOLS), and further focusing on costumers' willingness to select a greener profile should be pursued.

An explorative consumer (user) test provided the study with a relevant and useful insight into the challenges and design potentials that make both technologies (LEDs and HFOLS) more acceptable for the consumer and to establish their potential to provide users with a better light quality. At the same time, the intensive/participatory study allowed designers to foresee the potential for a great variety of aesthetic applications. It also provided an important insight into the possible added values and helped to identify the consumers that one needs to focus on as well as pinpointing new areas for implementation.

The use of the diffusion of innovation theory from Rogers opened up the possibilities to see, not only how the designers can learn from consumer and user feedback, but also how the whole system can learn from setting the consumer-user at the centre of the decision-making process. Feasibility, in this respect, has to be seen as part of the social learning process for all the main decision-makers, as well as the possibility to plan a more effective and faster development and implementation of the technologies. It also allows the identification and inclusion of the consumer-user and important stakeholders in the whole innovation life-cycle decision process of a new technology to real social and consumer demands so that selected technologies can have the desired effect.

The use of Porter's theory of competitive advance provided an insight into the products added values that can be pursued while developing the technologies, so that higher initial prices can be offset, by identifying strategies that can make them more attractive to first–mover consumers.

Chapter 7

# Components and Conditions Analysis

In Chapter 6, an analysis of value and price was carried out, as they are important elements in the evaluation of the implementation potential of new technology alternatives for the lighting sector. Several authors concur that even if a technology has enormous environmental improvement potential, the potential to deliver a superior service, and to become cheaper, it will not become a reality and develop from an idea into a product unless there are basic structural conditions to support its development and implementation (Porter, Nov. 1998; Andersen et al., 2006; and Carlsson et al., 2002). As discussed in Chapter 2, one needs to consider social relationships, current technological development (technological drivers), current market development (market drivers), and potential market formation (push-pull mechanisms) as basis to developing and sustaining a technological innovation system.

It is important to focus on social relationships between stakeholders, since they will support or obstruct the development and implementation of innovations at the structural level. Therefore, one needs to identify the elements and their functions within the technological innovation system.

In relation to the components or elements, Porter (Nov. 1998) for example, points to the interfaces between firms and their customers and suppliers (cluster theory) and their position on those social networks that can contribute to gaining access to knowledge and resource flows (Network Theory). This includes, for example, universities and research institutes, but also public bodies, influential interest organisations (e.g., industry associations and non-commercial organisations), and venture capitalists. Networks may be both formal and informal.

According to Bergek et al. (2008), it is not enough to identify the actors (structural components of the system), but it is further important to analyse their functions and identify how these functions are driving the current development of the technological innovation system (TIS). Among these functions, one can identify: knowledge and diffusion; influence of the direction of search; legitimation; development of positive externalities; entrepreneurial experimentation; market formation, and resource mobilisation. This chapter will use the first four functions, and in Chapter 8 the other three functions will be defined and used. Bergek et al. (2008) defines the four first functions as follows:

*Knowledge development and diffusion*
This function focuses on the current knowledge-base of the TIS, and how this changes over time, including how the knowledge is diffused and combined within the system.

*Influence of the direction of search*
This function can be defined as the possibility for a whole range of firms and other organisations to enter the TIS, combined with the sufficient incentives and/or pressures for the organisations to be encouraged to do so. It also includes the mechanisms that influence the direction of the search within the TIS, such as, different competing technologies, applications, markets, and business models. These are the result of several factors, including, a combination of vision, expectations and beliefs in growth potential; incentives for changing factor and product prices; contextual changes, such as climate change debates; development of complementary resources; actors' perceptions of the relevance of different types and sources of knowledge (for example, actors are more likely to look for new knowledge within their current technological frame); actors' assessments of the present and future technological opportunities and appropriateness of conditions, regulations and policy; articulation of demand from leading customers; and crises in current business.

*Legitimation*
Legitimation refers to social acceptance and compliance with relevant institutions: the new technology and its proponents need to be considered appropriate and desirable by relevant actors in order for resources to be mobilised, for demand to form and for actors in the new TIS to acquire political strength. This function does not happen automatically, according to Bergek et al, it is formed through

conscious actions by various organisations and individuals in a dynamic process of legitimation, which eventually may help the new TIS to overcome its 'liability of newness'. However, this process may take considerable time and is often complicated by competition from adversaries defending existing TISs and the institutional frameworks associated with them.

*Development of positive externalities*
This function refers to the entry of new firms into the emerging TIS. This can have an influence on reducing uncertainties regarding technologies and markets, and thereby influencing the 'direction of search' and market formation while, at the same time, legitimising the new TIS. Improving legitimacy may positively influence changes in four functions: 'resource mobilisation', 'influence on the direction of search', 'market formation' and 'entrepreneurial experimentation'.

The main question in this chapter is as follows: What are the possibilities to enhance the technological innovation system conditions and what can strengthen the technological drivers to further develop the suggested technologies in this sector? To answer this question, this chapter will be divided in the following manner: In the first part, a short introduction to the lighting sector will be provided including a *brief outline of this sector's Knowledge development in Demark*; followed by a description of the technological network (important institutions, research centres, networks, and actors in the value chain) and their relationships within the illumination sector. In the second part, the technological drivers in this sector will be outlined (for example, areas of expertise, main research focus, knowledge-share, knowledge support and legitimation). In both sections, a parallel will be drawn with a case study from this research (indicated by a green text box) in order to evaluate how the general conditions affect the specific case set out by this research. In the last part of this chapter, there will be a discussion of the general conditions for the sector and a discussion regarding the successful elements of this research as well as what elements should be changed in the general context to improve innovation in this sector. The empirical material for this chapter is based on seven in-depth interviews with key representatives of the value chain in Denmark, the experiences of participating in the two externally-financed research projects, and participation in three of the most relevant networks in this sector.

## 7.1 TECHNOLOGICAL INNOVATION NETWORK

### 7.1.1 General overview of the illumination sector in Denmark

The main common driver for the sector of illumination in Denmark is our need for light. However, traditionally, the expertise has either focused on artificial light or natural light. This distinction also has its clear-cut representatives, although it is not exclusive in any sense. Denmark has a very distinctive tradition in designing luminaires, and the names of PH, or Le Klint, for example, are known worldwide and very popular in Denmark. Consequently, Danish architects or designers have a distinctive niche of expertise in this area.

Another type of light design, and perhaps the oldest one, is the one that uses natural light based on windows or apertures in buildings. The original function of these was to let light come into the building so people could see both inside and outside. Later, the integration of daylight was driven mainly for aesthetic reasons. More recent research has also underlined the physiological influence of natural light on people (Rosenthal et al., 1985; Heller et al., 2001,). Today, natural light is increasingly on the agenda due to energy and climate considerations (Leslie, 2003; Thanachareonkit et al., 2005; Kotchen and Grant, 2011; and Lo Verso, et al., 2011). Many new buildings in Denmark have integrated natural light, for example, the DR building, the $CO_2$ neutral houses, and the Green Light House in Copenhagen.

In relation to artificial lighting, Denmark's expertise lies mainly in "light quality" and especially in the colour of light. Because of this, one of the areas of specialisation has been how to make the light from LEDs more like the light colour from incandescent lamps. As Carsten Dam-Hansen (perhaps one of the pioneers working with LEDs for illumination in Denmark) pointed out: "we have been researching in the quality of light and not in the efficiency of light" (interviewed 09-09-2008).

### 7.1.2 Research institutions

Within the area of architecture, the most representative institution is the Royal Danish Academy of Fine Arts - particularly the School of Architecture and Alborg University, where researchers are investigating issues such as quality of light, artificial light regulation and the effect of natural light on indoor spaces. However, the research is being carried out by single individuals within these institutions and no clear, consolidated research group has been formed by these institutions.

Other institutions, such as Kolding School of Design, have courses in the area of luminaire design. This institution has many examples of projects integrating LED technology into new luminaires.

Within the area of artificial light, the most representative institution is the Technical University of Denmark - especially DTU Fotonik (the Photonics Department). DTU Fotonik has, however, two locations, the Lyngby campus and the Risø campus. During the explorative interviews and talks with different actors in the value chain, it was established that the Risø campus is the institution that most of the actors identify as the main contact point in Denmark especially in connection with the design of luminaires that apply LEDs in their designs.

DTU Fotonik, previously known as the COM Institute, has a very high degree of specialisation in photonics, particularly in telecommunications, and is one of the leading institu-

**Box 7.1: Relevant research institutions for HFOLS research and development**

Since focusing on hybrid lighting for this case study using solar fibre optic systems and LEDs, the most obvious institution to seek knowledge from has been DTU-Fotonik, because of their knowledge of LEDs and fibre optics. Having a hybrid system naturally should appeal to experts that have expertise in both natural and artificial light. However, it could be said that they have not focused on optical fibres (particularly for the transmission of natural visible light), nor light efficiency, or on optical solar collectors, even though this technology could be used to strengthen the capacity to collect sunlight for conventional photovoltaic solar cells.

Another important institution to include in this research was Kolding School of Design.

Despite the fact that hybrid lighting and energy efficiency have not been within DTU Fotonik's research focus, there is confirmation that there is a highly specialised academic capacity within the institution and relevant experts are willing to collaborate to find new applications and test new technologies.

tions worldwide in the design of fibre optics for these purposes. It is important to note that LEDs are also considered within the same group of semiconductor technologies, as are lasers. This sector was in full swing in the 1990s. From 2000 to the present time, their consolidation in the photonic industry has been due to the departments´ ability to broaden its horizons to laser technologies and semiconductors.

The Institute for Environmental, Social and Spatial Change (ENSPAC)-Roskilde University is the host institution for this research. Among other areas of research, ENSPAC focuses on finding technological solutions to environmental problems taking into account the interaction between people, society, environmental and economic conditions. The knowledge that is contributed within this sector is providing a more holistic approach to solving complex environmental and societal problems that frequently require multi-disciplinary knowledge and management. Although it appears that there is a variety of research institutions participating in the development of illumination systems, the actors in the value chain were asked about what they considered was still missing from the development process. On a visit to the representative from Osram in Taastrup (Michael Ravnkjær, interview, 12-02-09), he highlighted that, although there are many *luminaire designers* in Denmark, there is not really *an education about light design* as there is in England. That is the reason why, in his opinion, many of the big projects that had required this kind of expertise in Denmark have to "import" this knowledge from abroad.

### 7.1.3 Value Chain

The industry of illumination is concentrated in light signals, lamps to be used at concerts and shows, luminaires for public illumination, and luminaires for indoors illumination. In each of these sectors one can clearly identify solutions already implementing LEDs. For example, one important industry is related to illumination for events, such as rock concerts (Roskilde Festival and other types of festivals) and it is characterised by many small companies. Here the integration of LEDs is developing rapidly, as LEDs for colour application were better and had an earlier development than LEDs for general illumination.

*Small companies producing luminaires*
There are also many small companies that import, sell and distribute lamps of all kinds. These companies usually buy their LEDs from companies such Philips, OSRAM and Cree, though some also import from other companies in China, Korea, USA and Thailand. Here, one can mention some examples like Professional Lamps Scandinavia as well as electrical consultant firms.

There is an increasing number of small companies that design solutions in Denmark for general illumination and also for public urban lighting. This segment is characterised by firms that already include LEDs in many of their luminaire solutions. For example, Morfoso, Teamtronic, Light Visions, Lumodan, RGB lamps, Louis Poulsen, and other famous luminaire designers in Denmark. In this way, even though Denmark does not produce lamps (bulbs), it is an important place, as the design and engineering of many applications in which bulbs are used is carried out in this country.

In most cases, the design is created in Denmark and then the large-scale production of luminaires takes place mainly in Asia, and in a few cases, some are finally assembled in Denmark. The biggest market for the national industry is also in Denmark or in Scandinavia. Yet, according to Zenia Franker (Regional Manager, Venture Cup, interviewed the 19-10-2011), the number of new start-up companies within the illumination sector in Denmark is low when compared to other sectors.

*Big lamp producers*
OSRAM, Philips and Cree do not have production plants in Denmark; however, they have some offices in the country. Despite the problems related to the mercury issue, in 2007 Philips invested EUR 25 million in its competence centre for energy saving Compact Fluorescent lamps in two of its lighting facilities in Poland (PHILIPS, 2007). In the same year, OSRAM also invested in new plants, where the focus of the product range is energy-saving T5 fluorescent lamps and compact fluorescent lamps (OSRAM press information, 2007). What is interesting to note with these actions is that, during 2007, these two business groups were part of the lobby group during the creation of the EU Eco-efficiency Preparatory Studies. These reports established that type T5 fluorescent lamps are the best available technology, whereas LEDs are considered as the best not yet available technology. However, when these two groups presented their solutions in Denmark, they promoted the implementation of fluorescent lamps and halogen lamps,

whereas LEDs were presented as something that can be implemented in the future. The representative of OSRAM was interviewed in 2009, and stated at that time that OSRAM have planned the implementation of LEDs in approximately ten years from 2009. This might be because it is a reality that LEDs are not ready yet, or because these two companies have already committed finances into fluorescent lamps. It is difficult to believe that LEDs are not currently ready for the market, as OSRAM, Philips and Cree announce almost annually that their products break records in relation to intensity and white colour varieties (e.g., Golden Dragon LED and the new LED spot UX:3 from OSRAM).

One of the reasons why mercury was not forbidden completely in fluorescent lamps was that there were no real alternatives for these types of bulbs (this was what the main industry argued at that time). Although there are plans to out-phase the *less* efficient fluorescent lamps from 2015, the production of lamps based on mercury will continue.

*Alternative luminaires*

In relation to fibre lighting, since the 1990s Roblon has specialised in fibre optics for illumination. Roblon also produce illumination systems called

**Box 7.2: HFOLS potential Value Chain in Denmark**

Roblon could contribute with basic knowledge in this area, as this Danish company already has experience with fibre optic illumination. Although this firm is not yet working with hybrid lighting, it could easily be integrated into a HFOLS value chain.

Kaleido is another interesting company which produces optical components in Denmark. This firm could also play an important role supplying component for solar collectors.

OFS is a Danish firm designing optical fibres which are basic for natural light transportation in combination with optical solar collectors.

However, there are no firms producing solar collectors in Denmark, even though the country has the human capacity to develop them. The lack of firms demanding this knowledge negatively influences the direction of search, as researchers cannot see who they should produce this knowledge for. Further, this gives the appearance that if there are no firms producing such products, it might be because there is no market for that technology.

fibre optic lighting, where a central *artificial* source of light (usually a 100 W lamp) provides the light that is then transported through optical fibres to places such as museum display cases (see Picture 7.1). In this manner, one obtains so called "cold light", meaning that the heat emission from the artificial light source do not take place near the, often fragile, objects. These systems also have interesting potential for places where relatively low temperatures have to be maintained, such as, cooling systems for food products, or where unpredictable environments may affect the electronic systems associated with the lighting systems.


***Picture 7.1:*** *Illumination with optic fibres in Denmark's Natural Museum.*

According to the representatives from Roblon, the cost saving in this system is the maintenance cost, as it is "easier" to replace one lamp. The normal procedure to replace lamps, for example, at the museum cases is often associated with a procedure, which includes the presence of security guards while the lamps are changed. Although this is a good niche market for the illumination sector, there has been little research in this area in Denmark (Torven Skov Hansen, interview, firm visit 18-02-2009).

***Light transport system producers***

The Danish company Velux is already utilising natural light for illumination. The recent introduction of light tunnels is one of *the best examples to show that big* companies in Denmark are focusing in this direction. These systems are designed using a light tunnel (with a diameter of 35 cm) where the tunnel can integrate a light kit. However, an automatic control system is not yet integrated into the solution. VELUX is a well-known and strong Danish company that has traditionally produced window systems, but which lately has made inroads into holistic solutions, being one of the main actors in the creation of the Zero $CO_2$ (carbon) house. The energy in these houses is supplied by solar cells, underground heating systems and using electronically controlled blind systems for the windows. As Velux is a large and well known firm, its presence in the Zero $CO_2$ house could have a positive effect, and focus more attention on hybrid lighting.

### 7.1.4 Networks

Within the most important networks in Denmark for the lighting sectors are:

**LysNet,** which is funded and supported by the initiative of the VELUX group. This Network is mainly formed by people interested in all types of light, and there is a convergence of all kinds of disciplines and consultant firms in the field of illumination. This network is very much dedicated to the distribution of knowledge, as well as to create an awareness of the main advances in illumination in Denmark and Scandinavia. They also often visit different institutions and firms to promote cooperation between members. Apart from professional discussion, some members have often discussed the lack of an education on light design, thereby concurring with the opinion of OSRAM. This network has taken the initiative to gather information from different institutions carrying out research on different types of light. However, as far as is currently known, there are no concrete plans to organise specific education in this field.

**Dansklys**: The Danish Lighting Innovation Network is a newly established network (from 1 June 2010, with financial support/aid from the Danish Agency for Science, Technology and Innovation) which focuses on light and lighting. This network is more innovation-oriented as it is a forum for present business ideas. Its objective is to connect people interested in light, but who are also interested in generating new business ideas that may not yet be found on the market.

**Danish Centre for Light**: An important forum for the communication of the newest advances in technology, EU new directives and Danish standards. This network represents the Danish Working Environment Service, the Academic Architects Union (AA), The Technical Electricity Installation Organisation (TEKNIQ), Danish Energy Net (Dansk Energy–Net), the Union for the Producers and

Distributors of Luminaires (FABA), producers, suppliers and importers in the illumination sector (VELTEK), suppliers of bulbs and, the Danish Association of Consulting Engineers (FRI).

**Go'energi.dk** is another institution providing broader information in Denmark under the Danish Energy Saving Trust. This organisation provides information for all types of sectors that use energy, and it also provides information to all types of actors , including consumers. However, according to findings for this research and as was mentioned in the previous chapter, the focus group to which this organisation directs its information is not optimally targeted. The reason is that the target is service providers, rather than targeting consumers in the public and service sectors directly.

While participating at a number of conferences, it was noticed that in the Dansk Centre for Light, the participation from OSRAM, Philips and Cree was constant, while Velux's participation was less visible. This might be due to the fact that this

**Box 7.3: HFOLS main Networks support**

The goals of Dansklys, LysNet, and the Danish Centre for Light a complement each other well and can be supportive for finding relevant knowledge, communicating the results of research, and for finding business connections and advice.

The interaction with Dansklys was positive when compared to other institutions whose aims are to support the creation of businesses. Firstly, this network focuses on this sector, which is an advantage, as the contacts one might obtain actually know some of the needs. Secondly, in order to participate and present business ideas one does not need to have a business plan as pre-requisite. Although this might sound unimportant, , if the requirements for business plans are too strict, it might present a barrier for people who are more technological or practically-minded.

Further, participants receive written feedback from the panel members, and this can be used to continue developing an idea or to fill the gaps to make an idea qualify as a product rather than a technology.

network is supported by luminaire designers, while there is no group that represents the application of windows for illumination. The inclusion of Velux in the Danish Centre for Light could have a positive impact in drawing attention to the potential utilisation of daylight.

## 7.2 TECHNOLOGICAL DRIVERS

The strongest technological push in this field has been the introduction of LEDs in the area of illumination. However, this technology is not yet fully implemented. The emergence of LEDs for general illumination has the potential to open a vast area of development and implementation possibilities for designers. Within this, the strongest contribution is from DTU Fotonik, who have been improving the colour and temperature spectrum of light from the LEDs (see Picture 7.2) and lately, this department is also looking for other alternatives such as Organic LEDs (OLEDs). However, OLEDs are still quite far from the point where they can be used in the general illumination sector (Beata Kardinal, interviewed 12-12-09). The reason being that their power conversion efficiency is still significantly lower than that for semiconductor LEDs.

***Picture 7.2**: Paul Michael Petersen explaining why LEDs should glow like incandescent lamps. LysNet Meeting 09-09-2009.*

**Box 7.4: HFOLS Technological drivers**

Despite a thorough search, it was not possible to find patents from Danish technical institutions for fibre optic solar collectors, nor fibres especially designed for the transmission of visible light, even though there is a highly qualified human capacity in the field of optics and photonics in Denmark.

Consequently, the technological drivers for HFOLS need to be strengthened by more research and development in this area. One of the fundamental areas is that of the development of solar collectors. The creation of strong Danish patents could provide a sound basis for encouraging investors and reducing the uncertainty surrounding this technology. Systems combining photovoltaic power and LEDs could also be another alternative, since Denmark already has good experience in this sector. Although this technology combines two types of energy and the output is only artificial light, if LEDs can deliver the required intensity and colour of light for the targeted consumers and users, this could be an interesting solution to pursue.

### 7.2.1 Direction of search

The researchers from DTU Risø campus have been pioneers in the area of colour and temperature of light in Denmark and have fought for many years to promote the use of LEDs by making them closer to the incandescent lamp in terms of light quality. The reason they believe this is a specific goal is that the Danish consumers are accustomed to this specific light quality, and therefore they combine it with the property of attractive illumination (Poul Michael Petersen, LysNet Meeting 09-09-2009, see Picture 7.2).

In relation to the intensive case development it was observed that efficiency has not been a key point in the DTU Fotonik focus. The technological push at the beginning of this research rested more on the applications than in the improvement of the LED, in terms of efficiency. In relation to the utilisation of daylight, the direction of search has been on solar energy using photovoltaic technology. However, the efforts have been more related to the production of energy than directed to making illumination systems more effective. This might derive from the fact that the researchers consider the efficiency only in terms of the LEDs, but not in terms of a whole product-service system. The argument, in relation to the efficiency of LEDs, is (according to Prof. Anders Bjarklev personal communication) that these devices are produced elsewhere and are not in Denmark, nor will they be the foreseeable future.

Looking at how to develop, not only one product but the possibilities of the whole system, one can see that the real strength of the LED technology is that it can deliver the same light quality as incandescent lamps, but it is flexible enough to adjust to *whatever* spectrum is needed, which makes it a better solution than LFLs. They are also superior because of their future energy saving potential, the reduction of other environmental and health risk potentials and thereby their greater capacity to respond to consumer demands. In summary, LEDs represent a better solution from a societal point of view.

### 7.2.2 Level of inclusion (legitimation)

When the Roblon representatives were asked about the level of technological cooperation with Universities both in Jutland and in Zeeland, they insisted that their technology has never been taken seriously by their colleges in DTU-Fotonik, and therefore, they have had very little contact with them recently, even when this would be the most natural institution to be in contact with (Torben Skov Hansen, firm visit 18-02-2009).

One has to take into consideration that the IT boom of the 90s drew a lot of attention to the communication sector. Even though DTU Fotonik is has substantial expertise in fibres for optical design and general optics, no focused research on designing optical systems for visible light has taken place. This is a real disadvantage for the development of daylight collectors and also photovoltaic technology. Current international trends show that optical components to concentrate natural light into smaller areas (Concentrated Solar Power) are some of the main improvements to make energy systems more efficient and to reduce the amount of materials needed (Barlev, Vidu, Stroeve, 2011). The use of optical fibres for illumination will play an important role in the further development of HFOLS. Broadening research out of the traditional areas could really enhance the level of innovation, not only in the illumination sector but also in the photonic sector in general.

### 7.2.3 Knowledge sharing

The Danish Centre for Light and DTU-Fotonik already play an important role in the dissemination of knowledge, with particular focus on LEDs. As mentioned above, information such as, new Danish standards, EU phase-out plans and regulations is widely disseminated. DTU-Fotonik also actively participates in conferences and network meetings.

Furthermore, DTU Fotonik supports many projects on to light characterisation. However, when the owners and company representatives in this value chain were interviewed they stated that, if they have any questions concerning LED technology, they typically go to Germany, particularly if the questions are about testing LED lifespan and efficiency. The reasons for this choice according to Prof. Anders Bjarklev (personal communication) could be that the German institutions have better equipped testing facilities available to industrial customers.

When investigating what different institutions could contribute with to support the development of the intensive study case it was observed that the themes that dominate the conferences organised by the Danish Centre for Light, when plans for phasing out inefficient light sources are discussed, are the new lamps that Philips, Cree, and OSRAM produce and the improvements to the efficiency of lamps rather than to the system as a whole. Furthermore, there is no place for presentation of other kind of systems that those based only on artificial light.

When the Diode Lasers and LED Systems Group from DTU Fotonik participates, the discussion always turns towards the issue of the colour of the light. In all the conferences attended, the issues of $CO_2$ emissions and energy efficiency were no more than briefly mentioned.

During the four years of this research, there was only one occasion in which an architect was invited to explain how she used natural light in her project, but there has never been a detailed discussion of the advantages of integrating both types light in an intelligent design, and how that intelligent combination can contribute to the reduction of environmental problems. Here for example, the use of different kinds of sensors and the role of electricity convertors could be very relevant. Although there is some written information about this topic (Munk and Clausen, 2008), the issue has only been discussed briefly, even though it warrants open discussion with examples of cases and measurement of efficiency improvements. This, however, implies that other fields of expertise are invited to participate in these conferences, such as, representatives from DTU Elektronik, Aalborg University (on power electronics), RUC and DTU-Byg.

There have been a small number of presentations from municipalities participating in the design of street luminaires using LEDs (e.g., Albertslund municipality), but there have been no evaluations of the electricity and $CO_2$ emissions savings made. Few case studies have been evaluated to assess if the solution has fulfilled user demands, and the results have not considered a total life cycle cost assessment. In relation to the implementation of LEDs for offices and/or commercial spaces,

**Box 7.5: Level of inclusion (legitimation)**

During the development of the intensive study case project the author was invited to participate on a panel debate at a conference organised by DTU-Fotonik in cooperation with Danish Centre for Light. The panel consisted of five other experts. Two of whom were politicians, another was a designer, and the remainder were engineers. The audience had the opportunity to ask questions, but without having any detailed background, the discussion once again turned to the theme of new lamps, poor light quality, and how to substitute the incandescent lamp (mainly in the household sector). As discussed before, what this sector needs to substitute is the inefficient linear fluorescent lamps and spots that currently predominate in the service, trade and public sector. Yet the event provided an opportunity to voice the opinion that the audience's (lighting branch) real concerns are not the environmental issues, but rather the aesthetic challenges to be overcome when replacing the incandescent lamp.

In another conference, one of the speakers was presented as an expert on eco-design. During the conference lunch the opportunity arose to ask him about his background and role in the eco-design preparatory studies. His response was that he was an economist and his company was hired to compile the costs of the list of components to be used in the LCA study, which was being carried out by another consultancy firm. His speciality was not eco-design, but economic studies.

Based on these experiences, there should be more forums for an increased number of professional discussions to take place, where other relevant fields of research can be invited to participate and have the opportunity to explain other aspects of this complex problem in more detail.

one can see that there is an emerging interest and some consumers are already looking for this type of solution, among them, Saxo Bank and Rosenborg Palace. However, in both cases, the focus is again on aesthetic issues and energy efficiency is taken for granted.

## 7.3 EVALUATION OF THE TECHNOLOGICAL NETWORK AND THE TECHNOLOGICAL DRIVERS

### 7.3.1 Evaluation of technological innovation network

Even when there are several research institutions in Denmark that could actively participate in the development of innovation within this sector, rather than just developing further innovations in lamp design, contributions from other fields of knowledge are still negligible. As Bergek et al. (2008) suggests, this might not be a voluntary conscious action. However, it will have an effect on the development of technological innovation systems, due to the lack of a product-service and innovation system perspective. Having a pure product-oriented perspective keeps representatives of these organisations focusing on only partial solutions and partial aspects of the technologies, thereby missing out on opportunities to develop a greater variety of solutions. Further, the lack of a more holistic perspective reflects in poorly-targeted efforts for the possible implementation of the available technologies.

The participation of Velux, and other industries related to use of daylight, is not as evident as it could be at the conferences attended, particularly at the Danish Centre for Light. The inclusion of these companies might improve the balance on both sides of the illumination sector. It could also contribute to finding new technologies, instead of Denmark being perceived as the "workshop" where technological applications driven by the larger industry players are realised.

The inclusion of Velux or other institutions working with natural daylight might motivate research institutions and networks to increase their focus on hybrid systems. This could also motivate the participation of other knowledge-based institutions, such as DTU-Elektronik and DTU Byg, as the development of automatic control systems will play a substantial role in this industry. It is also important to include other non-traditional actors that can assess solutions from broad and holistic perspectives, including environmental and socio-economic aspects. The role of RUC-ENSPAC is highly relevant in this instance.

This innovation network might benefit from broadening the research focus to energy efficiency in relation to illumination. As previously discussed, *efficiency* in the illumination technologies is a complex parameter that requires more than technological improvements. Here, legitimation, or inclusion and cooperation with other types of knowledge-based institutions, is fundamental and requires trans-disciplinary cooperation and management.

According to Bergek et al., "Actors do not necessarily share the same goal, and even if they do, they do not have to be working together consciously towards it (although some may be). Indeed, conflicts and tensions are part and parcel of the dynamics of innovation systems" (Bergek et al., 2008:408). However, Bergek suggest that for a technological system to succeed, the actors should not take legitimacy and inclusion for granted. Instead, the authors suggest a reasoned and thought-out approach when creating this:

> *"Legitimacy is not given, however, but is formed through conscious actions by various organizations and individuals in a dynamic process of legitimation, which eventually may help the new TIS to overcome its 'liability of newness' " (Bergek et al., 2008:417).*

A faster way to implement LEDs could be by combining them with daylight. However, in order to succeed, a new technological innovation system has to be created. As the goals of the different networks are complementary, the Danish Lighting Research Centre could be more inclusive. Currently, it appears that Velux has a greater presence on the LysNet Network than the Danish Centre for Light. The lack of inclusion also applies for other research disciplines, such as, social sciences and environmental sciences. The absence of diversification is evident, as the main exponents of the technologies are always related to DTU Fotonik, and in connection with light quality whereas, social, environmental, financial aspects are left out the scope. Most of the dissemination is based on the types of lamps one can use with a product-system perspective, but it lacks a more complete and holistic perspective of the problem. The inclusion of different types of experts to consider all the problems and complexities is decidedly important so as to be able to discuss, plan and find more holistic solutions and make use of the advantages of both types of illumination. For this to take place, all the different disciplines need to receive the same level of respect and representation. It is necessary to connect the relevant technological and knowledge-based actors with the environmental and socioeconomic areas of expertise that are available in Denmark. Including more experts with experience in the social and environmental sciences is fundamental for a more holistic and strategic development.

In short, one can say that the LED technological system is still characterised as an unbalanced Technological Innovation System, while the HFOL is quite underdeveloped.

### 7.3.2 Evaluation of technological drivers

There is some diversification of research in relation to artificial light, but much of the efforts concentrate on light quality for various purposes. Through this research collaboration with DTU Fotonik, it has become evident that this lack of diversification is not due to lack expertise in the area of efficiency, but more because their direction of research has focused on light quality and on applications where light quality is demanded, such as, museum illumination using a special colour of light to highlight the object being exhibited. These strategies use LEDs, and although the implementation of such technologies implies some energy savings, DTU Fotonik could do more to improve energy efficiency in the development of the LED technology. The combination natural daylight might be another way to achieve a better service and efficiency and to make more radical innovations in this sector. However, this will require broader and new methods of cooperation. There were indications in relation to the intensive study case that there is a lack of research focus on energy efficiency reflected in the absence of patents in this area from the Danish photonic sector. Considering that there is a great efficiency development potential in the LEDs, as was pointed out in Chapters 3 and 4, it is notable that there is so little research and so few patents in this area (energy efficiency) from the Danish photonic sector. The knowledge-bank is even scarcer when more radical innovation is considered.

This lack of research focus derives from a lack of focus from the big companies. As mentioned before, the lack of focus on efficiency from a life cycle and PSS perspective is also evident in the discourse of big companies that continue to vigorously promote the use of florescent lamps, even though they argue that the new LFLs (T5) are the best available solution.

On basis on the intensive study case it is argued thatt there is little focus on energy efficiency and the environmental impact of current alternatives. According to this analysis, further support for LEDs, TIS maturation and consolidation will be beneficial for their development.

It was also observed during the development of the intensive study research project that the rationale for Philips, OSRAM and Cree to focus on the efficiency of the lamp instead of the system might be due to their interest in using the recent inversion, made in 2007, for extra production facilities of Linear Fluorescent T5 lamps.  It is difficult to believe that their behaviour is due to lack of knowledge, as the same firms participated as following groups in the creation of the EU Eco-design preparatory studies, whose conclusions point to system solution (inclusion of day light ) and recommend a faster development of LEDs, both in price and efficiency.

The development of the intensive study case also pointed to the lack of specific education in this area. The stakeholders contacted during this research agreed that the lighting sector requires the creation of an education programme on light design in Denmark. To respond to the needs identified through this research, the curriculum for the education programme should include aspects, such as: energy efficiency of the lighting systems; colour of light; light intensity; combination of natural and artificial light; engineering of intelligent control systems; design of solar optical collectors; integration of low-voltage based systems; an eco-design perspective; product-service system perspective; and aesthetic factors.

However, this is a chicken and egg situation (what should come first?), since if the firms do not actively demand this knowledge (and invest in it), there will be no incentives for the universities to make such investments. These kinds of failures are the reason why policy instruments are necessary, and they will be discussed in Chapter 8.

As DTU-Fotonik is such a central institution, it is the opinion of this research that it should continue broadening its *direction of search* towards energy savings, the utilisation of natural light and the combination of both artificial and natural light, not only for the energy saving itself, but also because, as discussed in Chapter 6, consumers appreciate the use of natural light.

From communications with relevant stakeholders, it was clear that, when the collaboration with this research started, the combination of artificial light with natural daylight and efficiency was not on the DTU-Fotonik agenda. However, it was possible to put together the required expertise for this research. Although DTU-Fotonik was not researching efficiency at that time, their direction of research is currently incorporating this issue.

## 7.4 CONCLUSIONS

There are enough institutions and potential for a diverse and robust LED technological innovation network.  However, there is a strong indication that despite the level of maturation, the relationships between different potential contributors is still disarticulated and unbalanced.

Ways to solve this problem might be found through technological innovation, where cooperation between relevant institutions is  strengthened so they are able to address the different challenges that the development of technologies require in a more interdisciplinary way (between different disciplines of natural sciences) and through trans-disciplinary cooperation (between natural and social sciences). Upon the observation in the development of the study case it was observed that there is no innovation network for HFOLs. The challenge here will be to work towards its formation. This will require a concentrated focus on energy efficiency in relation to natural daylight and artificial light transport and control systems. This research discovered that there is interest and human capacity to build on, but again, it will require a fair integration of trans-disciplinary institutions and the inclusion of non-traditional companies, such as those traditionally working with daylight or a combination of both. As HFOL is in a rudimentary stage of development, it is more important to discuss the formation of its technological innovation network, rather than its market formation. This will be further discussed in Chapter 8.

It was also observed that the emergence of LED technology in the area of general illumination has been a major technological driver. However, the focus has been directed on the development of light quality rather than energy efficiency. It considers some characteristics of the PSS, but neglects a life cycle (product-system) perspective, where efficiency and the environmental impacts should also be considered.

This was evident in the tendency to direct most of the efforts to improving the colour of light in LEDs and light colour control application. Efficiency is less of a priority. This tendency is also reflected in the producers' discourse, which continues to focus on the implementation of linear fluorescent lamps (LFL T5). This diverts the focus of research from efficiency towards the aesthetic aspects of the lamps.

There were also indication in relation to this study case that Danish lighting sector also requires the creation of an education programme on light design, where aspects, such as: energy efficiency of the lighting *systems;* eco-design; combination of natural and artificial light; engineering of intelligent control systems; design of solar optical collectors; and integration of low-voltage based systems could be part of the curriculum. Other issues to consider would be colour of light and light intensity. Ideally, the research institution that should take this initiative is DTU Fotonik, due to its focus on light technologies and because of its engineering background.

In order to support LEDs, Technological Innovation System maturation and consolidation, observation in the study cased pointed to the necessity of projects which incorporate more diversity, and a wider trans-disciplinary cooperation.

It was also inferred from the intensive study case that in order to better support the formation stage of more radical alternatives seeking to combine natural and artificial light, such as HFOLS, this sector could further exploit its expertise in optics and fibre optic systems, and should consider visible natural light more seriously. It should also consider that efficacy and dematerialisation is essential for the further development of new technologies, for which the participation of institutions with environmental expertise should be pursued.

Observation on the study revealed that the integration of a consumer-oriented design also requires socio-technological expertise, which at the same time, should go hand and hand with technological development. Thus, it is important to ensure that this expertise exists within the technological network.

Chapter 8

# Market Conditions, Policy and Regulation Analysis

The primary aim of this chapter is to analyse the main barriers and opportunities faced by alternative products in this sector, and which incorporate LED technology, when they are introduced to the market in Denmark. The second aim of this chapter is to analyse political and regulation framework conditions to further develop products in which LEDs might be applied.

## 8.1 BRIDGING THE GAP BETWEEN TECHNOLOGY DEVELOPMENT, PRODUCT DEVELOPMENT AND DIFFUSION IN THE MARKET

Although discussion of the technological innovation network and the technological drivers (Chapter 7) has been divided from market and policy and regulations conditions (current chapter), these four aspects are highly interrelated and should not be seen as being isolated from each other. They actually have a mutual effect on each other, and the failure in one can affect the efficiency or inefficiency of the whole technological innovation system development (Jacobson and Lauber, 2006; Andersen et al. 2006; Kivimaa, 2007).

As introduced in Chapter 7, there are seven functions or conditions which Bergek et al. (2008) point out as important to evaluate how well, or how badly, the elements and relationships of technological systems perform in supporting the development and implementation of innovation within a given technological innovation system. These functions are: knowledge and diffusion; influence of the direction of search; legitimation; development of positive externalities; entrepreneurial experimentation; market formation (or market situation), and resource mobilisation. In this chapter, the focus is placed on the Danish LED and Hybrid

Technological Innovation Systems. This chapter will analyse the capacity of the technological innovation system (TIS) to provide the features that enable LEDs to be developed into different products or applications and to get to the market. Consequently, this analysis centres on the latter three functions mentioned above.

*Market formation*
This function includes the existence or formation, and the support or evolution of nursing markets and *formation of learning spaces*. These types of conditions refer to the development of a market where there is none, the articulation of customer demand, the enhancement of the product price performance, and the reduction of uncertainties.

*Entrepreneurial experimentation*
As was previously mentioned, neither innovations nor markets are invariant. This might produce uncertainty for the industrial development which is present throughout all the evolutionary phases of the TIS. One way of dealing with these uncertainties is through entrepreneurial experimentation.

Brown and Vergragt (2008) highlight to the fact that new environmental technologies challenge already established and dominant socio-technical systems which are difficult to change towards more sustainable socio-technical systems. In order to reduce this natural resistance to change, it is important to make use of Bounded Socio-Technical experiments.

Entrepreneurial experimentation affects market formation due to its potential to reduce uncertainties, both in the technological as well as in the innovation system. Rogers points out, in his diffusion of innovation theory (2003), that a key factor in reducing uncertainties is to provide experiences and information about the innovations in order to facilitate and accelerate the adoption decision process. Brown and Vergragt (2008) underline that new environmental technologies compete with already established and dominant socio-technical systems which are difficult to change towards more sustainable socio-technical systems. In order to reduce this natural resistance to change or uncertainty, it is important to make use of Bounded Socio-Technical experiments (BSTE). The central point to BSTE is to facilitate the implementation and diffusion of the new technologies by reducing uncertainty and resistance to change in the system. According to Brown and Vergragt, the benefits of using BSTE are: to provide contextualised knowledge (bounded to a specific time, set of actors and place); to facilitate a higher learning order (where redefinition of problems, conceptualisations and norms occur), and; to facilitate the reconfiguration of working groups and technological coalitions on the new technology (where both the technological and innovation networks also undergo an adaptation process).

*Resource mobilisation*
This refers to the ability to mobilise competence/human capital through education in specific scientific and technological fields, as well as in entrepreneurship, management and finance, financial capital (seed and venture capital, diversifying firms, etc.), and complementary assets, such as, complementary products, services, network infrastructure, etc.

Knowledge of entrepreneurship and management is also known as Business Capabilities (Murphy and Edwards, 2003; Heebøll, 2008). As the roles of both educational and knowledge institutions has already been discussed in Chapter 7, this chapter will concentrate on business capabilities and on the financial capital (seed and venture capital), since the focus in this chapter is market formation.

In order to test the connection between entrepreneurial experimentation and resource mobilisation, was sugested by Bergek, et al., (2008), "to map the number and variety of experiments taking place in terms of, for example

1. Number of new entrants, including diversifying established firms
2. Number of different types of applications, and
3. The breadth of technologies used and the character of the complementary technologies employed" (Bergek et al. 2008).

Although this methodological approach is interesting, it will only reveal, or point to, *where* most of the innovation initiatives took place, but it will not reveal *why* other activities did not. Therefore, this approach is not appropriate for analysing to which level the Danish LED/HFOL technological innovation system is developed in relation to the three functions mentioned above.

During this research, it was observed that that there are a number of activities related to the implementation of LEDs in the illumination sector in Denmark, mainly in luminaire design. But, it is not evident why other activities are not emerging. Therefore, instead of taking on extensive mapping, the author created a business plan and involved herself in an entrepreneurial activity to establish, in a more intensive form, what the current supporting conditions for alternative low carbon technological innovations are in this sector. The methodological objectives for this were: 1) to establish an intensive study by actively trying to develop the HFOLS option as a business idea that could be sold to actors in this sector who are interested in this type of solution and, 2) to use the specific experiences of this exercise to shed light on the quality of the Danish LED-TIS capacity to bridge the gap between technological development towards market development for new products in which LEDs might be applied. The analysis of this particular case study will be discussed in the green textboxes within this chapter, and they will provide an assessment of the three conditions mentioned above.

This chapter will also analyse the way in which the policies and regulations have affected, or will affect, market conditions, the innovation network, and technological drivers.

As was introduced in Chapter 2, the *policy push-pull* instruments can be viewed as environmental regulations that might require new scientific knowledge to find solutions to fulfil new legal or standard requirements. They can also be viewed as a market policy instrument that will open up possibilities for new markets, for example, by generating unmet needs or using demand-led policies. Here, it is also important to look at the financial possibilities and mechanisms for research and development (both private and public), as well as market policy possibilities to support the innovation in the illumination sector to fully complete the innovation cycle. In summary, financial mechanisms are indispensable for all phases of the innovation lifecycle. However, traditionally, these mechanisms had been public for technological development, and private for supporting a product or for market development. The intersection between push-pull mechanisms implies the coordination of different types of investments (public-private) during the whole innovation life cycle.

Proponents of the Valley of Death theory (Murphy and Edwards, 2003) argue that entrepreneurs might face a big funding gap when passing from public to private financing, where neither private nor public finance resources are available, especially when passing from technology creation to product development, towards an early commercialisation. This is called the Valley of Death, because it is in this phase, where many enterprises fail.

According to Murphy and Edwards:

> *"Not only can the respective goals of the public and private sectors often seem to be quite different, they are in some ways in opposition, especially in the context of profits and return on investment. Also, unfortunately, a commitment by the public sector to successfully develop technology in no way represents a commitment (or even interest!) on the part of the private sector to develop and commercialize products based on this technology. This is because public good doesn't necessarily translate into opportunities for profits especially in the short-term – thus the need for public sector involvement, including policy development in the early stages of developing technology that meets a public good"( Murphy and Edwards, 2003: 12).*

The number of experimentation feedback loops, especially when creating public goods, means that the transition from public to private will not happen in one move. It might not be a linear process and it might not happen at the edge of the public sector. Consequently, besides the regulatory push-pull, it would be important to identify the sources from which, and under what conditions, financial support is available to the illumination service sector. In this respect, it might not only be one gap, as Murphy and Edwards point out, but many gaps, particularly when considering the way financial programmes are structured in Denmark.

## 8.2 IS THERE A MARKET (MARKET DRIVERS)?

Bergek et al. (2008) distinguish between a formative phase and a growth phase in the development of a TIS. Following this idea, one can argue that, due to the technological development of LEDs, they can be placed in the formative phase, whereas HFOLS have not yet reached that point. They add that the formative phase is characterised by high uncertainty, in terms of technologies and markets. Consequently, it is important to see the functions or processes within the Technological Innovation System that can support the formative phase of new LED applications (in this case the HFOLS).

Some environmental innovation exponents often point to the fact that, most of the time, there is no initial market for eco-innovations, and therefore, markets need to be generated and supported through government help (Carlsson and Stankievickz, 1995; Porter, 1990; Jacobsson and Lauber, 2006). According to Jacobson and Lauber, one way to answer the question about the market, is by trying to find out if there is a market in the formative phase, which at the same time, is a question of exploring niche markets. The goal with this activity is to identify if the new technology is superior in some way, and if superiority is established, if it can be sold on the market. Another alternative is to find out if there is a protected space, or nursing market, where the learning processes can take place.

According to the interviews carried out with different firms in this value chain in the illumination sector, and empirical material (the intensive case study, see Box 8.1), there are indications that there is an increasing societal necessity (market opportunity) in Denmark. Firstly, because the levels of illumination in this sector are below the level recommended by the Danish standards – this will increase the level of light service demand; secondly, because the current out-phasing programmes in this sector will soon be implemented; thirdly, because most of the municipalities have already signed up to programmes such the Mayors' Covenant, where municipalities engage voluntarily to reduce $CO_2$ emissions- in this sector some public buildings, such as offices and schools, have an electricity consumption for illumination of up to 50% of the total energy consumption; and fourthly, because the national energy and $CO_2$ emissions saving goals have also been raised, as will be described later in this chapter.

Despite these facts, the market develops very slowly. According to Michael Raunkjær (OSRAM representative) there is very little interest for new investment to switch to the new technology, and the producers of luminaires are hesitant to develop products (applications) when there is no standardisation for the new LED technology. Consequently, the rate at which public building managers change luminaires each year is only 0.3% (Michael Raunkjær, LEDs Conference, Egedal Municipality. 04-02-2009).

So why, when there appear to be many drivers, does the market develop so slowly? Some of the reasons observed in the case study which explain why there is such a slow development of the market are shown in Box 8.1 and discussed in the evaluation of the market situation below it.

**Box 8.1 Hybrid lighting: Market situation**

In order to see if there were any potential buyers for this kind of system (HFOL), Stevns Municipality representatives were invited to see the installation test at Roskilde University. After viewing the test, Stevns Municipality representatives agreed to continue testing these systems in one of their public buildings (which gave rise to the second externally financed project).

Some of the observations arising from this cooperation are that there is great interest in this municipality to save energy and thereby reduce $CO_2$ emissions, as well as the need to improve the level of service, for which the use of more daylight proved to be an attractive option. This confirmed that HFOLS is different to other conventional products because of its ability to make use of natural light.

However, there is uncertainty about the functional performance of new technologies. Therefore, it is essential for the municipality to test the products before they decide to invest in large projects.

Despite this local interest, it was observed that, when presenting the business idea in VentureCup and DanskLys, the market focus of seed capital is not a local one (the Danish market). The venture investors believe that this is a very small market, as there are only 100 municipalities. The seed capital representative expressed that they want to invest only where there is a global market. Consequently, even when policies in Denmark are open for a local market, one might conclude that if there are not equally ambitious environmental policies on a global scale, the venture capitalists would not be likely to invest in this sector.

*Evaluating the market situation for the illumination sector*

The author found evidence in the intensive case study (Box 8.1), that there is an emerging market interest in alternative products. Nonetheless, the lack of a reliable, well-tested commercial product is a limitation, and consequently, uncertainty about technology performance is still one of the main barriers.

The decision makers are already looking for solutions, as environmental goals have increased faster than the development of the technology. For the LEDs, this might be one of the biggest barriers, as this situation might push the decisions makers to implement the already available technologies that are well tested, and moreover, seem cheaper when comparing the initial investment (e.g. LFLT5). Yet, they might not equally consider that the solution contains mercury, or if the selected technologies are the most effective. As was pointed out in Chapter 6, professional consultants still advise to continue using these types of lamps, since LEDs have not yet been fully legitimised.

On the other hand, even when a local market is opening, this does not seem to be sufficient motivation for investors, as they want to see a bigger international market before they invest.

Bergek et al. (2008) suggest that the formative phase is characterised by high uncertainty, but this uncertainty can be reduced by increasing the level of experimentation and variety creation. These two objectives can be achieved through entrepreneurial experimentation in such a way that knowledge development occurs within a number of different technological approaches and through the development of diverse applications. They add that: "For this to take place 'influence in the direction of search' and 'resource mobilisation' must stimulate not only the entry of new firms but also ventures embarked upon in many directions" (Bergek et al. 2008:419).

As it was argued in the previous chapter, that the direction of search is still very much focused on how to obtain high light quality, while energy consumption has been under-prioritised. As discussed above, and at the beginning of this thesis, the aim of opening the market is to find and develop even more efficient solutions. Although aesthetics are important, if the solutions do not also offer clearer energy savings, the fundamental problem will not be solved, and this will hinder the process of finding and making more diversified efficient applications.

The next section will discuss the extent to which entrepreneurial experimentation is supported in this sector.

## 8.3 ENTREPRENEURIAL EXPERIMENTATION

Entrepreneurial experimentation can reduce uncertainties, but it can also produce more knowledge and the creation of relevant technological and innovation actor networks ((Bergek et al. 2008). It can also help to test the value added in the new idea or product (Heebøll, 2008).

The innovation process requires many feedback loops. Heebøll (2008) defines the number of feedback loops that a conventional firm might conduct until a product is considered ready for the market. These are:

- *Proof of Principle:* Technology/knowledge vs. the problem.
- *Proof of Concept (PoC):* The customer's value creation is verified and the technology is proved to be unique and probably patentable. There are no infringements of IPR that cannot be handled through in-licensing.
- *Proof of Business:* The business is founded with able management and administration, and costumers start buying.
- *Proof of Market:* The pioneers start buying.
- *Proof of Pull:* So do early adopters.
- *Proof of Profit:* So does the early majority and the company begins to make a profit.
- *Proof of Expansion:* The company demonstrates its capacity for growth, indicated by increasing market shares and penetration of new geographical markets.
- *Proof of Exit:* Exit opportunities are unquestionable, and offers from investment brokers even start to appear in your mailbox.

Even when Heebøll suggests these steps from a company perspective, it confirms the necessity to firstly, carry out many tests and, secondly, the necessity to have a pragmatic approach. What is interesting here, is to see if new entrepreneurial activities can go through all the necessary "proofs" to get to the market, or identify where the initiatives find barriers to continue to the next steps of experimentation. Heebøll points out that: "Some confusion seems to exist as to the exact definition of the proofs" (Heebøll, 2008:92). Thus, the list is included here to clarify the definitions of proofs as some financial programmes uses these terms.

One of the elementary factors to enable an innovation to cross the Valley of Death is to create successful public-private partnerships. According to Heebøll (2008), this can be better achieved if the researcher/entrepreneur can demonstrate their ability to reduce the financing gaps that the above-mentioned experimentation demands. Heebøll advises that before approaching investors, entrepreneurs should work to reduce risk and increase prospective gains, showing to potential private partners that they are able to successfully raise early capital. He also suggests that a good strategy to reduce the fundraising risk is that, before the entrepreneur approaches the venture capitalist, they need to demonstrate as far as possible within the different proofs that they have a business case. The proofs also support the reduction of risk due to customer feedback in each of these phases. The point here is that the risk does not only come from the creation of the market, but also from the financial access and conditions to be able to develop a company at the same time as one develops the product. According to Heebøll, private partners evaluate the enterprises in relation to each of these proof-phases, therefore, timing of funding is essential. Consequently, his advice is to try to push through a proof before starting to negotiate partnerships with private potential partners.

Boxes 8.2a and 8.2.b describe the proof that this research applied for, and the conditions that were encountered.

**Box 8.2.a Hybrid lighting: Room for entrepreneurial experimentation**

In relation to research and development, as well as proof of principle, it was observed that there is good support from ELforsk, which assigns funding for research projects. However, the funding for such projects is only 25 million Danish kroner per year. This has an effect on the ambition, or scope, of the projects, as environmental technologies often require trans-disciplinary cooperation, where different experts are needed and where the cost for hardware is often high. Furthermore, the time span for the projects is limited to 2 years, which for projects with long-term development perspectives, means that the research team uses a considerable part of the research time applying for funds every two years.

As a result of the first externally-financed project, it was concluded that the development of solar collectors is a basic requirement for the development of these systems. Consequently, the author investigated the funding possibilities to design and build a more efficient solar collector. Special focus was placed on public funding to support proof of concept projects. It was observed that the only programme that actually supports public institutions in providing PoC funding is "Forsknings- og Innovations styrelsen". Yet, when the requirements to apply for funding were investigated, it was observed that this fund does not assign money to all public institutions in Denmark, as can seen from the following statement:

> *"Tilsammen dækker de to konsortier langt hovedparten af de offentlige forskningsmiljøer i landet. Enkelte forskningsinstitutioner er dog ikke omfattet af de to konsortier og har således ikke adgang til PoC-midlerne. Det gælder blandt andet Roskilde Universitet og IT universitetet i København, som imidlertid har meget få kommercialiseringsaktiviteter" (Forsknings og innovations styrelsen, 2010:29).*

Public proof of concept funding in Denmark is targeted to two consortiums. These are Øst-consortium and Vest-consortium. Øst–consortium (East-consortium), encompasses DTU and Copenhagen University, and DTU is the host institution. However, it is in this consortium that RUC and IT universities are not included, although they are located in the eastern part of Denmark. Vest-Consortium (West-consortium) encompasses Ålborg University, Syddansk University and Århus University, and the latter the host institution (Forsknings og Innovations Styrelsen, 2010:29).

To further enquire into this anomaly, Kåre Jarl was contacted (Chief Consultant, telephone communication. 10-03-2009). His response was, that due to the situation, that is not a RUC tradition to ask for such funds as it is not considered as part of the consortiums that can apply for this kind of funding. Further, for the rest of the institutions, it is a requisite that, in order to apply for proof of concept funding, the researcher-entrepreneur must have a patent already granted. This contradicts the definition of proof of concept mentioned above, as the stage, where the technology should be strengthened (by trial) and supported to be patentable. This, consequently, denies access for those ideas that have a market, but not yet a patent. Further, as discussed in Chapter 7, it also sets a barrier for the inclusion of complementary expertise to solve complex problems that require trans-disciplinary cooperation.

**Box 8.2 b Hybrid lighting: Room for entrepreneurial experimentation**

There is another programme that supports proof of concept projects (PoC from the European Research Council, established in 2011 – www.erc.europa.eu). However, it requires that the researcher has initially applied to a prior programme called the Starting Grant, which is only available to researchers who have already graduated as PhDs.

It was also found that there are more funding institutions for proof of business (almost the last part of the innovation life cycle) than for PoC projects (see Table 8.1). Proof of business, however, is a stage still very much ahead of where the HFOL technology is at present. The requisites here are: previous tests; patents; the existence of some already commercial prototypes; to involve, or form a business; and, a consolidated business plan and market strategy. Although this might be thought of as a kind of 'strategy' to encourage more entrepreneurship, it actually works as a barrier – at least as seen from the perspective of promoting ideas from the universities.

In order to see if it was possible to find an industrial partner, the author contacted Velux, as this institution has shown interest in using daylight as an illumination service. However, their respomse was that HFOL technology was still at a very early stage of development, and Velux was not interested in partnering/mentoring this idea at this stage of development.

Not having project-partner firms from the private sector is another barrier to gaining access to the many relevant funds that are available.

Both at the national and at the European level, there is an increasing number of programmes that support what this study defines as entrepreneurial experimentation (Table 8.1 describes the most relevant ones for this sector). As can be appreciate in Box 8.1.b and through the experience from this case study, EUDP, ELFORSK and Research and Innovation Authority support can be called *Proof of Principle.* The intensive case study experienced good accessibility and good level of inclusion at this level. Yet, in terms of Proof of Concept, financial support was reduced, as only one programme in Denamrk offers public funding (Research and Innovation Authority) without asking for a private partnership. As discussed in

Box 8.2.a, when considering the intensive case study, the level of inclusion in this fund was also deficient, as it excludes certain universities. Although there is one more programme from the EU, this fund excludes initiatives that might come from researchers that are currently on a PhD programme.

According to Heebøll, the proof-of-concept phase is important to develop patents and test the added value of the new application. The limitations to access this fund also limits the ability to work towards patentable solutions. Without patents the ideas do not look attractive to investors and, in this way, a vicious circle is created. At this particular stage, the development of the intensive case study stagnated in relation to developing a more efficient solar collector (one of the decisive components of the HFOLS). It is also the limit of the investigation for this thesis. The lack of a private partner proved to be the specific limitation in the intensive case study when it came to applying for the next proof-series level.

As shown in Table 8.1, other funding possibilities are available to products and enterprises that have already reached some of the more advanced stages of the proof-series, but those were untested for this project for the reasons already mentioned. However, it would be recommended for further research to continue testing these other proof-stages.

***Table 8.1:*** *Overview of relevant financial support programmes for the illumination sector. Source: based on www.ecoinnovation.dk/Emneoversigt/IsaerForVirksomheder/Finansiering_tilskud/.*

| Name of the programme | Objective of the support | Remarks |
|---|---|---|
| EUDP – Det energiteknologiske udviklings- og demonstrationsprogram<br>Energistyrelsen | Development and demonstration in relation to projects that support EU energy policy | The programme supports:<br>Already established firms;<br>Research into *large scale* development and demonstrations*; International cooperation and networking.*<br>*The firm has to document that there are realistic commercial perspectives.* |
| Elforsk (PSO)<br>Dansk energi | Effective use of electricity by diffusion of energy efficient products and installations, buildings, processes and consumer patterns | The programme supports:<br>Public institutions;<br>The inclusion of already established firms is an option, not a requirement;<br>Requires co-financing from project partners. |

| | | |
|---|---|---|
| Forsknings- og Innovation-sstyrelsen (Research and Innovation Authority ) | *Strategic research* | The programme supports:<br>Only basic research;<br>Possible participation of already established firm, but not a prerequisite;<br>A requirement is that participating firms need to provide co-finance ;<br>No support for product development and demonstration. |
| TEST – Din bæredygtige løsning til Byggeriet (RealDania) | Support for sustainable solutions in buildings | The programme supports:<br>Fully developed technologies;<br>Commercial prototypes through plans for production escalation;<br>A registered firm must apply. |
| **Innovation Centres** | | |
| Forsknings- og Innovationsstyrelsen | There are six innovation centres. *Their objective is to develop strong knowledge-based start-ups with unique competences and good commercial potential.*<br>*These centres are regionally distributed in Denmark.* | The programme supports :<br>Only newly-registered start-up firms with a turnover under 50,000 kr;<br>An important selection requirement is that the idea is strongly protected (patented) and a management team can be established for the project idea. |
| Vækstfonden | Offers different financing possibilities and services for private companies | Only for private companies that already are established;<br>Supports proof of business only. |
| **Regional local funds** | | |
| Region Hovedstaden<br>Region Hovedstaden – Bornholm<br>Region Sjælland<br>Region Syddanmark<br>Region Midtjylland<br>Region Nordjylland | Offers different financing possibilities and services for already-established private companies | Supports:<br>Mainly private companies;<br>Some regions also support private/public cooperation. |
| Programmes with EU- support | | |
| LIFE +<br>EU program | *Innovative demonstration projects within most themes related to environment and climate.* | Supports:<br>Demonstration projects;<br>Research and development of the product should already be done;<br>Private /public cooperation. |

| | | |
|---|---|---|
| CIP Intelligent Energy Europe<br><br>EU program | Promotion and diffusion of innovation projects | Does not support technical development;<br><br>Does not support establishment of physical demonstration installations;<br><br>Prefers to support private/public partnerships. |
| EU. Framework 7 Programme | *Innovative demonstration projects within energy and environment.* | Supports:<br><br>Private/public projects.<br><br>Research support is limited in demonstration projects. |

*Evaluation of the room for entrepreneurial experimentation in the illumination sector*
According to the empirical experience presented (Box 8.2.a and 8.2.b), one can argue that the proof-of-principle stage is well supported, particularly at the Danish level (Table 8.1). Despite these efforts, the  proof of concept stage is still very much directed towards supporting already established companies. It has limited access for public institutions that could apply on their own, and lacks diversity, as there are very few programmes of this kind in existence.

The intensive case study provided evidence to show that public institutions that have taken the initiative to find cleaner technological solutions on their own, without having an industrial partner, have had difficulty accessing such funds. As argued before, when the innovation has broader societal interests than purely economic ones, universities might play a decisive role in pursuing solutions as, at one of the earliest phases of the entrepreneurial experimentation, development of these initiatives is limited.

As Murphy and Edwards (2003)pointed out, it is important that the public sector supports initiatives that pursue a public good. The proof of concept stage is very important, as it is the stage where patent creation and verification of value is carried out. The recommendation here is to reinforce the support of the proof of concept programmes for public institutions, particularly in the area of cleaner illumination technologies, to enable a reduction of risk for potential private investors, thereby making it easier for them to take part in the innovation process. According to the Valley of Death theories, it is important to support the whole innovation process (from invention to implementation) with partnerships between public and private capital in order to to minimise financial gaps. Accordingly, it is important to look at the process of how entrepreneurship is encouraged and supported (Murphy and Edwards, 2003). In relation to public/private funding, the intensive case study showed that, with the exception of ELForsk, a common denominator for most funders is the requirement for interaction and networking to take place between a firm and a technological institution.

In the case of LEDs this might not be a problem, as this is already a known technology. However, for more novel and more radical technologies, such as solar collectors (one of the components of HFOLS), the study showed that it is more difficult to apply for this kind of funding as the specific requirement of partnership set the biggest limitation. It is, however, interesting to look at these technologies, as they have potential to become niche markets due to the current environmental situation and political goals.

## 8.4 RESOURCE MOBILISATION

The intensive case study indicates that, right from the beggining of the innovation life cycle, not having the "right business team" is a key obstacle in moving from lab-based technology towards market experiments, or socio-technological experiments, as Bergek et al call them (see Boxes 8.3.1 and 8.3.2). As Zenia Francker pointed out, if you do not appear to have the right business team (capabilities), you would not be supported by private capital, even if the idea is a good one, and even if there is a market for it" (Zenia W. Francker, VentureCup Regional Manager, interviewed 19-10-11).

In order to acquire knowledge about the formation of a business team, different networks that support this issue were contacted using the intensive case study as a business idea. There are several entrepreneurial support networks, but only those relevant to the case study were contacted. These were: Connect Denmark, VentureCup, and Væksthus København.

The role of Connect Denmark is to support and advise entrepreneurs and small companies that have big growth potential. One of their main functions is to organise springboards, where entrepreneurs and small company owner(s) present their business ideas and plan and meet potential mentors or investors (http://www.connectdenmark.dk).

VentureCup's role is to provide funding via their competitions, key networking opportunities, and vital feedback for the entrepreneur's business idea. This institution's support consists of developing a pitch, guidance to help the entrepreneur to focus during the early stages, and building a bridge to springboards and investors (www.VentureCup.dk).

The role of Væksthus is to support already established companies (start-ups) with advice on business innovation capabilities, for example, protecting ideas, setting up a business board, consumer overview, formation of a business team, accountability, spin-off registration, legal constitution of the company, guidance and focus in the early stages, and building a bridge to springboards and investors. (www.startvaekst.dk).

According to Murphy and Edwards (2003), business capabilities are also identified as soft assets, which are as important as financial capital, because the financial rising capital within the enterprise depends on these soft assets. Having a strong business team is also a positive way to reduce uncertainty for potential investors, since it is the capacity of the business team that will make the transition from technology to a market focus possible.

The experience of the case study showed that, while, traditionally, the universities focus on technological issues, they expect the private sector to do its share. However, when talking about pushing technologies, where the main aim is to develop solutions to improve public goods, these traditional roles might not work as well as they could in supporting the desired innovation. Therefore, in order to accelerate the transition from the public to the private sectors, it is important that, beside of supporting the technological issues, universities also try to supply researchers with the necessary business capabilities. In summary: universities should be helping the researchers to find and assemble a strong management team. As discussed in Boxes 8.3.a and 8.3.b, these capabilities can be found outside the university environment, but they consume a lot of the researcher's time, as well as financial investment that the researchers might not have at hand.

Murphy and Edwards describe this as follows:

> *"If these issues are not fully appreciated, then there is a tendency for the venture to develop unevenly with the public sector abetting this process primarily by allowing,*

*or keeping (thus delaying) the entrepreneur from focusing on, and addressing the key business development issues that must be addressed, if the venture is to be successful.*

*Furthermore, by continuing to over emphasize technical issues, the entrepreneur and the early stage public sector sponsors can be easily misled into thinking that the venture is much further along in its development and more ready for public sector financing than it really is. This is because technical progress that is not guided by insights from the market/customer perspective may ultimately not be productive from a business perspective" Murphy and Edwards (2003).*

As pointed out in the intensive case study, full responsibility for acquiring the necessary business capabilities is left to the researcher, who has to find and finance this by themselves, without the support of the host university. As mentioned above, universities support the creation of business ideas, but in order to reduce the risk for private investors and make the transition process easier, more effort should be placed on assisting the researcher. This can be done by providing a strong management team that can help the researcher to create market-focused products which, as Murphy and Edwards (2003) advise, are based on the technology, can respond to developing markets, distribution channels, manufacturing for the product, and dealing with the competition.

**Box 8.3.a Hybrid lighting: Business capabilities**

When developing more sustainable technologies, this case study showed that the initiative to find a more sustainable solution in this sector started within a university but, in order to get funding, it was necessary to find a private partner. However, these partnerships are not a straightforward process. The case study indicated that private investors are not interested in technologies, they are interested in products. Furthermore, besides evaluating if there is a product, they evaluated the business idea, assessing if there was a strong business start-up team to carry out the process of bringing the technology towards a product, as investors are more interested in supporting business formation than research. Investors are not only interested in the technological network, but more so, if there is a business team (business management, marketing, sales experience and previous start-up experience). Thus, in order to be able to present the technologies as interesting products or interesting business opportunities, the researchers need to be supported with this type of expertise.

Universities encourage researchers to come up with business ideas. One of the mechanisms has been through prizes, and also by hosting within universities innovation support networks, such as VentureCup, which, again, encourages the production of business ideas. However, in this particular case study, it was observed that when the idea is ready to take another step forward, it was not possible to find knowledge support in terms of management and company structures within the same universities. Even when one company might have all these capabilities, conventional researchers might not. Positive support for this case study could have been present if the universities could support the business idea through a business innovation team, or a type of business accelerator, from within the universities in order to accelerate the transition from technology towards a product.

**Box 8.3.b Hybrid lighting: Business capabilities**

In order to evaluate the business feasibility of this particular case study, the author participated in a programme called "Clean-tech Bubble", organised by Væksthus Hovedstaden (Copenhagen region). During this event, it was stated that the business idea presented was good, but it lacked sales, management and business experience. The experience with Væksthus was positive, as business mentoring was provided.

This experience established that it is possible to find this insight in the innovation system. However, the researcher had to take on the additional role of entrepreneur and attempt to identify all the necessary business capabilities outside the university, as well as using personal financial resources to acquire these. When added to the activities of finding the research funds, this represents a big time and resource consumption for a researcher, who also has to attend to their university duties (research and teaching) and administration of the externally-financed projects. If a researcher is willing to take this risk they have to take on the double role of researcher/entrepreneur, they have to be able (in terms of time) to establish a firm, and have the capital at their disposal to start a company.

In order to clarify and enquire what the university policy would be for start-up activities, the innovation office and the patent office of the author's university was contacted. The innovation office could not answer this question, while the patent office stated that the university will say what their policy is at the point when the registration of the company becomes a reality. This adds an extra layer of uncertainty for the researcher, as they do not have any information about what the current employment position would be if they engage in an entrepreneurial activity.

*Seed capital and angel investors*

Other important stakeholders that can support resource mobilisation and the entrepreneurial experimentation are seed capital and angel investors. Through the intensive case study, the author contacted CAT-research Center, and during the VentureCup and DanskLys pitch events, the author learned about SEED CAPITAL (see Box 8.4).

The case study presented evidence that seed capital expects to see a certain level of maturation before they loan or invest money in a company. However, this maturation can, according to Brown and Vergagt (2008) and Heebøll (2008), only be reached by experimentation. Furthermore, according to Murphy and Edwards(2003), this maturation cannot be possible if the focus is only set on technology development and not on product development.

**Box 8.4 Hybrid lighting: Seed Capital and private-companies partnerships**

When financing opportunities through the CAT-research Centre were investigated for this particular case study, the feedback was that the HFOLS technology was still very expensive and will have a very long payback time. In order to get support from this institution, the HFOLS technology has to reach a level of maturation, where the payback is at the highest point in 3 years. This will not be possible, if there is no public funding for proof of concept projects that can support the development of cheaper solar fibre optical collector prototypes, or if private funds cannot be identified.

During the VentureCup and DanskLys events where the author participated, Seed Capital was introduced to the participating entrepreneurs. Seed Capital stated that they do not support emerging small business projects, but only already established firms that want to escalate their production for a global market and have already shown very good business performances.

Furthermore, in order to access seed capital, a strong property rights (patents) should be demonstrated. If there are no better possibilities for entrepreneurial experimentation, the process of patenting is limited, , particularly in the phase of proof of concept.

*Evaluation of resource mobilisation support in Denmark for the illumination sector*
Up t o this point, the analysis has focused on the problems experienced by technologies in the formation phase, in terms of: a) possibilities for entrepreneurial experimentation, b) resource mobilization, and c) how these two conditions implicitly affect market formation and the reduction of risk perceived by potential private investors.

- The intensive case study provided evidence that there are certain issues preventing the motivation and the achievement of more radical innovations (such as the HFOLS example) in this sector. The central issues observed in the case study were:
- That particular conditions arise for researchers that take the initiative to find technological environmental solutions with broader public goals, rather than purely research goals (lack of business experience, lack of a

business team, lack of funding for PoC projects, lack of private partners).

- The limited number of programmes directed towards supporting proof of concept excludes potentially important scientific institutions.
- That, as far as reducing the risks perceived by potential private investors, the number of programmes at the decisive Proof of Concept stage is still very small and lack diversity.
- That a private/public partnership might not always be there at the beginning of the innovation process, and that, at this stage, if there is a market but no private partners are interested yet, it might be necessary to support the researchers with the required business capabilities.

In the light of the analysis made above, valuable assistance for researchers could be provided by advisory groups within the universities. This would help to speed up the development of interesting companies for potential investors. Here, encouraging business departments to develop closer communication with technological departments would be an option, as would a closer cooperation with regional business schools, if the required expertise cannot be found within the universities.

Moreover, the development of clear research/entrepreneur policies could reduce the researcher's risk and uncertainty when dealing with such challenges. For this, it is necessary to discuss the role of the universities within the innovation process, particularly when finding solutions that require a longer development time and that address societal goals that established firms might still not yet perceive as interesting business opportunities.

## 8.5 PUSH-PULL DRIVERS SUPPORTING MARKET AND TECHNOLOGICAL CONDITIONS

The European Union has created many initiatives using both pull and push mechanisms to both provide incentives for technological development and to try to develop the market. There are, however, some conditions that set barriers for their full successful implementation, as will be argued through the intensive case study.

### 8.5.1 Policy push

This section will review political decisions made to push technological development. Firstly, one should mention the EU decision to phase out incandescent lamps from 2009, and secondly, the EU decision to phase out inefficient fluorescent lamps. More recently, the RoHS - Directive 2002/95/EC, restricted the use of persistent pollutant materials, in which the mercury content is limited to a lower percentage in relation to the whole lamp, but is not completely banned. In terms of reducing energy consumption, the EU Commission edited the Eco-Design Requirements for Energy-Using Products, 2005/32/EC. This directive was the basis for the programme to phase-out inefficient lamps (see Table 8.2). The effect of these directives have had a positive impact on the technological development of LEDs, and represent a slowdown of the development of fluorescent lamps, but not their complete phase-out. As one can see in Table 8.2, there is no limitation on LFL T5 sources and the out-phasing process in this sector will start in 2015. The solution favoured by these policies is the LFL T5 technology, despite the health risk that these lamps represent in the consumption and disposal phase. This is because the LFL T5 are cheaper today than LEDs and they have more or less the same efficacy.

*Evaluation of policy push effects*
The building regulations will encourage the development of systems that can regulate and automatically switch from one type of illumination to another. However, their implementation will be in a reduced number of buildings, as the number of new buildings that are added to the current building mass is minimal. From another perspective, the cheapest solution, with perhaps less energy efficiency, will be more attractive for older buildings, and where the building mass is bigger. In the latter situation, regulations will not have such strict consequences and will encourage rentable solutions, therefore the solutions that will be adopted will be those that are already on the market, and which are currently the easiest and the cheapest to install (e.g., LFL T5). This will create difficult competitive conditions for LEDs and also for mor radical innovations such HFOLS and thereby extend the time to their implementation.

Fluorescent lamps T5 are still presented as the best available solution, which makes consumers hesitate when considering other "not well-tested products". In order to reduce this competition, which is unbalanced with respect to environmental

***Table 8.2:** Phasing-out plan according to EuP Directive, 2005/32/EC. Source: (http://www.osram.hr/_global/pdf/Consumer/General_Lighting/Incandescent_lamps/199R104GB_EuP.pdf)*

Summary of the consequences of the EuP directive:

| | Street, office and industrial lighting | Household lighting |
|---|---|---|
| 2009 | | 01.09.2009:<br>• Clear lamps: Minimum requirement Energy Class C for lamps $\geq$ 950 lm, Class E for other lamps (e.g. phase out GLS $\geq$ 100 W)<br>• Non-clear lamps: Minimum requirement Energy Class A for all lamps (at present some CFLi and LEDs)<br>• Requirements for new product information on the packaging<br>• New technical specifications required for each technology |
| 2010 | • T8 halophosphate fluorescent lamps* → phase out | 01.09.2010:<br>• Clear lamps: Minimum requirement Energy Class C for lamps $\geq$ 725 lm (e.g. phase out GLS $\geq$ 75 W) |
| 2011 | | 01.09.2011:<br>• Clear lamps: Minimum requirement Energy Class C for lamps $\geq$ 450 lm (e.g. phase out GLS $\geq$ 60 W) |
| 2012 | • T12 fluorescent lamps* → phase out<br>• High-pressure sodium lamps (HPS): HPS standard quality (only E27/E40/PGZ12 affected) → phase out<br>• Metal halide lamp lamps (MH): Less efficient MH lamps (only E27/E40/PGZ12 affected) → phase out | 01.09.2012:<br>• Clear lamps: Minimum requirement Energy Class C for lamps $\geq$ 60 lm (e.g. phase out GLS $\geq$ 7 W) |
| 2013 | | 01.09.2013:<br>• Increased requirements for technical specifications, defined in 2009<br>• Phase out lamps with S14, S15 or S19 bases |
| 2014 | • Review of the regulations by the EU Commission | • Review of the regulations by the EU Commission |
| 2015 | • High-pressure mercury lamps (HPM) → phase out<br>• Plug-in/retrofit high-pressure sodium lamps** → phase out (= direct replacement for HPM) | |
| 2016 | | • Clear lamps: Minimum requirement Energy Class B for all lamps except those with G9 and R7s bases (= phase out the current Class C HALOGEN ENERGY SAVER)<br>• Phase out lamps with E14/E27/B22d/B15d bases and voltages $\leq$ 60 V |
| 2017 | • Poor performing metal halide lamps (MH) (only E27/E40/PGZ12 affected) → phase out | |

* through minimum efficiency requirements
** Plug-in lamps must correspond to Super/Plus HPS level; almost all plug-in/retrofit lamps will be banned
Information correct as of December 2008; data may differ from the final EU directive.

challenges, the author agrees with Munk and Clausen (2008) that the building regulations should be applied to both old and new buildings.

Evidence from the intensive case study points to the fact that, when switching towards more sustainable technologies current electricity prices in the service and trade sector might be a limitation to viewing the comparative financial benefits that LEDs might represent, as these are not substantial when the initial higher investment is taken into account.

## 8.5.2 Policy pull

An important regulation for energy saving in Danish Buildings was introduced between 2006 and 2008 and was formalised in the Danish Building Regulation-BR08. This regulation establishes that the energy consumption from illumination should not be over 95 + 2200/A kWh/m$^2$/year. This figure has to be multiplied by a factor of 2.5 to be comparable with other energy consumption purposes (Johansson og Petersen, 2009). However, while it is obligatory for new buildings to comply with this requirement, for older buildings, this means that they will only need to have an energy mark from A to F (see Figure 8.1). Under this regulation, old public and municipal buildings have to implement *rentable* energy savings within the next seven to ten years after the implementation of this regulation. According to Munk and Clausen, this will mean that *new* buildings projects will need to think in ways other than the usual pay-back inversion time, while managers of older building will continue with current practices. The result of this is that, often, the easiest and cheapest solutions are adopted in older buildings - despite the potential energy savings or reduction of environmental impacts available through alternative technologies (Munk and Clausen, 2008).

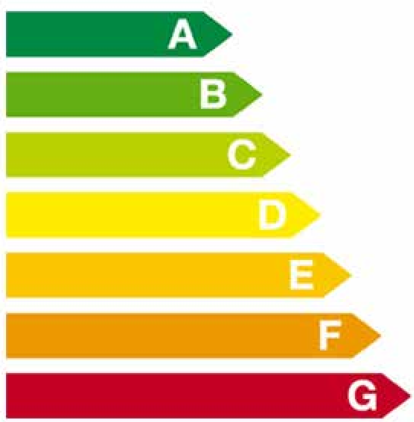



***Figure 8.1****: Energy marks. A is the solution with the lowest energy consumption. Source: goenergi.dk*

Despite these efforts, the encouragement to change to a more sustainable technology, in terms of electricity prices, is lower in the trade and service sector than in the household sector. As one can see from Figure 8.2, the price gap between the business and the household sector has become even broader during the last fourteen years. This might also be the reason why the household percentage of electricity consumption for lighting decreased from 18% to 12%, while the service and trade sector still is around 35% to 40% around the same period. The effect of such policies for the intensive case study are assessed in Box 8.5.

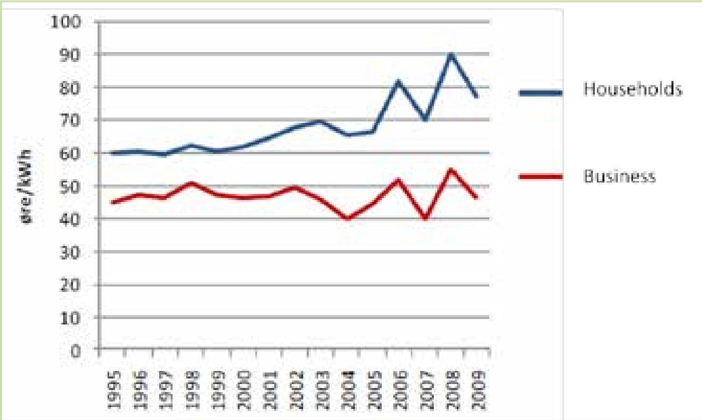



***Figure 8.2:*** *Electricity prices in Denmark for households and for business. Fixed prices for 2009, exclusive of taxes, public service obligation and other charges. Source: Togeby, M., Larsen, A.E. and Nimb, N. 2011.*

The above graph shows that the target group making the greatest reduction of electricity for illumination is the households, and not the trade and service sector. This is because the electricity prices for the household sector are higher than those for the tertiary sector. Further, one can see that energy companies might not view the increasing consumption of electricity (mainly based on fossil fuels) as one of the main problems related to the illumination sector, or their responsibility to change these trends, particularly while the full responsibility is carried by the bulb producers.

Standards for workplace illumination in Denmark have established a minimum of 200 lux for general illumination and 500 lux for working or reading areas. According to Richard Schalburg (Chief-consultant, Dansk Energi, telephone interview 13.01.09) most of the workplaces in Denmark have very much lower illumination levels than the ones suggested by those standards. To achieve these standards will require the consumption of more lamps, and consequently, the consumption of more electricity. As the limit per lamp is restricted, the way of increasing the number of lumens will be by increasing the number of lamps. If

**Box 8.5 Hybrid lighting: Policy-pull effects**

In relation to this particular case, it was observed that the electricity price is a challenge, since as long as electricity prices remain low, the real environmental and financial cost will not be revealed. Furthermore, according to Rennings (2000) this produces a problem of double externality, where eco-innovations cannot compete in terms of cost with conventional technologies. This is precisely the case for LEDs and HFOLS.

One solution to this problem would be to work towards a parallel index system. This should be adjusted in a way that, in the same proportion as the efficiency of new alternatives increases, the prices of electricity could be raised - at equal proportion and speed. In this way, if consumers want to maintain the same level of expenses for electricity for illumination, they will be motivated to change to solutions that can maintain the current cost level. Again, this suggestion should not only be applied in the local plan, but also at the European level, to avoid creating unbalanced competition between companies and between countries.

It was also observed that there is strong competition and, to date, the LFL T5 is still presented as the best available option. It was further stated that very few users and consumers were aware of the mercury content of LFLT5 and therefore are not aware of the special conditions for recycling.

the chosen technology is LFLT5 this will also mean an increase of mercury in the disposal phase.

Other important policies include the national energy and climate policies. The national goals related to such policies have shown a rising ambition, passing in the last four years from 20% to 40% $CO_2$ emission savings by 2020, and from 30% to a total substitution of fossil fuels and zero $CO_2$ emissions by 2050 in Denmark, when the goals at the European level continue to be lower.

Furthermore, in order to activate the market for eco-innovation, particularly in the public sector, the European Commission launched an initiative called Green Public Procurement (COM (2008) 400). With this initiative the EU is pursuing two goals: one is to reduce the environmental impact caused by public sector consumption, and the other is to stimulate innovation in environmental technologies, products and services. "At EU level, the European Commission set an indicative target that, by 2010, 50% of all public tendering procedures should be green, where 'green' means compliant with endorsed common core EU GPP criteria" (http://ec.europa.eu/environment/gpp/gpp_policy_en.htm).

Other business models have been suggested with the objective of reducing the initial investment burden that building owners have to pay for changing to a more energy-saving system, such as Energy Saving Companies (ESCO) and Intracting. **ESCO** "are usually differentiated from other firms that offer energy efficiency improvement or energy services, such as consulting firms and equipment contractors, by the concept of performance-based contracting, which means that the ESCO's payment is directly linked to the amount of energy saved (in physical or monetary terms)" (Ürge-Vorsatz et al. 2007).

**Intracting:** takes up the idea of contracting, but operates entirely with city administration budget funds. This is an option for promoting the implementation of energy conservation measures. However, a precondition to this approach is that there is an office within the administration which, firstly, can provide a technical appraisal of potential measures and, secondly, has an overview of potential savings throughout the entire administration (Energy-Cities, 2002).

In order to see how these business models will help to implement both LEDs and HFOLS, the intensive case study was used again (see Box 8.6).

*Evaluation of policy-pull mechanisms*

Based on the intensive case study, it can be argued that, in relation to electricity prices, there is an indication of miss-targeted efforts, as the sector with the highest level and fastest increase in electricity consumption for illumination (trade and service sector) still has lower prices than the household sector. Consequently, the emerging new applications which use LEDs as their basic technology will be in an unfavourable situation, as their initial price compared with the energy saving will be underestimated.

In relation to the policy market pull mechanisms, one can argue that the green procurement policies will open the existing market even more, which is positive for LED technological systems, as well as for more radical innovations, such as

**Box 8.6 Hybrid lighting: Assessing suggested business model to support the market**

In order to see how the Green Public Procurement programme will work for this case study, the author participated in the conference organized by Furesø Municipality and Væksthus on the 11 October 2011. This information was then cross checked with Stevns Municipality representatives.

The cases that were introduced (Copenhagen and Furesø) do not focus on green public procurement, but rather on public procurement in the broad innovation sense. Secondly, the criteria to assign these projects are: the firm has to show that it already has sales, strong experience in selling such products, and that it can provide a reference from a previous commercial project.
Although the original intention of these programmes is attractive for cases like the one presented here, they are implemented in Danish municipalities in a way that does not result in any advantages for small emerging firms. The original goal of these programmes, according to Murphy and Edwards (2003) and COWI (2009) should be to create a market, where there was no market before. Yet, the issue is that, according to the information provided at the conference, in order to enter into these programmes the incipient firms have to show they already have sales. Consequently, the firms that will make use of these programs will be those for which already have a market.

An existing business model is the ESCO, however, during this case study it was observed that potential ESCO firms are only interested in ideas which have a payback time as low as three years. Consequently, during dialogue with investors when the author participated in VentureCup she was informed that HFOLS do not qualify for a ESCO model..

According to the dialogue with the Stevns Municipality representative, it was revealed that there is little information about other market pull business models. In relation to the Intracting model, the Stevns Municipality representative also stated that there is not much information about this in Denmark. This, however, could be an option, but it requires an internal building capacity that can put together a technical appraisal of potential measures, and an overview of potential savings throughout the entire administration.

HFOLS. However, there are considerable indications that one of the main current obstacles is the way the different business models are being diffused and how the municipalities' own organisational structure can adapt and make use of those business models. This issue requires further and deeper research, because it is one of the most important factors in order to accelerate the commercialisation (implementation) of emergent cleaner technologies in this sector.

Based on the intensive case study, there are strong indications that the main problem is that private investors in this sector in Denmark are still cautious about investing in technologies with long-term perspectives. This might also be seen in a period, when the EU is experiencing a serious financial crisis, which the Valley of Death theory might not have taken into account. Perhaps in this period of crises, one might say that, instead of waiting for already established companies to invest in a given technology, the government could support more the critical stages, where *new potential start-ups from universities* can be created (e.g. providing support through more public funding for proof of concept projects, and ensuring a broader inclusion).

According to COWI's report (2009) the biggest barrier that eco-innovation need to confront within the EU is that: "manufacturers wait until there is a demonstrated demand before they develop and commercialise technologies, but buyers wait to see the product on the market before they demonstrate they will buy it" (COWI. 2009).

According to COWI report, the way to solve this problem is by reducing the uncertainty from investors. The intensive case study used in this thesis provided evidence that investor uncertainty is more in relation to the question of whether it is, or is not, a real product, or whether there are real possibilities to develop a product, rather than questioning if there is a market for this type of illumination system. For this reason, entrepreneurial experimentation is quite important and should be supported more strongly in this sector, while also supporting the researchers to access the business capabilities that are necessary to present attractive business products.

## 8.6 GENERAL DISCUSSION OF THE CONDITIONS, POLICIES AND REGULATIONS

Based on the interviews with potential consumers, innovation support networks, and collaboration with the industry tested by using the intensive case study, it was observed that, although well-intentioned, the European and Danish policies are not having a full impact on environmental innovations in this sector in Denmark.

The intensive case study provided evidence that there is sufficient and balanced support from networks that encourage entrepreneurship. There is also evidence to show that this support is not working, as the pre-market process for getting a product ready for market might be failing. The reasons for this are:

There is indication that there is little room for entrepreneurial experimentation, since the funding system for proof of concept excludes some universities from applying. There is only one public fund in Denmark for public institutions which will finance this important phase in which the development of patents should be carried out, and it is only available to some universities.

It was observed that the proof of concept idea is misunderstood, as before the author would be able to apply for this type of funding, she was required to already have patents in process or granted.

It was also observed in the case study that universities still consider innovation as research or inventing something new, but the whole process of innovation (invention, product development, diffusion and implementation) is considered as a process that goes on outside the universities.

There is also an indication of an unbalanced distribution of funds, and that some universities receive more support, to the detriment of others who are also important participants in the innovation process. Furthermore, this exclusion might strengthen the legitimation issues pointed out in Chapter 7.

The case study also showed that the integration of business capabilities was complicated, if there is no possibility of establishing early public/private partnerships. This is reinforced in universities where there is a lack of internal business incubators.

Many private capital investors will wait until they can see a final product as an investment object. This attitude may not be a surprise, since the private companies' objective is to create value for their owners, and if the universities do not present their ideas as the best option to do this, the companies will tend to focus on their own core business. Here, it is important to note that many universities work on ideas with  quite a long time perspective (typically 10-20 years), and there might be a mismatch with the private capital perspective of creating commercial value within just a few years.

The evidence described in the intensive case study points to the possibility that private investors do not enter into early partnerships because some university ideas are presented without the relevant business capabilities, and are therefore not viewed as interesting enough by investors.  It is important to point to out that investors would not buy an idea, but they will invest in strong and solid start-ups with good ideas. For this to occur, is important to support researcher-entrepreneurs with the right business team and with clear and consistent policies that will guide them in this direction.

There exists financial support that "encourages" the participation of public-private cooperation, but as many private investors might not see it as their responsibility to take on the development of products emerging from universities, they will chose not to get involved at this phase. This automatically excludes the universities or researchers that have ideas with good market potential, but which do not have private partners to access public/private funding (as was the case when looking for funding to make a solar collector prototype). Thus, even when public/private partnerships are desired, they become a barrier for any ideas which originate mainly from universities.

There are also strong indications that there is still much focus on financial programmes to pull the market, and too little attention is given to the technological drivers. This is reflected in the current electricity supply situation, as it is not targeting the sector where the real consumption problem is, and the Danish building regulations (BR08), that only enforce the regulations on new buildings. The case study evidenced that lower electricity prices within the business sector and the lack of a ban on mercury for the production of lamps might still encourage the production of a very strong competitive technology (LFL5). A step-down out-phasing process of the mercury content in lamps could help towards an even faster development of LED technologies. This might work as a regulation framework to encourage strategic investment in more research into the production and development of LEDs. On the other hand, if the real environmental cost of the production of electricity in the business sector is considered, it might reveal the real extra value of such alternatives.

Based on the findings of this case study, there are indications that the real goal of the Green Public Procurement policies has not been fully adopted by those who have to implement them. This might be due to the issue that few Municipalities have knowledge about this programme (e.g. Albertlunds Municipality and Hørsholm Municipality). Other Municipalities have not implemented GPP, and give preference to firms that already have a market but have no specific focus on eco-innovations (e.g. Copenhagen Municipality), which is not the objective of such programmes.

During the dialogue with the Stevns Municipality representatives, it was noticed that there is little information about the different financial possibilities and business models for Municipality representatives. An option to better implement business models in first mover municipalities could be by improving intern-building capacity to be able to put together technical appraisals of potential measures, and to have a better overview of potential savings throughout the entire administration. This study would recommend further and deeper research into this area, as it is fundamental for the implementation stage.

Furthermore, the intensive case study highlighted the issue that the public procurement strategy might not be focusing effectively on eco-innovations. If this is the case in other municipalities, eco-innovations will be exposed to an inequitable competitive market situation, as other spill-overs, such as energy and $CO_2$ emissions reduction will not be taken into account in their performance.

Theoretically the hand-in-hand participation of both public and private capital should help to increase and ensure innovation, from the initial idea to the market, faster and more effectively than with isolated efforts (Theory of Valley of Death, Murphy and Edwards, 2003). From the experience gained during the intensive case study, there is an indication that this is not happening in the illumination sector, as different types of logic exist in both sectors. The private/public partnerships are actually a barrier to acquiring funds for ideas born in universities. During the case study, it was observed that large private firms and investors choose to wait for the ventures to become mature before they invest their money in eco-innovation. The intensive case study also showed evidence that public financial support is not distributed evenly through the different phases of the innovation life cycle. An explanation for this might be that the private sector still places too much focus on the present market, while the public sector still focuses too much on long-term research. Product development and business development are not well supported both in terms of entrepreneurial experimentation and in terms of resource mobilisation - particularly in the proof of concept phase, where there is greater uncertainty about the product development potential. A final observation was that, even when there is an increasing local market, this does not create enough motivation for private capital to make more private/public partnerships, as the goals at the European level are not yet as strict as those in Denmark. One way to encourage more engaged participation from the private sector could be working towards more ambitious goals, at least at the European level, so investors can see a market not only within Denmark but also with an international market.

## 8.7 CONCLUSIONS

The feasibility perspective, which has been used for Chapters 7 and 8, has to be seen in the light of the different components (actor networks), relationships (qualitative dimension) and conditions (quantitative –qualitative dimensions) that are necessary to establish a link between the technological-innovation systems. Here, it is important to stress that it is not enough to have technological capacities, and a good number of innovation networks, but there is also a need to look at other more qualitative relationships and conditions that arise in order to plan for a more strategic implementation of cleaner technologies, and to be able to truly harvest the energy savings.

The feasibility perspective is about identifying how one reduces the natural resistance in the innovation system so as to achieve *sustainable development* by implementing more sustainable solutions to societal concerns, such as achieving climate and environmental goals, while also looking for business opportunities. Having a pragmatic approach allowed the author to use social-*innovation* experiments, where it was possible to get feedback from real business actors that will be key players in implementing the desired technologies so as to reshape the object, and at the same time suggest changes for the technological innovation system. As an overall conclusion from this chapter and the intensive case study, there are indications of efforts that both encourage the market and the technological drivers. However, there has to be more room for entrepreneurial experimentation and more inclusion. This will provide more possibilities for improvement and for legitimation of the system.

University support in relation to resource mobilisation seems to be the cornerstone for researchers who lack private partnerships. However, this makes it necessary discuss more deeply and with more focus what the new role of the researcher in our current society is, if one really aims to contribute sustainable changes to society and not only in the scientific world.

In order to get the private investors on board there is strong indications that the socio-economic and environmental goals have to be very clear and sufficiently ambitious -particularly at the European level, so that they also represent a sustainable development for the business partnerships. Universities need to provide more internal support to entrepreneurs with good business ideas, so they can demonstrate that there is business feasibility within the technologies. This is important, if the aim is to accelerate the commercialisation (implementation) of more sustainable technologies.

# Conclusions

The aim of this chapter is to discuss and conclude the overall research question in this thesis. The main general objectives within this dissertation were:

To identify the technology, or technologies, with further potential to reduce the illumination sector's $CO_2$ emissions by assessing and identifying:

- The technologies with the lowest environmental impacts;
- The technological improvement possibilities to further reduce $CO_2$ emissions;
- The possibility for the alternatives to become cost-competitive;
- Technological possibilities to improve the service in relation to the consumer-user demand;
- The necessary components and conditions to support the technological innovation system to develop the technologies in focus, and;
- The market, policies and regulations that can support their implementation.

This thesis also had as an integrated objective, to contribute with a discussion of the elements that a new framework for eco-design and innovation feasibility studies should encompass in order to support decision makers to select more sustainable technologies and thereby encourage their subsequent development and implementation. This was done, at the same time, with the purpose to contribute to the understanding of how to design and implement technologies with a lower environmental impact which will respond to the environmental, energy and economic challenges we face today.

In order to fulfil these objectives, the following thesis research question was created:

Where and what are the main possibilities for the Danish lighting industry to efficiently reduce the illumination technologies' $CO_2$ emissions in the office lighting sector, and what conditions are necessary to support their implementation?

The following sections in this chapter will discuss the way in which all the above mentioned research objectives were pursued and how they are integrated in the project design and in the overall conclusions of the research work carried out for this dissertation.

Suggestions are also made for a preliminary new eco-design and eco-innovation feasibility studies framework. The chapter concludes by reflecting on the scientific method and theories used to achieve the objectives.

## 9.1 THE TECHNOLOGIES WITH THE LOWEST ENVIRONMENTAL IMPACT

In order to identify the technology, or technologies, with the lowest environmental impact, a product system oriented analysis was carried out. The theoretical foundation for this analysis was on product-system and life cycle theory. This theoretical approach allowed for an analysis of the material and physical dimension of the technological alternatives and their environmental improvement potentials. The environmental impacts were identified, as was the stage at which improvements could be carried out in relation to the current best available technologies, and the best - but not yet available - technologies for the illumination sector were described. The focus was set on the trade and service sector (by analysing a concrete case study in the office sub-sector) as electricity consumption for illumination in this sector is the highest.

Based on the critical analysis of three different life cycle assessments of illumination systems for the office sector, in which incandescent lamps, linear fluorescent lamps (LFL T5) and light emitting diodes (LED) lamps were evaluated, the use phase was identified as the stage, where changes are needed. In this phase, the main environmental impact is caused by electricity consumption, which is mainly based on fossil fuels (78% is the present percentage in Denmark). There are other impacts along the illumination life cycle (manufacturing, transport and disposal), however, the use phase constitutes the biggest burden to the environment in relation to resources, waste, emissions to air and emissions to water. The life cycle assessment category with the highest environmental impact was the potential for global warming.

The best available technology is considered to be Linear Fluorescent Lamps of the LFL T5 type, whereas, the best not-yet-available technology is based on LEDs. It is worth noting that, over the timespan of this study, LEDs have evolved significantly, but the technology is still in the development phase. The mercury content in LFL T5 lamps is still thought to be a problem due to health risks for the use phase and for the disposal life cycle stages. In relation to energy consumption, Linear Fluorescent Light sources (LFLs) and Light Emitting Diodes (LEDs) have a similar impact. The use phase is one of the main stages in which to reduce their environmental impact and increase the efficiency of LEDs and LFLs. Increasing efficiency, especially in LEDs, could contribute, with a positive feedback loop, to the reduction of heat sinks (which also have an important negative contribution in several environmental categories).

The use of hazardous materials, mercury and lead represents an important issue within the component parts (lamps, ballast, converters, batteries and luminaires). Particularly important impacts are caused by the converters and ballasts in LEDs and LFLs due the significant size of these components. Therefore, more research into more effective ballasts and converters, or finding ways to avoid using them (e.g. through local implementation of low-voltage systems) will contribute to the reduction of the environmental impact of the whole system.

In relation to the entire product life cycle, the intelligent (automatic) integration and combination of daylight/artificial light was suggested as the biggest possibility for increasing the product-system overall luminous efficacy, both for fluorescent lamps and LEDs.

## 9.2 THE TECHNOLOGICAL IMPROVEMENT POSSIBILITIES TO FURTHER REDUCE $CO_2$ EMISSIONS

This research objective was pursued by assessing which of the current alternatives have more potential to continue providing higher luminous efficacy in the future, and by assessing the possibilities to achieve total electrical power reduction (and thereby less $CO_2$ emissions) using a comparative analysis on the inputs and outputs of the energy consumption.

The theoretical foundation for this analysis was on product-service perspectives using the concepts of eco-design and life cycle theory and was based empirically on three different and independent LCA reports and interviews with experts in the field.

A particular focus of attention was the possibility that these alternatives could be combined with current solutions that integrate natural daylight. Here, as an intensive case study, fibre optic solar collectors were selected.

Because there are many producers of LED armatures, and their direct comparison to electricity consumption and resulting light intensity is variable, compact fluorescent light (CFL) and LED bulbs were compared in order to make a proportional energy evaluation. This was done because these devices have reached a higher degree of maturity. Thereafter, the inputs and outputs of a hybrid system using LED bulbs and a Solar Optical Fibre system were compared. The result of these calculations was used to evaluate the proportional saving potential when assessing the life cycle cost of the alternatives. These factors were applied to the specific *office illumination system* example outlined by IBSEN (Electrician firm, and project partner).

Although the environmental performance between Light Emitting Diodes (LEDs) and Linear Fluorescent Light sources (LFLs) are similar, the product-service system advantages from LEDs was superior to LFLs. These advantages include more possibilities for energy efficiency development, plus better and more flexible service to fulfil consumer demands in the future. Consequently, this study recommends focusing on LED technology for future applications.

With the results of this research stage, the author of this thesis suggested and participated in the design of a solar hybrid lamp, which was a concrete result and an example of the development of an application using LEDs. This concrete result made it possible to test both the LEDs and the integration of light transport systems in a new application, and to see the potential for more radical innovations in more concrete terms.

The proportional saving factor potential of the inclusion of a Solar Fibre Optical system with an automatic switch on/off control system was calculated to be around 36% of savings of primary energy. However, in order to be accepted by the users, the design of the system has to focus on reducing the fibre losses and designing better light characteristics. Here, the issue of light colour characterization showed to be particularly important for the experts in this field.

The average peak electricity consumption hours could be reduced - particularly during summer. However, the power system should still be able to deliver full effective power during days where no bright sunlight is present (mainly during winter or cloudy days), in this case, contributing positively to the heating system. Likewise, these savings could reduce the need for extra energy for air-conditioning, since the lower heat level generated by the LEDs will reduce the air-conditioning energy in the same proportions - particularly during the summer months.

In terms of green responsibility, the use of sunlight has further potential to make these products different from others, since renewable sources are used. Consequently, this parameter was assessed in relation to consumer demands.

For the Solar fibre optic collector systems, it is also recommended to focus on the size of the components, material consumption and flexibility of the materials, so as to further extend its use within the already existing buildings and expand their potential use.

## 9.3 THE POSSIBILITY FOR THE ALTERNATIVES TO BECOME COST-COMPETITIVE

Using the specific office illumination system example outlined by IBSEN (Electrician firm, project partner) and the proportional energy saving potentials of the solar fibre optic systems (36%), a life cycle cost assessment was made focusing on the use phase and on the office segment, as a sub-sector of the service and trade sector. This is where most of the electricity consumption for illumination was observed. The comparison encompasses life cycle costs, energy saving and the proportional $CO_2$ emissions saving potential.

The technologies assessed were:

a. an illumination system based on T5 linear fluorescent lamps;
b. an illumination system based on LEDs, and
c. an illumination system combining a solar fibre collector and LEDs using an automatic switch off/on function (hybrid fibre optic lighting systems – HFOLS suggested by the author of this thesis and designed by a team in which the author was personally involved).

The base line case for this section of analysis was the system based on LFL T5 sources. This assessment took into account the costs of materials, installation, energy, etc. and evaluated these in terms of net present value.

The theoretical basis for this analysis was based on the Life-Cycle-Cost methodology, including consumer perceptions of cost acceptance from the Diffusion of Innovation theory. The study was structured using the Product Development Perspective from the Eco-design Theory. Empirically, the study was based on an iterative communication process with relevant experts in this field and through organising meetings with two to three project partners at time. Consequently, a life-cycle-cost assessment was conducted which compared the three illumination systems. The objective was to establish if LEDs and HFOLs could be cost-competitive in comparison with the best available solution suggested by the EU preparatory studies for the office sector (LFLT5). Furthermore, a calculation of energy and $CO_2$ emissions savings was carried out on the use phase of the illumination service life cycle. The illumination service was calculated for an office space, where both general light and focus task illumination was considered. The illumination calculations were made considering two scenarios: a single-user office and a multiple-user office.

From this part of the study, the main conclusions for both scenarios were the following:

The worst option of the three analysed cases in terms of energy consumption and $CO_2$ emission was the illumination system based on linear florescent lamps T5.

The system based on LED lamps showed an energy *saving of 36%* and thereby, a reduction by the same proportion of $CO_2$ emissions in comparison to LFL T5.

With the hybrid lighting system (solar fibre collector/LED lamps and an automatic switch off/on function), it was found that the whole system could *save 59%* of primary energy, and thereby 59% of $CO_2$ emissions when compared to the LFL T5 base case. Even though this option was the best solution in terms of energy and $CO_2$ emissions savings, it is still currently the most costly. The next most expensive solution was the one based on LEDs, while the cheapest solution was the one based on LFLs of the T5 type.

Both for LEDs and HFOLS the cost of materials and installation showed to be the main inputs and made up the greatest proportion of the costs. This is mainly because there are few solutions available for replacing LFLs with LED lamps. Most of the LED lamps are usually integrated into the luminaires, which requires a completely new installation of the whole system. The same is also applicable for HFOLS. Thus the author's suggestion to reduce the installation cost by making it easier to switch to LEDs is to focus on the manufacture of compatible lamps for this sector (e.g. LED linear lamps that can fit into currently existing luminaires). If this can be achieved, the LEDs could become price-competitive with LFLs T5 sooner.

To make HFOLS systems cheaper, the following options are suggested:

*Improvement option one:*
One way of making HFOLS more effective could be by using less materials and collecting solar light more efficiently per $m^2$. This seems to be the strategy that Parans has opted for in their new PS3 model. This model has a more compact distribution of the lenses that capture light, reducing the collector size by almost half when compared to the one that was assessed during the work reported in this thesis.

*Improvement option 2:*
Another way of making the systems cheaper would be to reduce the price by avoiding expensive sun-tracking systems, and designing and making the optical fibre solar collectors as passive systems. This option would require using more optical engineering and sacrificing some of the system's efficiency. By making the system cheaper, and thereby more affordable, it would help to obtain a faster implementation. Thinking about the installation process will also make a significant difference. The idea with this option would be to introduce these systems to the

market at an attractive price, while escalating the production and improving their cost/efficiency development.

A central point in this analysis was the conclusion that, if the products are to be competitive in the market, the assessment of overall cost leadership cannot stand alone in an evaluation.  Consumer perceptions of the innovation may be used to identify added values, and the identification of target groups must be assessed to determine the innovation's real commercial potential.

Another observation on the use of life cycle cost, is that it is a very useful tool to establish where further improvements can be made in the design phase. However, its main limitation in relation to the intensive case studied in this work was that it operates with a completely different rationality when compared to what really motivates decision makers to adopt new technologies in relation to price. According to discussions which took place during this study, the dominant way of making decisions in this sector is not entirely through life cycle cost, but rather a short payback time logic (max 3 years) and the possibility of enjoying a better light quality which is as close to the daylight natural spectrum as possible.

## 9.4 TECHNOLOGICAL POSSIBILITIES TO IMPROVE THE SERVICE IN RELATION TO THE CONSUMER-USER DEMAND

In order to identify the potential consumer acceptance for LEDs and HFOLS, an intensive case study was carried out for this study. This part of the analysis focused on the potential added value that both LEDs and HFOLS could offer the consumer in terms of differentiation, or by solving the needs of a specific group. As part of the empirical material, preliminary hybrid fibre lamp prototypes were designed and installed together with solar collectors from Parans so to make a HFOLS, followed by a simple user test. This took place in addition to the key consumers' in-depth interviews.

The main theoretical framework for this segment of research was based on the concept of value, and the concept of target and differentiation strategies from the Competitive Advantage Theory. Additionally, this research objective also was discussed using the Perceived Attributes of Innovations (past experiences, relative advantage and compatibility) from the Diffusion of Innovation Theory. Finally, service improvement from the product-service-system concept and product-improvement potential from Eco-design theory was applied.

The results from the intensive case study showed that LEDs have substantial potential consumer acceptability - particularly for their quality of being able to provide different types of colour spectrum, their consequently flexible adaptation to different areas in which they are required, and their potential to become more effective, and to provide $CO_2$ emissions reductions. Their ability to adjust the colour of light makes them very flexible for use in different types of consumer spaces, and therefore unique. Based on these observations, the study recommends using these qualities for a differentiation strategy.

In order to lower the currently high price of LEDs when compared to LFL T5, the study recommends pursuing a strategy which combines differentiation and focus on consumers in the public sector, such as municipalities and the owners of trade and service buildings. Currently, more of the focus is on the residential sector. In the case of the service sector, there are strong indications that most of the information is provided to consultants or service providers. It is, therefore, important to target strategic decision makers (for example, municipality representatives in charge of procurement, and technical management departments) more directly, and ensure that the information gets to these consumers directly. Equally important is the need to continue reducing the overall cost of the product by continuous development of LED compatibility within this sector (this means making linear lamps instead of bulbs). It is important to work towards LEDs that can be easily replaced. This will reduce the uncertainty in relation to the duration of the whole system, and at the same time, it will considerably reduce the life cycle cost, thereby making their implementation more attractive.

In terms of user tests, the light intensity (luminous emittance) of LEDs still needs improvements, and the colour of the light selected to provide this service has to be as close as possible to the daylight spectrum (for this sector). Yet it is important to maintain a good interaction with key consumers and users to ensure delivery of the right solution and to integrate the key decision takers into the co-design/innovation process and reduce the uncertainties that they might have about the new products. This will require different degrees of consumer inclusion, according to the level of product development and complexity of the solution, which will also determine the type of consumer tests to carry out. Although this approach requires more time and resource investment than traditional design approaches, it can accelerate the adoption and implementation process and the investment in time and resources will not be in vain.

In the HFOLS intensive case study, the system's ability to deliver real natural sunlight worked very positively in relation to consumer acceptance, and their ability to combine both natural and artificial light in the same light source was something new for the consumer, and therefore, also a unique property. The implementation of the system however, needs to be at places where general lighting is needed. Their development depends on the improvement of the LEDs intensity capacity, on the colour of light and on the improvement of the solar collectors. Their unique characteristic of being a greener technology and providing real natural sunlight can be used to differentiate these products, and the customers' willingness to adopt a greener profile should be pursued.

An explorative consumer (user) test played a very important role in the deployment of the Product-Service System perspective. In the level of development for this intensive case study (HFOLS), it was observed that this technology was very incipient (there were no hybrid lamps in the market at all), and therefore, the aim of the test was to establish if *the team's hybrid lamp suggestion of* using LEDs combined with Solar optical systems could be made and it could work. The objective was also to investigate if the new system could provide at least the level of illumination that consumers demand for a conventional system, and therefore, a more practical approach was adopted.

Although the aim of the research was to define some simple tests, these tests could benefit from an increased level of complexity and in exploring the consumers' perceptions more deeply in the future particularly those made by companies, as they may have a more commercial orientation. For the present work and at this stage of the design, it was important to have feedback for the technological design of the whole system and be able to see if the system could be installed and function effectively.

The PSS perspective gave this research a preliminary insight into these technologies acceptance for the consumer in this sector, allowing the *dialogue* and inclusion of the consumer in a more active way by having something *concrete* to evaluate. It also facilitated a social process, where the project research team, together with the consumers and users, can now continue to shape the technology and exchange knowledge and information with each other (designers-consumers) in a more direct and strategic way.

This pragmatic approach might appear more complicated than the traditional approach, however, it is exactly this iterative process that can better influence the lamp design in a way that can be implemented realistically and that will obtain the desired effect (an effective reduction of $CO_2$ emissions), as well as supporting a process where the users also adapt to the new technology.

## 9.5 THE NECESSARY COMPONENTS AND CONDITIONS TO SUPPORT THE TECHNOLOGICAL INNOVATION SYSTEM TO DEVELOP THE TECHNOLOGIES IN FOCUS

This objective was pursued by analysing the innovation network (components) and the current technological conditions to further develop the technologies in focus (LEDs). Once again, this was done using the HFOLS as an intensive case study (for example, as an application in which LEDs can be used). The Analysis used as starting points: the conditions for innovation framework from the Technological Innovation System theory; the components (network and actors) of the innovation system from the Technological Innovation networks theory, and; technological drivers from the Innovation System Conditions theories.

Based on the intensive case study (HFOLS) there were evidences that there are enough institutions and potential for a highly varied and strong technological innovation network. However, there is not yet a formal, consolidated research technological network in the area of hybrid lighting in combination with energy efficiency in Denmark. There were also indications that, on the one hand, there are not enough patents and research to allow more innovations in the area of energy efficiency, as most of the efforts have focused on improving the LED colour of light and light colour control applications. On the other hand, the limited number of innovations might also play a part, because producers still focus on the implementation of linear fluorescent lamps. In this sense, even when there has been much effort to improve LED light quality to support the implementation of this technology, it is still remarkably difficult to compete with linear fluorescent lamps T5. Additional factors that, according to the particular case study, showed to contribute to the slow implementation of LEDs are: legislation for users of mercury in linear fluorescent lamps, and; the fact that big international companies still have interest in the implementation of this technology before they cross over to the full implementation of LEDs.

As indicated in Chapters 3 and 4, the fast international development of LEDs, in terms of efficiency and other qualitative performance, has increased considerably in the last few years. This has coincided with the regulations moving towards the phasing out plans of many countries and the eco-design requirements limiting the use of mercury. Similar efforts to further reduce the use of mercury should be encouraged in time spans that give the industry time for economic and technical restructuring towards a strategic transition.

Furthermore, based on the case study, there were strong indications that this sector needs a more open level of inclusion of relevant disciplines and actors. This might derive from the lack of recognition that the problem has to be solved by using a trans-disciplinary effort and areas of expertise. One way to resolve this issue is to look at the problem from a more multi-holistic perspective, where efficiency transcends the level of product-system orientation, takes into account the real target group and the problem, and further considers the innovation possibilities for the future.

The dialogue with key actors in this sector also pointed out the necessity to develop an education on light design. Through the experience gained by testing more radical innovation, it was realised that this education could consider aspects in the curriculum, such as, energy efficiency of the lighting *systems,* eco-design, combination of natural and artificial light, engineering of intelligent control systems, design of solar optical collectors, and integration of low-voltage based systems, colour of light, light intensity, light distribution and aesthetic aspects. The research institution that is ideally placed to take this initiative forward is DTU Fotonik, due to their focus on light technologies and also because of their engineering background.

Based on the intensive case study, there are strong indications that levels of inclusion and legitimation are not so strong in the LED technological network. In order to improve the technological network consolidation, and thereby the possibilities in this sector to better contribute in designing strategic technologies, the suggestions based on the findings of this study are: It would be an advantage, if current research diversifies its focus by opening up wider trans-disciplinary cooperation. The engineering base could further exploit their internal expertise on optics, fibre optic systems and knowledge on optics, and could consider visible natural light in a more inclusive way. This sector might benefit from considering that efficacy and dematerialisation are essential for further developing new technologies, for which the participation of institutions with environmental expertise should be pursed. The integration of the systemic levels of analysis suggested in this thesis requires the inclusion of socio-technological expertise, which should go hand and hand with technological-engineering expertise. Thus, it is important to ensure the expertise within this technological network. In other words, strengthening trans-disciplinary cooperation could be beneficial to the consolidation of this technological- system.

## 9.6 THE MARKET, POLICIES AND REGULATIONS THAT CAN SUPPORT THEIR IMPLEMENTATION

In order to assess possibilities in the illumination sector and suggest some actions, the HFOLS intensive case study was used again, but this time as a business idea to test market conditions, as well as the impact of the policies and regulations that support the implementation phase of the innovation life cycle. In order to achieve this, the author of the thesis wrote a business plan, participated in different pitch events and held interviews with potential private partners. This pragmatic approach was taken due to socio-technological- and innovation experimentation perspectives.

The theoretical framework for this section was based on the conditions supporting innovation from the technological innovation system theory, business capabilities and private/public partnerships, from the Valley of Death theory, and Market drivers, policies, regulations and push-pull drivers from Conditions for Innovation theories.

Through empirical and theoretical material, this study concluded that there are strong indications of the existence of an emerging market for illumination technologies in Denmark, although this is created more for local (national) efforts and not because of the impacts of EU policies. There is significant and balanced support from networks in Denmark that encourages entrepreneurship. Yet, although well intentioned, Danish policies and the emergence of a varied support network do not have a strong impact on environmental innovations in this sector in Denmark.

Based on the study of the market formation conditions and the push/pull determinants the intensive case study indicated that there are several reasons for this:

- There is a problem of inclusion, and thereby legitimation of non-traditional technological institutions to access direct funding for proof of concept projects.
- The policies relating to market pull have been stronger than the regulations to support the technological drivers.
- Universities still consider innovation as inventing something new or creating new knowledge, and not as a holistic process (e.g. invention, development, test, diffusion and implementation).
- Seed capital does not invest in ideas until they are very close to the market.
- Business capabilities are not supported sufficiently, as the early partnerships between universities and private capital are not taking place, or they occur only in the final stages of the innovation life cycle.
- Business capabilities are not provided within the universities (they are provided mostly to already established firms and outside the university setting).
- Green procurement policies are known and adopted only by a few municipalities.
- Public support is not distributed evenly in all phases of the innovation life cycle, but support more public/private partnerships when the products are very close to the market.

*Suggestions for solving these problems are:*
The Danish government should allocate more money to supporting public initiatives, such as, emerging start-ups in universities. This is particularly important for innovations that have a deeper social impact, rather  than a purely economic impact, and which also comply with environmental and energy goals.

This public financial support has to be increased in relation to the *proof-of-concept* phase. It needs to be more inclusive and directed towards *all* universities, as these kinds of problems require trans-disciplinary cooperation. The distribution of financial funds should also be equitable, without discrimination on grounds of university size or research traditions, but rather be based on the quality of the ideas. This support should also emphasise the importance of the development phase for the development of products.

In order to enhance a researcher's business capabilities, universities could develop more collaborations with funds, such as, Væksthus, Venture Cup and Connect Denmark, with specific focus on product development and start-up legal issues concerning university regulations and possibilities *within* the same universities. There is an indication that Universities could better support innovation through clarifying their regulations and policies for university spin-offs, and they could improve their support by providing faster responses to questions relating to legal aspects. This will require a closer collaboration between researchers and the university legal teams.

Where there are market opportunities through governmental policies, and where there is a need to switch from technology to a product, it would be beneficial if universities could also work within the fields of social science and technical science so as to work in cooperation with business schools. In other words, it is also important to strengthen the funding and access to business capabilities for researchers-entrepreneurs within the universities.

An interesting academic discussion would be to focus on the researcher's current role as an actor of change and analyse how this can contribute to enhancing, not only scientific knowledge, but also how a researcher can contribute more effectively to technological transition and become more proactive in the entrepreneurial process. This could be easily justified, as eco-innovation is also seen as a public good, and therefore, could also be incorporated within the university system. However, this extension of a university's responsibilities would require additional resources, and a mechanism should be considered to give back to the universities some of the additional values that will be created in society.

Through the case study, it was observed that seed capital could better support the spin-off process by participating earlier in the development of technologies towards products. For example, the formation of *pre*-seed capital funds could be an interesting option. In order to encourage such activities, it is very important that the high-risk investments should not be limited by being taxed too soon.

These issues are quite complex, but it is important to point out that in Denmark (and most places in the world) politicians have a very powerful tool for influencing private initiative through the tax system.

Institutions, such as Danish Centre for Light, could provide a wider forum for the discussion of the societal and environmental impacts of the technologies in this sector. Additionally, they could provide a space for discussing and informing on different financial possibilities and business models, targeting municipal representatives in particular.

In order to reduce the double externalities caused by the unbalanced electricity prices which were noted as a limitation in the HFOLS case study, this thesis suggests working towards a parallel-index system adjusted in line with the efficiency of new technological alternatives, so that, as their efficiency increases, the prices of electricity is raised. In this way, if consumers want to maintain the same cost of electricity for illumination, they will be motivated to change to solutions that maintain the current level of costs. Again, this suggestion should not only be applied to local planning, but also at the European level to avoid creating unbalanced competition between companies and between countries, and it should be adjusted as the development of the technology progresses.

Based on the intensive case study for the HFOLS, it was observed that another of the general conditions affecting the development of the investment in new entrepreneurial activities in this sector is the lack of motivation of private investors due to the lack of global market opportunities. To change this condition the European Union should also raise their energy and climate goals to a more ambitious level, and thereby create a greater market for eco-friendly technologies.

One of the general conditions that could be improved so that cases like the one described in this thesis could be better implemented, is to increase the information on the goal and objectives of Public Procurement Policies, both for municipalities and for the private sector, so diffusion takes place at the same time as the market-pull policies are implemented.

As the case study presented in this thesis shows, another condition that could be improved so as to better support the implementation of new applications which include LEDs is that the private sector could take its responsibility in supporting university-based research and development initiatives at an earlier stage of the innovation process. This may be through investing in a project, but also through mentoring, or by participating as a following group for externally-financed programmes. This should be done in order to accelerate the development of technologies towards products, particularly in situations of difficult economic conjunctures. In return, if there are new start-up possibilities, private partners could have first rights to the purchase of patents and/or shares.

## 9.7 NEW METHODOLOGY FOR ECO-DESIGN AND ECO-INNOVATION FEASIBILITY STUDIES

In order to make an analysis of the possibilities for environmental solutions under an eco-design and eco-innovation perspective, it was necessary to create an analytical model that would help to analyse and understand the different system interactions, their components and dynamics.

The final conclusions are a result of an analysis that required an understanding of the objects, their material dimension and their constituents. At the same time, these objects are placed in a sociological order which is determined by market forces and social-technological relationships. Market and technological forces contribute in shaping the solutions, which are not fully developed, as society's needs are not static. Furthermore, these solutions are either supported or blocked by policy actions that affect the material dimension of the object, in the same way as the forces that contribute to forming the solutions.

Consequently, in order to grasp this complexity, it was necessary to create a scientific method through which to organise, guide and present the results of this research. This was achieved by considering three levels of analysis: adopting a multi-system perspective taking into account a Product-System, a Product-Service System, and a Technological Innovation System. Through this praxis, a new methodological framework was suggested and used in this dissertation (see Figure 9.1).

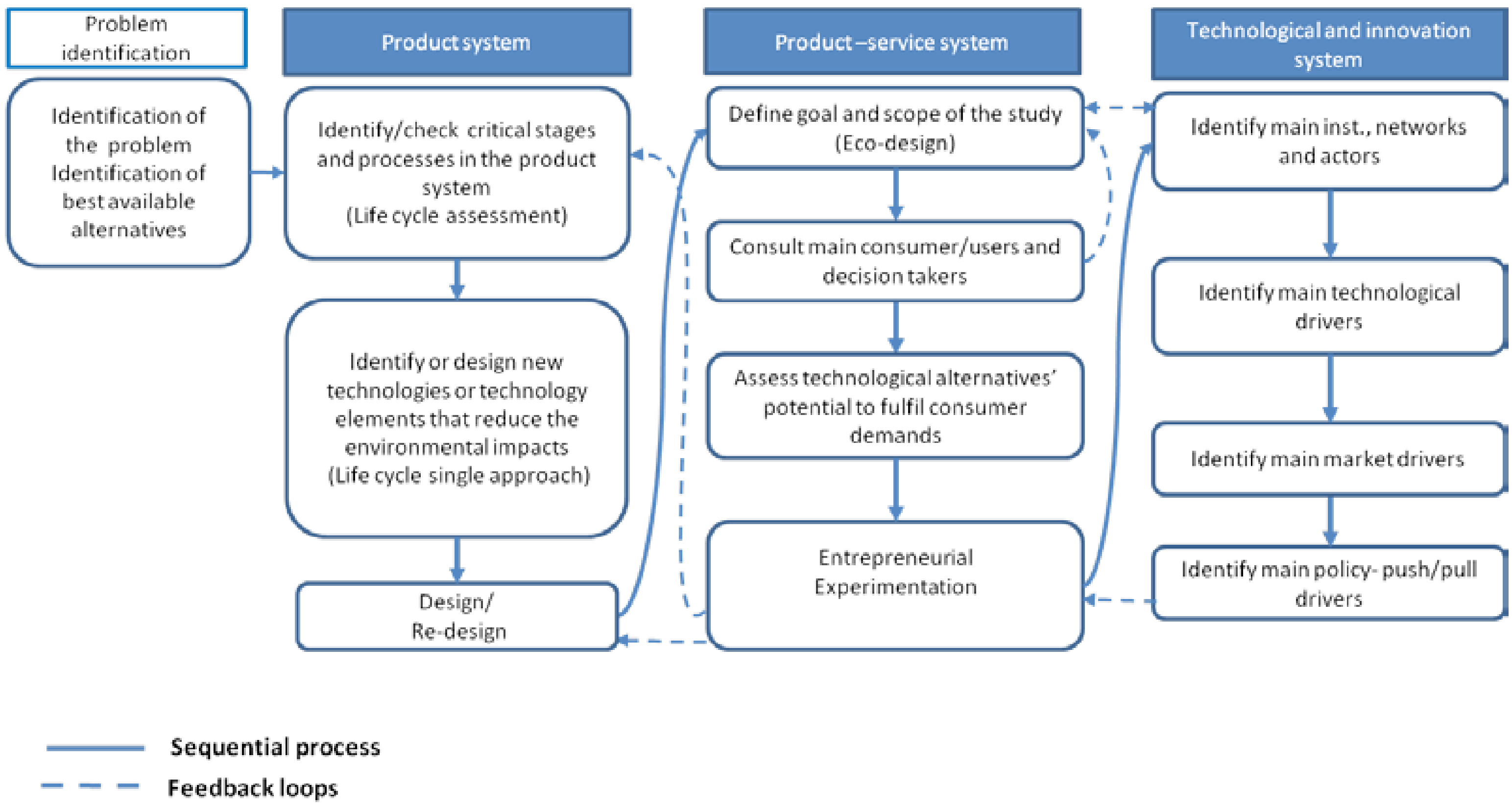



***Figure 9 1.:*** *Eco-design and innovation feasibility studies method of analysis (Author's own diagram).*

This construction was useful to create the research objectives, to structure the thesis work in relation to the empirical material and for the discussion and presentation of the results in an organised manner.

***New Framework for Eco-Design and Innovation Feasibility Studies***

Besides creating the new methodology and using it for the development of this thesis, a new conceptualisation of feasibility studies was suggested.

A conceptualisation of an eco-design and innovation feasibility analysis was defined by the author of this thesis as:

> A study which can provide policy makers and funding institutions a broad knowledge of the material (environmental, resource and health risks) impacts of a technology, the technologies' potential to improve the product-service (value) for consumers and society, and the innovation framework conditions for a realistic implementation. This should be considered, when taking decisions on cleaner technologies that can be financially and politically supported in order to reach climate, resource and sustainable development goals.

The author's suggestion for a theoretical framework for a *preliminary* eco-design and eco-innovation feasibility study is illustrated in Figure 9.2.

*Guiding principles*

In order to achieve a more sustainable low-carbon technological transition, studies of this kind should consider the following guiding principles:

*Product System*

The study should present a feasibility insight at the Product System level, not only for the evaluation of current technologies, but also for their technological potential to further redesign and develop the technology. In this way new technological designs can reduce the consumption of energy based on fossil fuels both quantitatively and materially, and thereby reduce $CO_2$ emissions. The LCA considerations are important for suggesting strategic alternatives that consider resources and other environmental and health risks. This process will help the new alternatives to avoid side effects, while allowing the project manager to focus on the problematic stages of the life cycle where strategic changes need to be made and to design holistic solutions.

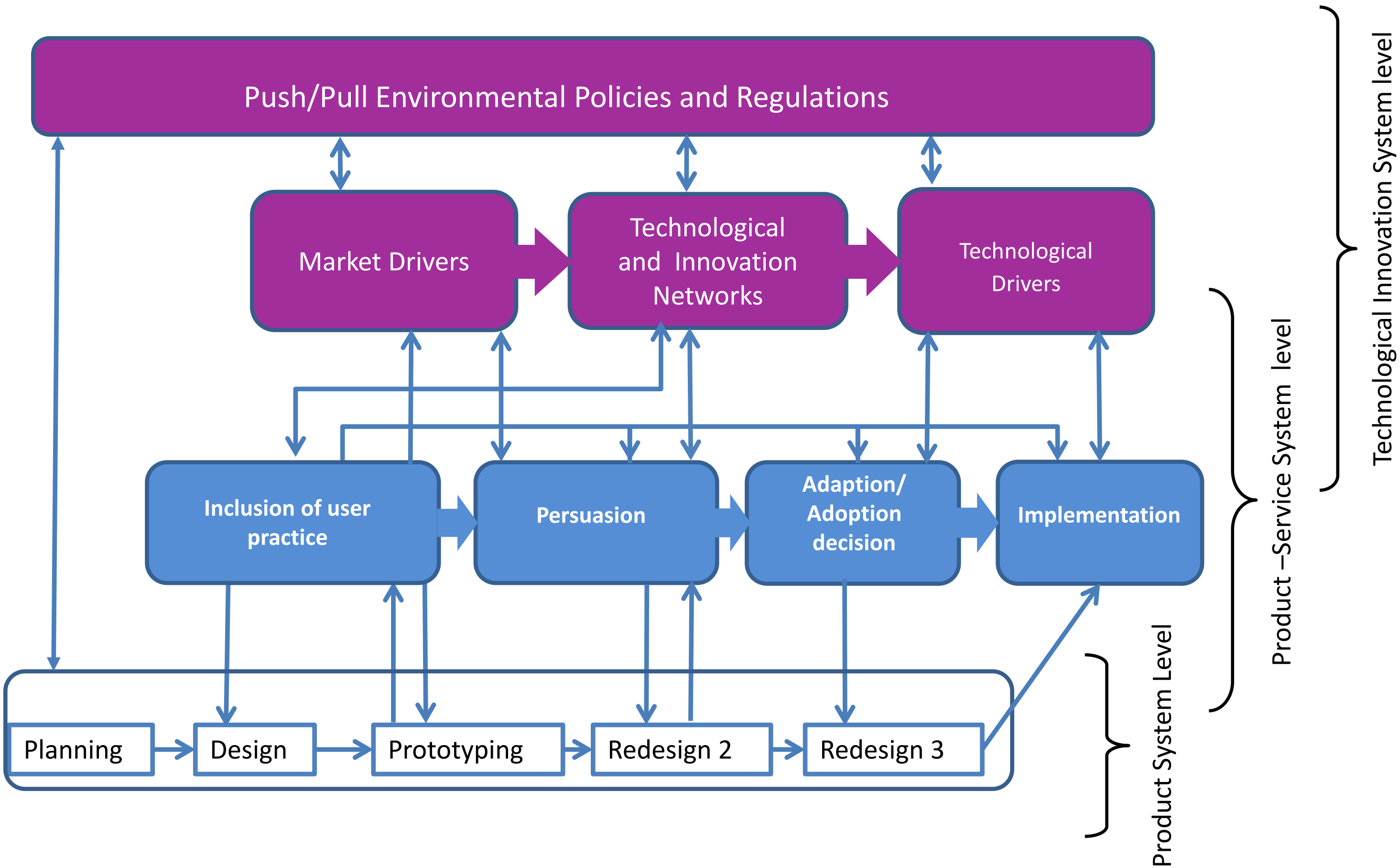



***Figure 9.2:*** *Eco-design and eco-innovation feasibility preliminary framework (Author's own diagram). The blue arrows represent the communication channels.*

*Product-Service System*

An insight into the Product-Service system is unavoidable, because both the design and innovation activities are part of a social process, where it is important to make a concrete evaluation of the technologies. Also because this is an iterative process that both shapes the material dimension of the objects and perceptions and perspectives on subjects relating to the new object. It requires the inclusion of the key value chain actors (consumers/users) as co-developers of the technology in the different decision stages of diffusion of an innovation, and in the identification of relevant decision makers in the market framework. The product service system perspective allows targeting and including in a more tailored form those agents that are critical in supporting the development of a technology towards a product process, and thereby, will provide the basis for better planned implementation of more sustainable technologies.

*Technological- Innovation System*

It is important that feasibility studies on eco-design and eco-innovation include the perspective at the Technological innovation system level. Firstly, it is important to determine the potential to reduce resistance of change that might exist in the technological innovation actor and institutional network. Secondly, while technological projects whose objective is to develop cleaner technologies look for business opportunities, they also need to identify the potential conditions to implement more sustainable solutions that are motivated by societal interests, such as achieving climate and environmental goals. Thirdly, these studies should document how the projects will support the objective of technological transition to a lower-carbon society. Here, it is important to keep track of technology development opportunities, particularly of the regulation framework for strategic research and development investment.

In other words, programmes that aim to promote a strategic technological transition should consider these three levels of feasibility: the material/technological aspects, the capacity of the actors and institutions that constitute the technological system, and the framework conditions (components, quality of the relationships and drivers) to establish the transition and to further support the technological innovation system development of more sustainable technologies.

*Main questions that an eco-design and feasibility study should answer*

Based on the theoretical and empirical material used in this dissertation, the main questions that this type of feasibility analysis should answer are:

1. What are the main environmental impacts of the current technology's product system (LCA) in which stages of the product- service life cycle do the major impacts take place?
2. Which technologies have further potential to reduce $CO_2$ emissions and continue the technological development of their life cycle?
3. What can be improved to make the new technological alternative systems cost-competitive?
4. What can be improved in the product-service system so that the alternatives can provide a more satisfactory service for the consumer, and what added value do they have?
5. What possibilities are there to enhance the technological innovation system conditions, and what can strengthen the technological drivers to further develop the suggested technologies in the sector in question? and,
6. What possibilities are there to develop a market for the sector, and what can be done to further improve the current push/pull policies and regulations to support the technology's whole innovation process in the future?

The two first questions are related to the product system, questions three and four relate to the product-service system, whereas questions 5 and 6 relate to the technological innovation system.

As mentioned above, this is a preliminary effort to sketch a theoretical framework for the eco-design and innovation of a low-carbon technology feasibility study, and therefore, this thesis recommends that further research and discussion should be done to develop these findings.

The above questions have been used as research tasks to guide the investigation and to provide relevant knowledge to the three levels of analysis established earlier in this study. Resolving the first two questions provided practical knowledge to establish the material and technological improvements, so that a strategic detection of the technology with the biggest development potential could be selected. Furthermore, they provided the basis for other creative and more radical ideas. Resolving the third and fourth questions provided the knowledge to establish the added value that the selected, and the new, technologies could contribute, both as value for society ($CO_2$ emissions savings) and for pointing out further technological and service improvement potentials and value for the consumers. Finally, resolving questions five and six highlighted the potential in the conditions and components of the illumination technology system, identifying the main institutions and actors to support ideas like the ones that this study has assessed within this sector. Additionally, the last two questions also revealed the regulation and policies that can support technological development, but also detected the places where improvements could be made in the innovation system to improve overall conditions and to enhance the emergence of further business ideas in this sector. The process for creating such question was not linear. In order to reach the final versions, it has been necessary to follow several feedback loops between theory and praxis. Nevertheless, once they were established, they worked well for the purposes of this research.

## 9.8 USE OF A PROBLEM-ORIENTED SCIENTIFIC APPROACH

Having a problem/object-oriented scientific approach was helpful, because as the studies progressed through the knowledge process, the complexity increased. This approach helped the work to select the most important problems, and thereby, delimit the study objects and set the boundaries for the study. Furthermore, it increased the awareness of the type of knowledge that was needed and facilitated the selection of project partners and actors that were needed for the different system levels.

Using abstraction logic was also useful for combining and managing trans-disciplinary knowledge so as to obtain solutions that could be concrete in terms of events and objects. It allowed the work to move from the micro to the macro level, to be able to pass from one system of an analysis to another according to the process in which the problems were identified. By doing this, it was possible to see not only the problem, but also the causes, and who contributes to the problem or to its resolution. The selection of study cases (tests) provided the opportunity, not only to observe from outside the problems, but to get involved in praxis. This allowed a clearer view of the type of relationships and process that are really taking place in the field. Thus, instead of just pure description, a practical explanation could also be given.

It was a creative process, as it also allowed for experiments (intensive/participatory research) in order to test the hypothesis and results in the research. Using this method facilitated intensive tests which achieved a good combination of practical and scientific knowledge that can be incorporated into concrete suggestions and solutions. It was also useful to use the concrete examples in order to observe situations that are taking place in a general context.

One of the main challenges using this approach has been to distance oneself from the specific case study and view it from an analytical position. As a researcher and co-participant, the author has been deeply involved, and it has sometimes been difficult to separate two roles. Here, discussions with thesis supervisors and colleagues have been of great support to the author in resolving this dilemma.

### 9.8.1 Use of theories and concepts

In accordance with the chosen scientific method, the theories applied here have been used as tools. They were used according to their usefulness and relevance in relation the problem ontology, rather than as general rules that had to be tested. For this reason, the study does not offer an analysis of contrasting theories. The abstraction exercise focuses on finding the elements of the theories that fill specific areas where there is a gap in knowledge in the other theories used. Because the study made use of abstraction for the analysis, it did not concentrate on all the elements of the theories, but rather on the parts that were useful for the specific analysis. As an example, the use of several innovation theory parts was used to construct the framework of the product-service system and the technological-innovation system. The idea was not to prove the theories wrong, or false, and/or to test one against the other, but rather to concentrate on the parts that could help towards analysing the elements encountered in the praxis in relation to the intensive/participatory case study.

One of the challenges here is that the researcher needs to have a wide knowledge of, and access to many theories, since it is not always a straightforward process to find the exact elements one is looking for. Here, discussions and guidance from supervisors and colleagues provided useful support.

The different concepts about knowledge from Sayers provided this study with the flexibility to grasp a concrete problem and its causal dimensions. Through this approach, it was possible to both grasp the material aspects of the problem and the perspectives and relationships of the most relevant stakeholders related to the study objects analysed.

A pragmatic approach towards the generation of knowledge allowed the author to involve herself and to gather the relevant actors in a process of social learning. This process provided an in-depth knowledge that would not have been achieved if a different approach had been used. It was also useful to direct the attention of relevant stakeholders to discuss and focus on an area of knowledge that they might have not focused on before, and to be part of the process of knowledge creation. The participation of scientists and engineers provided this study with an indispensable academic support, the inclusion of designers with practical and concrete results, while the participation of the electrical company IBSEN APS, provided an invaluable insight of the real praxis in the outside world. This approach was useful to identifying the necessary and relevant knowledge needed by the author to fulfil the research objectives.

The pragmatic approach and the process of getting involved in the co-production of knowledge provided a valuable tool with which to firm up ideas into concrete objects that were the basis for more knowledge production. Working with HFOLS in praxis, and as intensive case study, was a methodical choice. It has become a development project in its own right, with its own progress and with a new set of research objectives.

The abstraction theory provided the framework to be able to use both quantitative and qualitative methods, according to the nature of the research task. It made it possible to pass from the micro to the macro level of analysis. It further supported the structure and planning of the research activities.

The strength of this method is that it supports the research through an in-depth perspective of the study object, even when the conclusions cannot be generalised. This method was selected because the objective was to suggest changes in praxis and to be able to mould concrete objects rather than to create laws for an unspecific context.

In this specific case, the objective was to find knowledge that could be used and be applicable. In this sense, it is hoped that, if the methodology and the framework presented can be used for further comparable technological studies, one of the author's main objectives will be fulfilled. It is also hoped that the suggestions for this specific sector can be used to further strengthen the LED technological system and provide a space for other more radical applications.

Although this approach has many advantages in relation to the quality of knowledge, one can argue that it would benefit from more time and resources to conduct this kind of research. For example, in order to get involved in the externally financed projects, one needs to gather key actors together to be part of the project team. Further, an application for each of the projects had to be written (as well as applications for proof of concept, which was unsuccessful and the business plans requested by some of the TIS-network institutions). Although the author was happy to do this work, it consumed a great deal of time and resources, which had to be planned to fit into the three year PhD programme. Without the support of ELforsk, public support, and the flexibility of the work leave rules at the author's home university, this project would had been difficult to develop in the time allowed.

*Use of analytical theories:*
The use of the product-service perspective was useful in providing focus at the material and technological level. Using the LCA as an approach contributed to a holistic perspective at this level of analysis and also to enable further work focusing on the environmental improvement potentials that the selected technologies could provide. However, it is still difficult to obtain LCAs directly from producers.

At this level, the ecological footprint theory was also revised - but more as a background for the LCA in relation to resource consumption limitations (natural capital available). The cradle-to-cradle method was also revised, but considered more normative than instrumental. Even when the emphasis is on recyclable practices to reduce the environmental impact, the practices of recycling might not always be carried out as estimated, as was observed with the recycling fluorescent lamps. The concept of the product-service system provided the foundation for the next system expansion. The use of the Innovation-decision model from Diffusion of Innovation theory created possibilities to see, not only how the designers can learn from consumer and user feedback, but also how the whole system can learn from placing the consumer-user at the centre of the decision making process. The feasibility of this needs to be seen in relation to the social learning process for all the main decision makers, and the possibilities to plan a more strategic development of the technologies. It also allows the inclusion of the consumer-users and important stakeholders in the process of both adaptation and adoption of a new technology, which will allow the technology to respond to real social demands. It will also help to identify other relevant stakeholders who can take part in this social process. Although this theory highlighted the cost as a one of the elements consumers look at, it did not provide an insight into how to make the products more competitive or cost attractive for consumers. To fill this knowledge gap Porter theory on competitive advance was included.

The use of Porter's theory of competitive advance provided an insight into the market added values and strategies that can be pursued while developing the technologies, but before they reach a level of competitive costs that make them attractive to first–movers consumers. The combination of elements from the Diffusion of Innovation theory and from the Competitive Advantage theory provided an insight into strategic consumer targeting, by focusing on the key actors in the market for the development and implementation of the technology. Using elements of the Diffusion of Innovation theory was also useful to gain an insight into involving key consumers, both in the process of adaption and adoption to the strategic environmental solutions.

However, even when the input from Rogers provided the work with an insight into the societal needs and preferences of the market, it did not reveal the structural conditions necessary to *sustain* and make possible the implementation of alternative low-carbon technologies. Rogers description of the societal relationships that take place in the communication and knowledge formation of the design and innovation process do not reveal the qualitative functions and structural conditions needed to produce and bring the new technologies to the market. Nor does it reveal the business feasibility dimension that is necessary to successfully close the innovation life cycle. This theory also lacks the focus on value creation, both from a company and societal perspective that was necessary to complement with Porter's contribution (competitive strategy). The differentiation between value and cost was also useful when comparing the life cycle cost logic to the logic that was encountered in praxis.

Different complementary approaches to the innovation framework conditions contributed by identifying the elements (networks and actors), the quality of relationships and the conditions within the LED technological innovation system. A limitation of the Valley of Death theory is its rational character, as it does not consider conjectural aspects (e.g. the current financial crisis), and therefore, the fifty/fifty (private/public) partnership might not always work as planned. If this is the case, the government should go a little further and take the emergent spin-offs closer to in the kick-off *business process*. The Valley of Death might not only be caused by economic reasons. As was argued in the last part of this dissertation, there may be other qualitative conditions and relationships between the different institutions forming part of the technological innovation system that need to be resolved in order to make the link between the public and the private,

### 9.8.2 Use of empirical material

One of the strengths of this research has been its basis on praxis, which has generated practical knowledge that can be put into practice in the future. One example is the first trans-disciplinary research project "Hybrid fibre Optical systems towards a smaller ecological footprint". This project contributed to bring together a number of research institutions to investigate different aspects of light, through a common project objective: to increase the focus on energy efficiency and establish the potential environmental improvements that alternative technologies could contribute. It also highlighted this new research area and focussed the attention of the illumination sector on the fact that, in Denmark, new applications of LEDs can be pursued in combination with daylight. As mentioned previously, this effort has taken its own direction and a second project, entitled "Hybrid lighting goes to school", has arisen from the first initiative. This new project is continuing on the path of energy and environmental efficiency research, where a deeper degree of consumer participation is planned, and where other applications of LEDs in form of hybrid systems can be demonstrated. Both projects are co-financed by Elforsk, DTU, Roskilde University, School of Design Kolding, and IBSEN APS, and the second one is also supported by the Stevns Municipality.

The creation of an intensive concrete case study also facilitated an experimental approach, where it was possible to contribute with innovative and creative ideas to new designs of hybrid luminaires. In relation to feasibility studies that support eco-designed low-carbon technological solutions, this research takes on a different quality, as instead of focusing on identifying barriers, this approach contributes to finding future creative solutions and focuses more on the possibilities, as well as finding strategic solutions to barriers.

Action research has the advantage of strengthening feasibility studies by engaging strategic actors within technological networks and bringing them together to support the consolidation of typically emergent new technological innovation systems. Through this trans-disciplinary expertise it also helps to ensure that issues, such as the design and innovation of low carbon technologies, experience a more strategic low-carbon technology implementation.

Using active observation (through explorative and in-depth interviews) was helpful to establish the problems and situations that actors are experiencing, from their own perspective, whereas, the use of the active research method as a tool (through iterative dialogue and communication) allowed the study to become aware of more in-depth causes.

This approach, however, would not have been possible without the economic and professional support of the different institutions engaged in this research. The author acknowledges and is grateful for the valuable and diligent cooperation of her colleagues and project partners. The search for a robust, empirical research constitutes an essential investment in society.

Although the above mentioned empirical elements proved to be the most exciting part of this research, it would have been incomplete without the insight provided by the statistical, quantitative and previous professional research reports which contributed to the delimitation and definition of the problem.

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# Contributions by the author

## Book chapters

**B1)** Bjarklev, A; Andersen, J; Laursen, K, and Kjær T. 2012 (submitted). Possibilities and challenges designing low-carbon-energy technologies- The case of the lighting sector. In Rethinking Climate Change Research : Clean-Technology, Culture and Communication. Editors Pernille Almlund, Per Homann Jespersen, Søren Riis. Ashgate, 2012. ISBN 978-1-4094-2866-4

## Peer-review articles in conferences proceedings

**P1)** Bjarklev, Araceli ; Bjarklev, Anders. 2010. Future Illumination Systems and the Climate Change Challenge - The case of Danish office lighting. In: Proceedings of CIE 2010 "Lighting Quality and Energy Efficiency". Commission Internationale de L'Eclairage , 2010. p. 94-102

**P2)** Bjarklev, Araceli. 2010. Possibilities and Challenges designing Low-carbon-energy Technologies- The case of the lighting sector. In: RUC Sunrise Triple C Conference: Climate-Change – Communication. Roskilde University April 2010. Clean technology track.

**P3)** Bjarklev, Araceli; Andersen, Jan; Kjær, Tyge. Barriers and Possibilities for the Emerging Alternative Lighting Technologies. In: Proceeding - Joint Actions on Climate Change [Online]. Roskilde 2009. ISBN 978-87-91830-30-3

**P4)** Bjarklev, Araceli ; Andersen, Jan ; Kjær, Tyge. 2009. In which Sectors Could New Illumination Technology Strategically Reduce CO2 Emissions? In: Proceedings of SPIE: International Symposium on Photo electronic Detection and Imaging 2009: Material and Device Technology for Sensors. Vol. 7381 SPIE - International Society for Optical Engineering, 2009. (Proceedings of SPIE). DOI:10.1117/12.834588

Other research and communication activities can be seen at: http://rucforsk.ruc.dk/site/en/persons/araceli-bjarklev(5a1fe85c-d9d6-4c7b-ab50-f1bf4174c706).html

# Book Chapter

# Opportunities and Challenges for Innovation in the Design of Low-carbon Energy Technologies - a Case Study of the Lighting Sector

*Araceli Bjarklev, Kent Laursen, Jan Andersen and Tyge Kjær*

## 1. Introduction

The total electricity consumption across the EU-27 countries showed an absolute increase of 28.7% between the years 1990 and 2005. The average electricity use per capita in the EU-27 is almost 2.5 times the global average. Total world consumption of energy is projected to increase by 44% from 2006 to 2030 (EIA 2010). These tendencies for growing electricity consumption still take place despite the emergence of countless numbers of energy saving devices. At the same time, the production and use of electronic devices is growing rapidly. The amount of resources required to fuel this consumption and production at a global scale is leaving a huge ecological footprint, and the EU contributes to this significantly. The decision of the European Commission to ban incandescent lighting has opened a huge debate on whether we have the technology in place to replace the Edison bulb in terms of price and current consumer demands and habits.

One of the main reasons for banning incandescent lighting is that the world cannot continue to increase its consumption of electricity because the levels of $CO_2$ are already surpassing the limits of a sustainable ecological footprint. When referring to a sustainable footprint, we are referring to the available energy sources (today primarily fossil fuels), the impact on the resources necessary to absorb their emissions, and to the impact of these materials and chemicals on the environment (Wackernagel 2005).

Although there is broad consensus that one of the solutions to the current environmental challenge will be based on the use of low-carbon technologies, and even though there is substantial potential to adopt more sustainable design and innovation, there are several elements that need to be taken into account to achieve efficient reductions of energy and $CO_2$ emissions. At the same time, and especially concerning lighting devices, to ensure their strategic implementation it will be necessary to design a product which is attractive to the consumer in terms of price, level of service and aesthetic demands. Several studies (Sandhal et al. 2006, Mert et al. 2008 and Lefèvre et al. 2006) have pointed out that, besides technological characteristics, some of the main historical barriers to the successful implementation of energy saving devices have been price competitivity with current market devices and the aesthetic design. In the case of lighting devices, this refers to the quality of light, including colour, intensity and distribution, which are related to the design of both the lamp and luminaire. This chapter takes the example of the Danish office lighting sector as a case study and discusses the question: What are the main opportunities and challenges for the design and innovation of low-carbon lighting technologies?

To answer this question, we use a systemic approach including environmental, economic, energy and political issues using relevant concepts from the Ecological Footprint, concepts and tools from Life Cycle Assessment (LCA), relevant elements from eco-efficiency and diffusion of innovation theoretical frameworks. Often, systemic approaches tend to be driven by completely rational models. However, our main contribution is to consider a more holistic approach integrating socio-psychological aspects such as consumers' perceptions (aesthetic disposition, habits and different light tastes and needs) to plan a more strategic implementation or to increase the opportunities to bring innovation in this sector to the market. Our empirical material is based on iterative interviews with relevant actors and experts within the Danish lighting sector and a preliminary consumer (user) accept test that included qualitative interviews and a quantitative survey. Furthermore, as a central part, with the cooperation of a trans-disciplinary team, our research included the design, fabrication and test of a new hybrid illumination system based on optical fibres and Light Emitting Diodes (LEDs) (Elforsk Projekt no. 341-043) .

## 2. Methods

We have as our standpoint a problem-oriented design and innovation approach, which allows for four different possibilities:

1. We take a holistic and systemic approach that ensures relevant innovation and avoids partial and unrealistic solutions.
2. We pursue a combination of technological and social solutions, where all aspects of the production chain are considered. However, we focus our approach on the most problematic stages (in our case the use phase). Even when this approach is technologically based, we further consider its societal implications so the new technology can be implemented.
3. We aim to obtain a synergy between the eco-design and eco-innovation by pursuing several benefits such as the reduction of climate impact and the reduction of the use of energy based on fossil fuels, in combination with socio-economic aspects such as local business development.
4. We pursue a strategic implementation of the innovations by using relevant elements from the Stages in the Innovation Decision Process Model from the Diffusion of Innovation theory (Rogers 2003).

Our conceptualisation of eco-design and eco-innovation is a combination of product-service life cycle and the innovation life cycle to find a more strategic implementation, as shown in Figure 1, combining the relevant elements of the following approaches:

- Using Eco-design (ISO 1462) or design for the environment, taking as a standpoint the life cycle or the production chain as a precondition for the new design.

- Using a System perspective, the design takes into consideration the intersection of combined product chains to pursue an optimal advantage or effect, in other words, switching the focus from only being single product oriented to also being service oriented. For example, instead of focusing at the lamp as a final product, we focus at the kind of service that has to be provided, in this case the service of illumination. We use a product-service system approach (UNEP 2002), which is defined as the result of an innovation strategy, shifting the business focus from the design and selling of one physical product only, to selling a system of products to deliver an integrated service. Consequently, the lamp passes from being a final product to being one of the inputs necessary to provide the service of illumination. In this way, besides considering the effects of the lamp we are also able to evaluate alternatives for other inputs, such as electricity based on fossil fuels, and find ways to improve the whole product-service system.
- Using the design concept from Eco-innovation, derived from the EU's program (COM 2009), which seeks a combination of the two previous concepts.
- Strategic and consumer-oriented innovation is pursued by including user-practice in the process of design and innovation by letting consumers test our prototypes at different stages of the innovation-decision process. By doing this we achieve a more effective dialogue with and knowledge of potential consumers. We also provide more information about the comparative advantages of our new product thereby speeding up the rate of diffusion and, at the same time, achieving a more effective consumer-oriented design.

The product-service system analysis was supported by iterative interviews with relevant actors and experts within the Danish lighting sector. We further investigated how potential users within the office lighting sector perceived our design by conducting qualitative interviews to identify the most important functions and qualitative parameters that an ideal lighting system should have in order to be accepted by the consumer. Ten face-to-face random in-depth interviews with university staff were carried out. The most important factors from the qualitative interviews were then used to design a consumer quantitative test allowing volunteers from university staff to test our system. Thirty-five persons answered the questionnaire. The whole process involved a total of 45 persons. We must stress that the test was designed to explore further considerations to support our design decisions rather than as statistical scientific research. Thus, the results of the test have been used to further re-design and develop new hybrid lighting systems from which members of our team wrote two patent applications.

The total life cycle cost of the three systems was calculated using DEEP's LCC tool (http://deep.iclei-europe.org). Because of its simplicity, this tool was chosen to assess the total energy consumption both for the initial and for future costs.

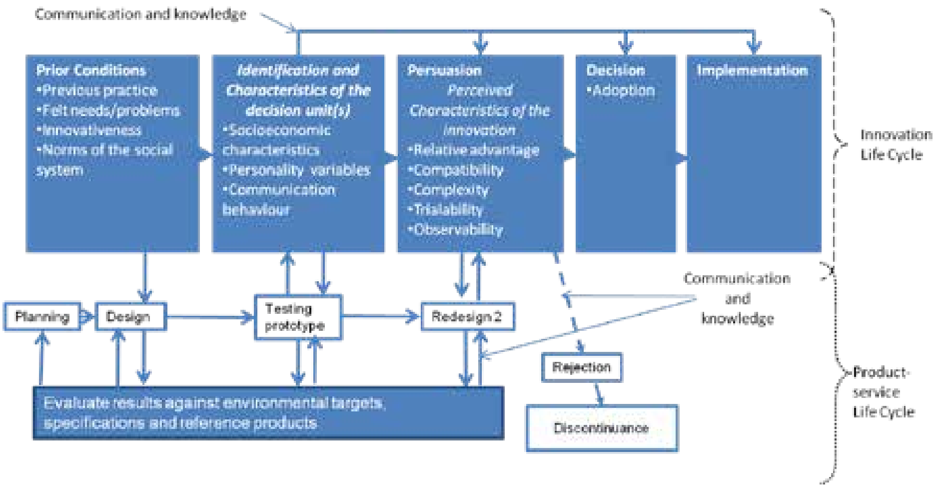



**Figure 1 User Practice Inclusive ECO-Design and Innovation life cycle framework**

## 3. Tackling the climate and energy challenge

Rising electricity consumption in the lighting sector is very problematic as the production of electricity in most countries is mainly based on fossil fuels, therefore the production of $CO_2$ will increase as consumption grows. Furthermore, the increasing urbanisation process in the world demands more lighting services. Levels of lighting services in industrialised countries are still too low compared with consumers' current standards and demands. Thus, the main challenge is to reduce $CO_2$ emissions, taking into account that consumers will not accept a reduction in the quality of service. This might explain why even when there are energy-saving alternative bulbs available, the electricity consumption due to lighting is still growing. On the one hand, it is necessary to design technologies that maintain or even improve the service of lighting using less energy, or using less energy based on fossil fuels. On the other hand, and perhaps even more importantly, is the need to ensure consumer and user acceptance, so the new technologies can be effectively implemented. By effective implementation we mean completing the innovation cycle, from designing a new product or service to ensuring its way to market.

The best lighting technology available today for the office sector, according to the European Assessment for Energy-using Products (EuP), is the tri-phosphate fluorescent lamp using electronic ballast. However, even implementing this technology (which is considered the best available) the consumption of electricity compared to 1990, will require *25%* more energy and produce *66%* more emissions of persistent organic pollutants in 2020, while emitting almost *30%* more $CO_2$ than in 1990 (Van Tichelen, et al. 2007). Note that the different percentage values are due to a changed relative distribution between the sources of power used in electricity production.

## 4. Environmental impacts within the life cycle

In order to find an environmental solution to the energy consumption problem within this sector, we needed to determine in which phase of the lighting technology life cycle the most significant environmental impact occurred, and which processes should be improved to reduce it.

Thus, we chose to analyse this problem from a life cycle perspective. To achieve this objective, we made use of latest life cycle assessments that had detected and measured the main impacts caused by incandescent, fluorescent and LED lamps in Europe (Van Tichelen, et al., 2007 and OSRAM 2009). These assessments were important to identify the stages where a new design was needed focusing in the life cycle single approaches suggested by Coles (2002). The biggest environmental impacts were shown to be in the use phase. This helped us to focus on the specific efforts and eco-design demands in this specific stage (see Figure 2).

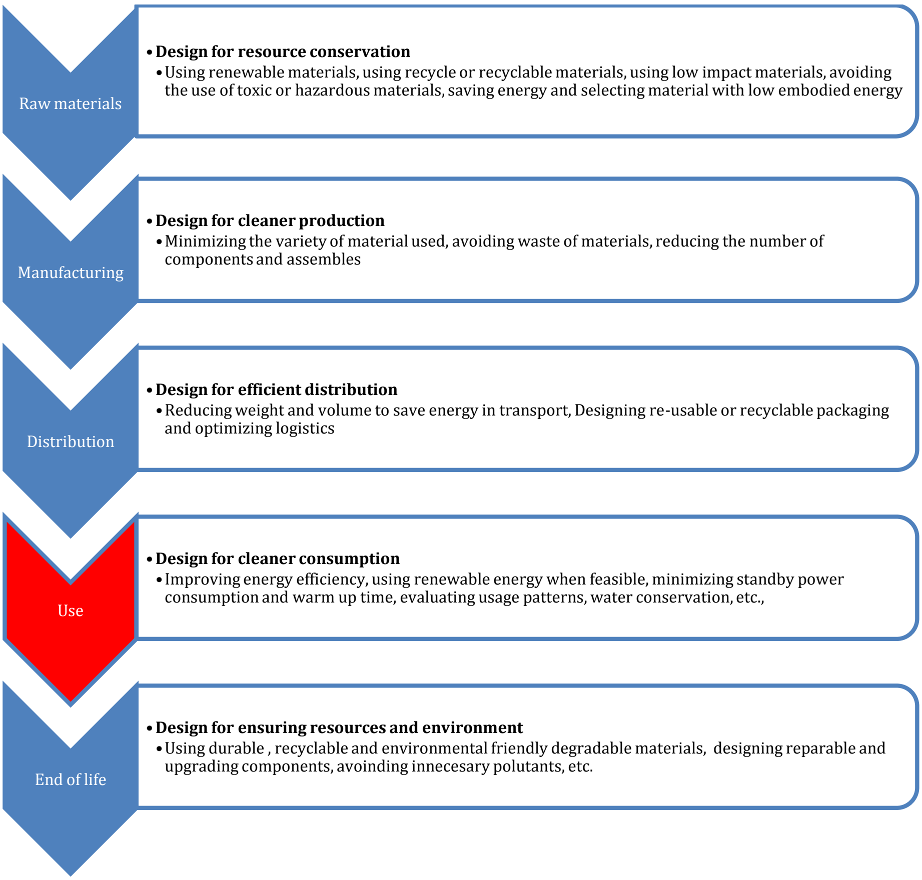



**Figure 2 Eco-design single issue approaches.**

## 5. Improvement potential within the product-service system

One of the main tendencies in the lighting industry has been to improve the energy efficiency of the lamp/bulb. The most representative technologies are linear fluorescent lamps (LFLs), and more recently, light emitting diodes (LEDs). On looking at the product-service system we realised that electricity consumption in the use phase of the lighting sector is actually causing the biggest environmental impact. Consequently, it became our objective to analyse how to reduce energy consumption and losses throughout the product-service system (see Figure 3) and to find alternative substitutes for electricity based on fossil fuels in order to deliver a more sustainable lighting service.

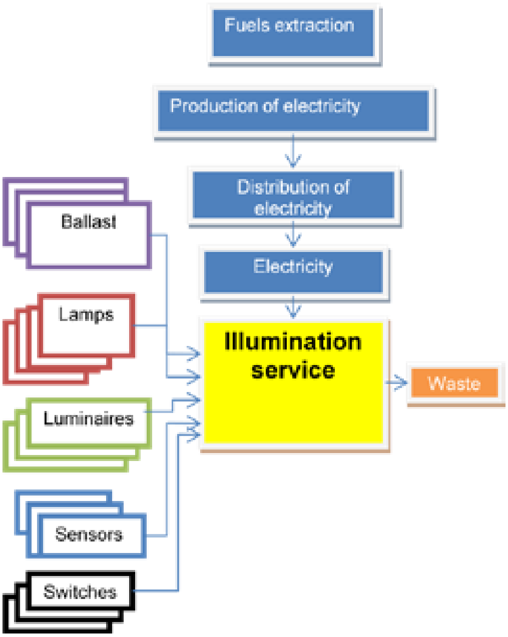



**Figure 3 Lighting product-service system. The system not only considers the lighting source but also all the other necessary inputs to deliver the whole lighting service.**

## 6. Efficiency challenges

When considering a lighting product-service system it is necessary to consider efficiency from three different perspectives. In general, efficiency is considered as the amount of input as a proportion of output. We focused on electricity, as it is one of the main inputs. Even if the system can convert 100% of electricity to light, it does not mean that all the light can be seen by the human eye. So, it is important to consider different types of efficiency (see Figure 4 and Box 1). Schubert defines three different kinds of efficiency: *internal quantum efficiency*, *external quantum efficiency,* and *power efficiency*.

However, although we can produce a certain number of photons in a given area, it is uncertain whether we can get them all out of the device. To know how much the output really is we need to look at the *external quantum efficiency* which measures how effective the process is, for example comparing the number of electrons that come into the system and the number of photons that one actually gets out of the device. The third category, *power efficiency*, tells us how much electrical power was needed to produce a given amount of optical power. This is useful in order to establish how much electrical power was lost in the process and how much electrical power one needs to produce one photon (Schubert 2007).

Although it is important to know how much optical power is available, it is also important to know how much the human eye can see from that light, since the human eye can only perceive certain frequencies of light. The *luminux flux* tells us how much visible light the human eye can really see. Thus, in order to measure how efficient a given source (the light source) is at producing light that the human eye can see, we need to measure it in terms of *luminous efficacy* (Schubert 2007).Traditionally, this sector has focused on analysing how much electricity we use per photon (external quantum efficiency) with a high luminous efficacy, so users can see the light or have a better lighting service (red circle, see Figure 4). This comparison is what Schubert (2007) calls *luminous efficacy.*

However, tendencies for continuing development indicate that the floor space area of an office will increase, and therefore so will the consumption of lighting devices. Increasing office space will result in an increased consumption of energy. Thus, from a technological point of view, the most relevant alternatives will be those with the potential to further increase luminous efficacy and which at the same time can reduce the consumption of electricity based on fossil fuel.

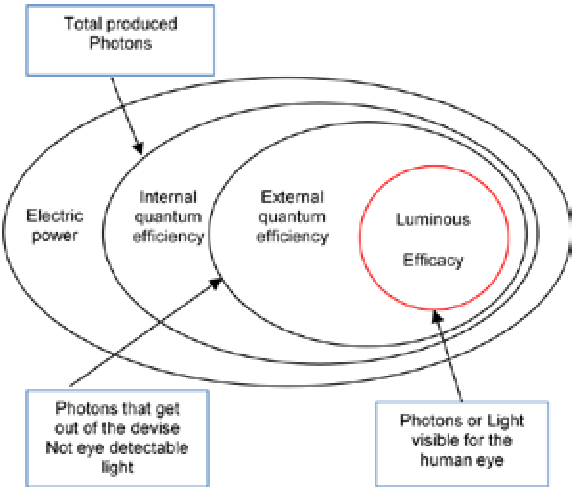



**Figure 4  Illumination service – different types of efficiencies**

During our research we established that one of the main technological limitations is set by the physical limits of increasing luminous efficacy with currently available technologies (fluorescent lights and LEDs). However, we saw the possibility of including technologies that could make use of renewable energy sources such as daylight in a more useful way than windows do at present. This was the result of looking at current consumption patterns or habits in the office lighting sector in Denmark. By doing this, we established that 38% of electricity used for lighting is used between 7 am and 5 pm (Elsparefonden 2010), a time when sunlight is available.

This finding suggested a variety of further technological possibilities, in particular those relating to direct light and/or solar energy. We saw the possibility of using hybrid lighting as one of the potential innovations. From the great variety of daylight transport systems, we chose to focus on fibre optical solar lighting systems. We initially wanted to test a hybrid system and compared the energy saving with a lighting system based on linear fluorescent lamps such as the one that is recommended as the best available technology by the EU Eco-design Preparatory Studies for office lighting, and the best available technology within LEDs. However, though we made an extensive search for this kind of product, there were few companies on the market advertising such systems. Moreover, when we contacted them, only Sunlight Direct Inc. responded, and told us that we could not have this product during the year of our test, 2009-2010. Not finding this product on the market, we proceeded to design and make our own prototype. This was done with the cooperation of the Technical University of Denmark (DTU Fotonik), designers from Kolding School of Design, and the assistance of IBSEN, an electrical installation contractor. To design our prototype we used a solar light transport system based on optical fibre from the company PARANS (note that the PARANS systems were not hybrid at the time that we conducted this project) and therefore we designed a system that could integrate electrical illumination (artificial light) in combination with natural light (daylight transported through fibres). For these purposes, an on/off switch system was designed and special hybrid lighting luminaires were also designed.

Although one of the main concerns in general is the question of what should replace incandescent lighting, especially when one looks at the domestic sector, the question has to be differently formulated for the office sector. In the office sector, there will be other challenges such as replacing the inefficient linear fluorescent lamps (LFLs). The problem here is that the limitation in relation to mercury content will set a very strong barrier to the further increase of luminous efficacy of LFLs and this will cause problems in fulfilling the Danish standard of providing 500 lumen per $m^2$ in working areas (DS 700:2005). Complying with the required Danish standard will mean a severe increase in electrical consumption and thereby potential disposal of mercury into the environment.

Recently, LED technology has been seen as the favourite to replace even LFLs. Although the EU preparatory studies for the eco-design directives for office lighting (Van Tichelen, et al. 2007) considered that LEDs were not yet ready due to the colour of the light emitted, lumens per watt and price. Further developments over the last three years have made it possible to consider this technology as a viable solution for the future in relation to colour rendering and temperature of the light. In relation to price, findings show that LED prices are still high compared to conventional devices.

## 7. Opportunities

It is important to bear in mind that the EU preparatory studies for the eco-design directives on office lighting (Van Tichelen, et al. 2007) pointed out that some of the main improvements in this sector can be achieved by including sensors, improving the maintenance level of the lighting system and, most importantly, by including natural daylight. These recommendations are important because the studies consider the whole lighting service and not only the lamp's life cycle. Therefore further opportunities beyond those relating to the lamps may exist.

These improvements consist not only of increasing the efficiency of the lamps but also of making the systems easier to maintain and clean, and of including sensors both for dimming the light, when there is more daylight available, and for detecting movement. By doing this, savings of between 50% and 80% of the total consumption of electricity may be achieved (Van Tichelen, et al. 2007 and Verhaar 2010).

Considering daylight, we can envisage further opportunities. One obvious possibility is the use of windows. Consequently some of the current responses to these challenges emphasise the use of more windows. However, recent studies show that when more windows are included the increased load on the heating or cooling systems increases the overall energy demand of the building (Asdrubali, et al. 2010).

In practice, the use of windows can result in additional use of electricity for lighting because the users close the blinds and turn on electrical light (see Pictures 1, 2 and 3). From left to right, the pictures show an office at a research institution, a commercial centre and a meeting room in a office building. The three pictures were taken when there was full sunshine outdoors during summer 2009 in different public spaces. Notice than in the three cases the artificial light is on.

**Pictures 1, 2 and 3 Consumers' habits using windows for lighting purposes**

The impact of constructing new buildings with more windows is relatively small as the number of new buildings represents a very small percentage of the whole building mass in Denmark. Although it is very important to construct new buildings in a more sustainable way, one of the biggest challenges in this sector is how to include more daylight in the existing private and public office buildings within the service sector without causing glare or increasing the heating or cooling loads inside the buildings, thereby worsening the environmental working conditions.

Therefore, we focused on light transport systems that were flexible and easy to install within existing typical buildings. These features were found in solar optical systems. Although light transport systems are already known, little attention has been paid to them. However, they provide interesting opportunities for future lighting system applications. Thus, in cooperation with a trans-disciplinary team, we designed a hybrid lighting system (see Figure 6). This was based on a commercial solar transport system from PARANS using commercial LEDs. Financial support for this work was obtained from the Danish Elforsk program.

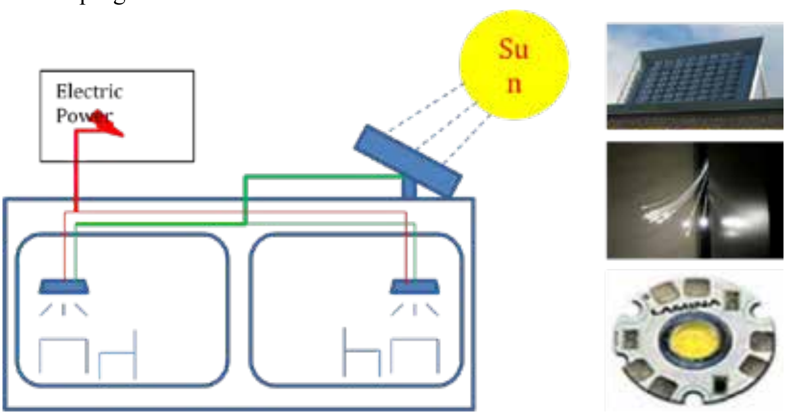



**Figure 5. Hybrid lighting system, at the right solar collector, optical fibres and LEDs.**

The main idea was to produce a hybrid lighting system using electric power and direct sunlight to provide a high quality and constantly reliable lighting service. Hybrid lighting systems are a combination of four technologies: collecting natural light, generating artificial light, transporting and distributing light to where it is needed, and controlling the amounts of both natural and artificial light continuously during usage. The overall idea is not new. The US Department of Energy (DOE), in collaboration with the Oak Ridge National Laboratory, has published a large number of articles pointing out the advantages of hybrid solar fibre optical systems in terms of energy savings. However, when we started this project in 2009, it was not possible to purchase a hybrid lighting system based on fibre optic technology. It was only possible to buy solar systems based on fibre optic technologies. When both systems are installed without an automatic switch they only add an extra cost and no energy savings are obtained.

The main principles behind designing a hybrid luminaire are:

- In order to harvest energy savings, electrical power is switched off automatically when the sun is shining with a sufficiently high intensity to provide a pleasant indoor light intensity.
- Electrical power is switched on automatically when it is dark or cloudy.
- The system can use a standard electricity supply either from renewable or non-renewable networks (smart grid) working even when it is overcast.

Designing and testing this hybrid system led us to some very interesting results. First of all, we calculated that considering all the inputs of energy and outputs in lumens for our three comparison cases - LFL, LEDs and LEDs/solar optical transport system (hybrid system) - the energy savings, and thereby the $CO_2$ savings, to be 59% as they are proportional to the energy savings as shown in Figure 7.

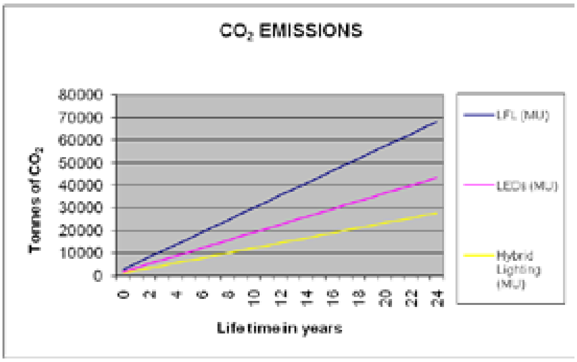



**Figure 6 $CO_2$ emissions for the three options for a Multiple User office (MU) using the DEEP's LCC tool (http://deep.iclei-europe.org).**

## 8. Consumer acceptance and price

According to Rogers (2003) the diffusion of innovation, or the rate at which the consumers will accept or reject an innovation, will depend of the communication channels used to communicate the benefits of the product or service. Although Rogers describes several types of communication channels, the interpersonal ones are of interest to us. He argues that often the most successful methods for the diffusion of innovation take place when an innovation has been conveyed to people by other individuals like themselves who have already adopted that innovation. Therefore, identifying the main stakeholders and consumers/users that will adopt this innovation is of central importance. As with any kind of environmental innovation, consumers' acceptance and price are decisive for any technology to be implemented (Kjær and Andersen 1993). According to Rogers (2003), not all innovations are equivalent in terms of analysis, and therefore it is important to identify the characteristics of innovation as perceived by individuals, as well as the type of individuals. As we have stated earlier, the main problem in relation to $CO_2$ emissions is in the trade and service sector therefore we focused on these individuals, identifying the main stakeholders and their perceived needs.

***Identification of decision makers***

One needs to identify who decides what lighting system should be bought to satisfy the demand for public buildings. When it comes to office lighting there are several stakeholders who influence the decision-making process about which type of technology should be adopted. In order to establish whose habits and established traditions had to be considered we needed to identify the role of these stakeholders clearly. For this specific study we identified: 1) regulators, 2) service providers, such as consultancy firms, lighting designers, architects, engineers and urban developers, 3) consumers, such as those who pay for the service and for whom the price will be important, and 4) users, such as employees who use the service but do not necessarily pay for it. For this last group the relative advantages of the innovation will be more important than the price.

***Price***

In order to assess the cost, we used DEEP's LCC tool (http://deep.iclei-europe.org). This tool was chosen for its simplicity to assess the total energy consumption both for the initial and future cost. It takes into account the costs, such as materials and installation, and evaluates them in terms of Net Present Value.

To calculate the Net Present Value we assumed a current discount rate of 3% (Denmark National Bank, 25 March 2010, ref. 2010-14E), an 'on-peak electricity tariff price escalator' of 3% as an average value for the different energy sources (Bolt, 2009) and a carbon factor of 0.801kg $CO_2$/kWh (DONG Energy, 2008). We further considered that the lifetime for the hybrid system will be 25 years, as the LEDs will be used less. The emission factor reported by the EU Commission is 0.041kg $CO_2$/kWh. However, we do not consider this value, as it is representative of an average of all kinds of energy sources (renewable and non-renewable). We chose to consider 0.801kg CO2/kWh, since it is more representative for the marginal energy produced by non-renewable sources. The comparison of the base cases is shown in Figure 9.

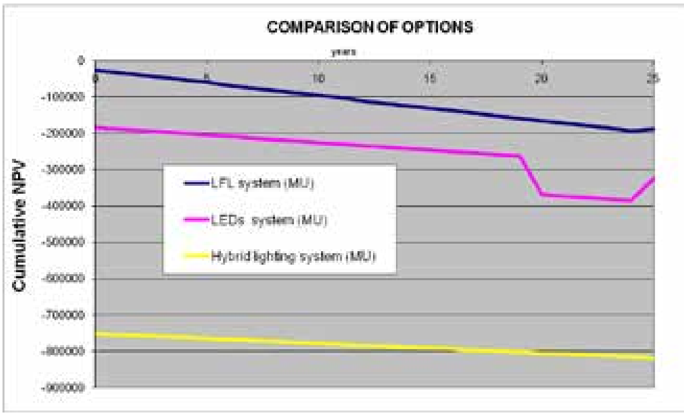



**Figure 7 Comparison of options in terms of Net Present Value.**

As can be seen from Figure 7, the main barrier for this design is the price of the system tested. The life cycle cost is almost eight times higher that the LFL system and four times higher than the LED system. Thus, even when the hybrid system is the best option for lower $CO_2$ emissions, the price will limit its implementation. Taking the whole life cycle of the hybrid systems into account, we assessed that the contributing factors to this barrier were complexity of the electronic system to drive the lenses in the solar collector system, the quantity of material used and the installation costs. Therefore, in order to improve the design of the solar collector system we suggested going back to the Eco-design single-issue approaches (Figure 2) and investigating the materials and manufacturing stages in this specific product. We recommend as well further research and development in this direction.

***Required innovation characteristics***

This requires looking at subjective preferences or properties in relation to function. In the case of values ascribed to lighting during the development of this research, we have learned from dialogue with key stakeholders, consumers and users that temperature of light (colour), spectral composition and noise (non-oscillating light), as well as aesthetic and prestige values are important characteristics that will cause Danish consumers and users to accept or reject an innovation. When looking at the material dimension, as a base of comparison, practitioners of the LCA suggest considering the service provided by the product as a functional unit (see Table 1). The functional unit, according to Wenzel and Caspersen, (1999) should be defined considering both the obligatory properties (tangible dimensions) and the positioning properties (intangible dimensions) of a product or a service.

The aim is to quantify the product or service with respect to volume and time, looking for potential improvements, in this case the lamp. Shostack (1977) suggested some time ago that in order to see possibilities that can reach the market, one should pass from being product-oriented to being service-oriented. This requires being able to see the tangible dimension (materials) but also to see the intangible dimension (characteristics of the service).

| **Obligatory properties** | **Positioning properties** |
| --- | --- |
| Supplying 500 lux to a working area in a typical Danish office | - Non-blinding effect<br>- Avoiding overheating<br>- Optimal spectral composition of light for a working space (colour and warmth of light)<br>- Aesthetic components of the room<br>- Reducing $CO_2$ emissions<br>- Indication of 'green responsibility' |

**Table 1  Functional unit**

Although LCA practitioners recognise the importance of the intangible dimension, the disadvantage of the LCA approach is that in practice the positioning properties are always defined by the designer or engineer (either working individually or in a team). Taking into account the stages model of the innovation-decision model we integrate users' practice and opinions into the re-design or re-invention process, as Rogers named it (Rogers, 2003). Rogers' point is that innovations are not invariant. On the contrary, they usually change as they are diffused (Rogers, 2003). The advantages of integrating this approach compared to that of the LCA is that including this approach helps to achieve a more effective consumer-oriented design in a very early stage of the design thereby improving the changes for a more effective implementation.

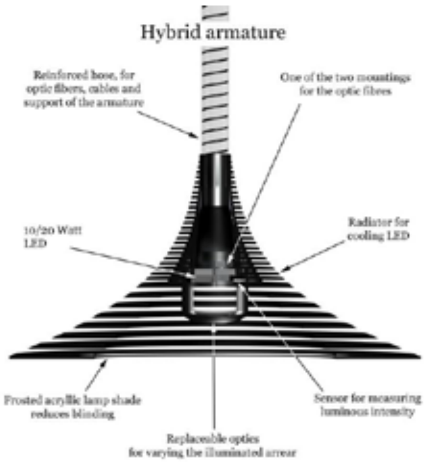
The importance of including users practice and opinion can be appreciated comparing Table 1 and Table 2. Table 1 shows the consideration that we as a design group made at the beginning of this project. Table 2 was completed after the user quantitative and qualitative test. One of the main issues when architects and lighting designers in particular discuss 'quality of light' is that the light should be warm and therefore as close to the light from incandescent lamps as possible. During the development of this study we met some architects who expressed their disappointment with the new regulations, since in their opinion; there was no satisfactory substitute for the incandescent lamp. To our surprise, when we asked users in the office sector, they stated that if the light were soft and warm they would fall asleep in their offices.

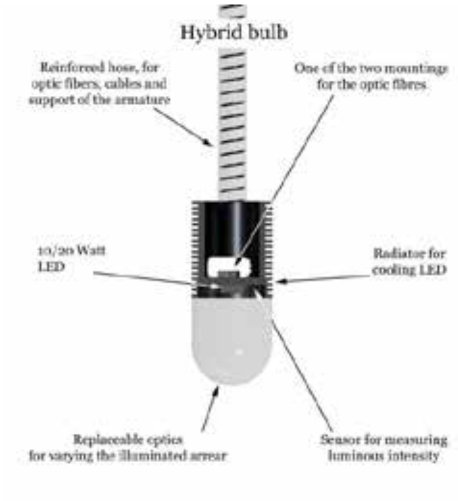
| **Obligatory properties** | **Positioning properties** |
|---|---|
| Supplying 500 lux to a working area in a typical Danish office | - It should be possible to read and write comfortably<br>- It should be possible to work at a computer without being affected by reflected light<br>- It should be possible to see peoples' faces while holding meetings<br>- The light has to be as close to daylight as possible (indirect sun light) both in colour and intensity<br>- Avoiding overheating<br>- Direction of lighting should be at a comfortable angle (no blinding)<br>- The lighting should be aesthetically pleasing<br>- Ability to be flexible (regulation of intensity)<br>- Reduce $CO_2$ emissions<br>- It should not contain mercury<br>- Indication of daylight usage ('green responsibility') |

**Table 2 Functional unit including users' practice and opinions.**

*Designing a hybrid lamp*

The contribution of our project partners from Kolding School of Design consisted of the design and construction of two prototypes of hybrid luminaires. One of them is an integrated, ready-to-install end solution (see Pictures 4 and 5). The other luminaire is an adaptable solution designed with the intention of giving consumers the option of bulb replacement in existing luminaires. This option offers the possibility of conserving classical luminaires that consumers value highly, for example famous Danish designed luminaires (see Picture 6). Light emitting diodes (LEDs) were selected in the design of both luminaires because these kinds of devices do not contain mercury and have a longer life span. From a technological point of view, LEDs are more flexible for use together with on/off switches when interacting with solar lighting, achieving real energy savings. They have the potential to become more effective in the future. Their intensity and colour of light is flexible, so they can be designed to fulfill consumer expectations. From an aesthetic point of view, their size and flexibility allows for many new forms and expressions. The lamps were designed with an automatic intelligent on/off switch that allows the change from natural light to artificial light by making use of two fibre optic bundles to provide the direct solar light. In this way, even when it is overcast, the lamps can deliver a constant and reliable light source at all times of the day. Besides these two lamps, design students from Kolding School of Design were invited to participate to learn more about this technology as they will be key stakeholders in the lighting sector in the future.




**Pictures 4, 5 and 6  From left to right: Armature suspension, hybrid armature and hybrid bulb.**

*Testing our first prototype at Roskilde University in one of the main buildings*

We conducted a user focus group. We installed the fibre optic solar collector system from PARANS and the hybrid luminaires that were designed during this project including those designed by the students. On the basis of our explorative qualitative interviews with user focus group, we formulated a questionnaire. The questionnaire worked as the document test for reading and writing tasks, and we provided a laptop computer for the use of respondents. The test group was composed of staff and student volunteers at Roskilde University who agreed to test the system. The system was set up in one of the rooms near the central cafeteria of Roskilde University (see Picture 7, 8, 9 and 10).

**Pictures 7, 8, 9 and 10  From left to right: installation of the solar collector, installation of the optical fibres, and installation of the luminaires and the layout of the room.**

***Suitability for the performance of office work***

From consumer feedback we concluded that there was broad acceptance that the service fulfilled user criteria. We also realised that older people required greater light intensity in order to read. Reading and writing using a computer seemed to be an improvement, even considering that the computer has its own light source. In relation to holding meetings, the lighting provided by the hybrid system was satisfactory since this activity does not necessarily require too much reading and writing. From these responses we concluded that, for general lighting purposes, the light intensity is acceptable but for work task areas, the system should provide the possibility of increasing the intensity according to the user's physiological demands.

***Light dynamics***

In relation to our test, 91% of the respondents had experienced lighting variations. This occurred, when the sky was overcast and when the sun started to shine again or vice versa. Nine percent of the respondents did not experience lighting variations. This might be because there was sunshine or an overcast sky during the entire period of the test.

There are some losses from the red part of the spectrum in relation to fibre optic lighting and this was observable in our test, since the designers used warm white LEDs. As indicated in our qualitative interviews, light dynamics were within the parameters that our focus group considered important. On further enquiry into whether they liked the light emitted by our system, the reasons given for this were that they found the light pleasant, that there is an indication of daylight, and that the light appears natural.
We learned that most people liked the light dynamics of the test system, especially those in the 20-30 and 30-40 age groups. The main reasons given were that they found it *pleasant* and *because it demonstrates the use of daylight*. This was a positive indicator as one of the positioning properties listed by the users suggested that light should have this value. From this, we can conclude that even when the light emitted by the optical fibres is a bit greenish, *it is not a big limitation* for the user to accept or like the system as it was tested. However, further product development and tests should be carried out to also reach population older than 50 years old. In order to have a fuller and broader acceptance from all types of user, the system should be as close to the natural light (daylight) spectrum as possible, considering the qualitative interviews, and this should be as important for the LED colour selection as for the light coming from the optical fibres.

*Temperature, colour and quality of light*
Taking into account the feedback below, our team is currently designing a series of new improvements that can better satisfy our test users in the future, as we are convinced that not only has the technology strong energy and $CO_2$ savings potential, but also strong consumer acceptance potential. One of the next steps is to make a more permanent installation so that not only end users, but also other decision makers can test systems like these. Further, our task also consists of improving the price in order to be competitive with current lighting systems.

***Light Temperature***
When the users were asked if they experienced warm or cold light, 71% of the interviewees answered that they had experienced more cold light. This might be due to the fact that the system was operating in full sunshine most of the time and the LED light took only part of the time.

***Colour of light***
In relation to the colour of the light, to our surprise, 67% of the users indicated that they experienced blue light. As we mentioned before, one of the characteristics of the PARANS solar system is that the spectrum of light is dominated by the green part. However, it is interesting to see that what users perceived as cold light is related to the colour blue.

***Blinding effect***
We allowed the respondents to mark more than one option in relation to the quality of light. When the respondents marked more than one option, we gave all responses the same

weight. 70.9% of respondents answered that the light did not blind them. This was a positive answer. However, we need to improve the design so that all the users are satisfied.

***Even distribution of light in the room***

It is important to remember that some of the lamps were prototypes developed in a five week project by students of Kolding School of Design and not commercial examples. These lamps were fragile, and although we asked the users not to touch them, many of the test users wanted to see the interior of the lamp, the LEDs, the optical fibres and the automatic switch. This showed that there is great excitement from consumers when using new types of lighting that emit natural light and which they are therefore not used to. Due to this, some of the lamps' electrical systems stopped working and were operating with only natural light, so when it was overcast only the remaining lamps worked and the room was only partially lit. It is not surprising that only 40.6% of the users thought that the light was distributed evenly within the room. From this we learned that our new prototypes have to be very robust to be able to satisfy users' curiosity.

***Influence of the armature design***

Both women (50%) and men (75%) stated that they had been influenced by the luminaire's design when considering their acceptance of this innovation. This means that we need to continue working on this area when we ask users to test the technology and we also need to improve the design for the final commercial product.

## 9. Conclusions

One of the main limitations to planning strategic implementation of eco-design and innovation within the clean technologies sector is the lack of broad holistic approaches. Existing approaches refer to isolated parameters such as function–cost or environmental issues such as energy efficiency and cost assessment. They also lack the inclusion and evaluation of characteristics of innovation as perceived by individuals. Not including a consumer-oriented approach might result in slow introduction to the market, or even implementation failure (rejection), which can be very expensive and increase uncertainty for potential investors or business developers. On the other hand, isolated consumer-oriented research may result in technological and environmental failures, as consumers often are not experts, nor are they aware of the many environmental challenges as they are very complex issues, and this may also result in innovation failure.

The main benefit of using our suggested framework is that at the same time as revealing the technological, environmental and cost improvements, it also leads to the possibility of innovative solutions and the opportunity of new business niches. The methodology also provides, in a simple way, a good overview of consumer needs and the opportunity to communicate the properties of a new product or service. It further provides the opportunity to receive feedback from the consumers' point of view in relation to the suggested innovation, and in this way includes the consumer in the process of redesign and diffusion from an early stage making it possible to plan the implementation more strategically.

The main limitation for hybrid optical fibre lighting systems is still their initial high cost. However, looking at the material and production processes, to redesign them could bring the price down and thereby make them more price-competitive during their life cycle. During the test phase, we have made some design suggestions. An exploratory consumer (user) test, even if not strongly scientifically based, provided us with a relevant and useful insight into the challenges and design potential of making this technology more acceptable to consumers and to see the product's potential to provide users with better quality lighting. At the same time, we foresee the potential for a great variety of aesthetic applications and, more importantly, a promising potential niche market.

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# Articles 1

# FUTURE ILLUMINATION SYSTEMS AND THE CLIMATE CHANGE CHALLENGE - THE CASE OF DANISH OFFICE LIGHTING

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## ABSTRACT

Higher eco-design requirements from the EU Directives and higher lighting standard requirements for working places open a new and challenging chapter of development for the illumination systems of the future. Electricity consumption due to illumination in offices in Europe will continue to rise due to the increasing number of offices and due to the new illumination standards. The total annual primary energy consumption of the European office lighting stock in 2005 was 281 PJ, of which 271.73 PJ was due to electricity use. It is estimated that office lighting generates 519 kton of non-hazardous (or landfill) waste and 7.2 kton hazardous (or incinerated) waste; 12.5 Mt $CO_2$-eq. greenhouse gas emissions; 73 kt $SO_2$-eq. acidifying gasses. It emits heavy metals in an amount of 5.7 ton Ni-eq. to air and 2.7 ton Hg to water.

This paper discusses the question: What kind of considerations should the photonic industry take into account when designing future low-carbon illumination systems to efficiently reduce the $CO_2$ emissions, when evaluating the possibilities for the future?

*Keywords*: Illumination, Life cycle approach, product-service systems, electricity consumption, low-carbon technologies and eco-innovation.

## 1. INTRODUCTION

Electricity consumption in the office sector is expected to increase about 85% from 2005 to 2020, and so will the emissions of $CO_2$ and other environmental impacts as they are related directly to the production of electricity. The achievements that are anticipated by implementing the best available technology - as suggested by the European Preparatory Study for eco-design requirements - will only reduce about 20% of that increment (Van Tichelen, B., et al, 2007).

Furthermore, the best available technology suggested to bring this reduction into reality is based on fluorescent lamps. Yet, the goal of reducing 20% of the $CO_2$ emissions by 2020 compared to 2005 levels are far from being reached within this sector. On one hand, increased energy efficiency can only contribute partially to meet the challenge and the goals suggested. On the other hand, Denmark has set as further goals that the share of renewable energy must be increased to at least 30% of the energy consumption by 2025 and that the energy consumption must not rise. Achieving these goals require the introduction of technologies that both are practical to include in connection with renewable energy and can make further energy savings possible.

Developing technologies that can contribute to the reduction of $CO_2$ emissions is a complex problem that has to be addressed from many angles. If we see the problem from a systemic point of view, we have to consider that providing an illumination service both comprehend the technological devises, we are using to provide that service, as well as we have to consider the way in which we are producing electricity. Furthermore, we have to consider the regimen and practices in this sector.

Unfortunately, getting rid of the incandescent lamps does not necessarily mean that we are going to solve the Green House Gas emissions from the illumination sector at once. To efficiently reduce the illumination ecological foot print requires that we determine where the most serious impacts are created and what kind of collateral impacts should be taken into account. Thus, we need to find systems that can both have a bigger potential of luminous efficacy than the fluorescent lamps in the future and as much as possible be able to reduce the consumption of fossil fuels, materials and chemicals.

However, even if we are good at finding the technological solutions, environmental innovations have the risk of not being competitive enough in relation to conventional technologies. The lack of competiveness might derive from weaknesses in the research, development and also from the commercialization phases.

## 2. METHODS

From the environmental point of view, we look at the entire life cycle of the possibilities or alternatives and assess, where the improvement potentials are. To do this, we used the Life Cycle Assessment results from the European Preparatory Studies for eco-design requirements in the office lighting sector. In this study, the selected alternatives were assessed in relation to energy consumption and their life time. Just recently OSRAM (November 2009) released a LCA comparing incandescent lamps vs. CFLs and LEDs. The results of this assessment are also taken into our analysis in order to see the environmental issues that need to be taken into consideration, if LEDs are considered as a feasible alternative. This is done with the intention to set the boundaries around the problematic areas and to identify where in the life cycle of the service strategic changes might be done. In other words, we aim to establish, where the best improvement potentials are to be found for further developing the illumination of the future.

### 2.1 Cases for the analyses

In order to make a feasibility analysis (finding the possibilities and directions for new technologies), we use some relevant examples or alternatives:

As a base line, we consider an illumination system based on Tri-phosphate fluorescent lamps. We consider this system, since it was suggested as the best available technology as a result of the Preparatory Studies for Eco-design Requirements of EuPs (Van Tichelen, B., et al, 2007).

We consider a system based on white Light Emitting Diodes (LEDs). LEDs were considered as best not yet available technology in the same studies, due to the number of lumen/W in the year 2006 (only 30 L/W). Today, however, only three years after, LEDs have reached an efficiency of at least 90 L/W.

To further achieve some energy savings in combination with LEDs, we consider optical solar lighting systems.

The main objective with this article is to establish a framework that allows us to design a new illumination system with a minor ecological footprint than the one offered by the current best available technology.

In order to find new technological alternatives, we formed a working group with professional designers from Designskolen Kolding, engineers from the Technical University of Denmark (DTU-Fotonik, Department of Photonics Engineering), envirironmental planers form Roskilde University and representatives of professional installation competences IBSEN ApS.

## 3. THEORETICAL CONSIDERATIONS

One of the first motivations to start this research was that currently Europe uses too much energy for illumination, and even banning the incandescent lamp, the electricity consumption will still rise. The other consideration is that we cannot continue increasing the consumption of electricity, because the levels of $CO_2$ are already surpassing the limits of a sustainable ecological footprint. When referring to a sustainable foot print, we are referring to the energy sources available to produce energy (fossil fuels) and the impact on the resources necessary to absorb their emissions and also to the materials and chemicals' impact on the environment (Wackernagel. M., 2005).

The rising electricity consumption is very problematic, since it is mainly based on fossil fuels, and, therefore, the production of $CO_2$ will increase as the consumption grows. For the same reason, we also have to consider that what we want is to reduce the $CO_2$ emissions at the same time as we increase the levels of services. Thus, what it is necessary to find out is how to maintain or even improve the service of illumination using less energy – and do this as much as possible free of the use of fossil fuels. Consequently, it is very important to find alternative technologies in the area of illumination that may cope with these conditions. According to the European Assessment for Energy using products (EuP) for the illumination sector, the best available technology today for the office sector is the tri-phosphate fluorescent lamp using electronic ballast. Even implementing this technology (which is considered as the best available technology) the consumption of electricity compared to what was used in 1990, will be using 25% more energy and producing 66% more emissions of persistent organic pollutants in 2020, while emitting almost 30% more $CO_2$ than in 1990 (Van Tichelen,P., et al., April, 2007). (Note that the different percent values are due to a changed relative distribution between the sources of power used in the electricity production).

### 3.1 Life cycle approach

I order to find an environmental solution to this problem in this sector, we need to find out in which process of the life cycle of the illumination technologies the biggest environmental impact occurs, and what kind of process should be improved to reduce those impacts.

Thus it is important to analyze this problem from a life cycle perspective, considering all the stages of the illumination service life cycle and not only the life cycle of the lamp. To achieve this objective, we need to make use of a tool that can detect and measure the main impacts caused by providing this service. A life cycle assessment is practical for this purpose, since it is both an approach and a tool to make a systemic analysis. Taking a systemic approach, The aim should be to find the direction in which the service might be improved on the material basis.

### 3.2 Efficiency

Efficiency has to be seen from three perspectives. In general, efficiency is considered as the amount of inputs in relation to the outputs. In relation to illumination systems, what it is important then is electricity, which is one of the inputs at which we will focus. Even if the system can convert 100% of electricity to light, it does not mean that all that light can be appreciated by the human eye. Here then, it is important to consider different types of efficiency (see Figure 1). Schubert defines three different kinds of efficiency: Internal quantum efficiency, the external quantum efficiency and the power efficiency

Even if we inside a given component can produce a certain number of photons, it is not sure that we can get them all out of the device. To know how much the output really is, we need to look at the external quantum efficiency, which measures how effective the process is, for example comparing the number of electrons that come into the system and the number of photons that one actually gets out of the device.

The third category: power efficiency, tells us how much electric power was needed to produce a given amount of optical power. This is useful to see, how much electric power was lost in the process, and finally, how much electric power one needs in order to produce one photon. (Schubert F., 2007: 86 and 87)

Though, it is important to know how much optical power one can get, it is also important to know how much a human eye can see from that light, since the human eye only can perceive certain frequencies of the light. The luminux flux tells us how much visible light the human eye can really see. Thus, in order to measure how efficient a given source is to produce light that the human eye can see, we need to measure it in terms of luminous efficacy (Schubert F., 2007:284-285)

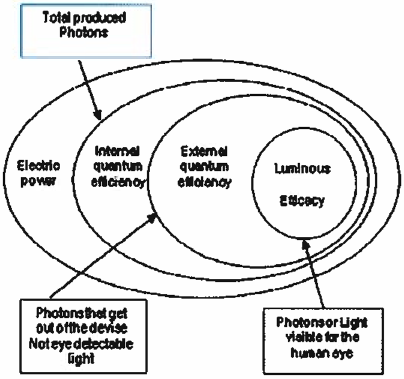


**Figure 1.** Different types of efficiency for illuminating devices.

What is interesting for our project then, is to analyze, how much electricity we use per photon (External quantum efficiency) with a high luminous efficacy (so the users can see the light, experience it as beeing pleasant, or in other words have a better service of illumination, red circle). This comparison is what Schubert (2007:284-285) calls Luminous efficacy. Thus, from the technology point of view, we will look at the most relevant alternatives with potential to further increase luminous efficacy.

Possibilities: beside the environmental point of view one should also consider, technological, social, and economic perspectives.

### 3.3 Technological possibilities

On one hand, one of the main constraints is the energy efficiency on which the $CO_2$ emissions depend. From this stand point, what it is important then is to determine, which of the technologies have more potential to improve the luminous efficacy. Here, the focus should be to reduce the energy consumption and losses, while we deliver the service. Thus, we have to consider that in order to have illumination, one part of the problem relies on the electronic devices performance, but the other part is how the electricity is produced.

As we already mentioned, from the environmental point of view, one needs to look at the entire life cycle of the possibilities or alternatives and assess where the improvement potentials are. By using this approach it becomes possible to analyze the selected alternatives in relation to energy consumption, material and resource consumption and the life time of separated products that form part of the whole illumination service.

The illumination service is an intersection of many outputs: illumination devises, cables, sensors luminaries, and electricity (See Figure 2)

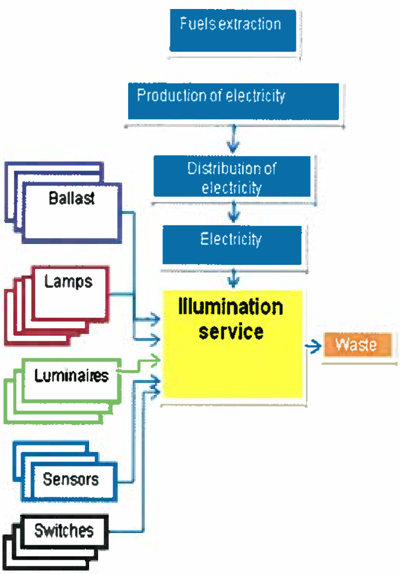


**Figure 2.** Illumination systems.

It is not only important to consider the service of illumination as exclusively the one provided by the lamp (the horizontal direction) it is also important to remember that the electricity is an essential part to provide the illumination service (vertical direction).

In relation to the lamps, we are critical to the suggestion that fluorescent lamps are the right solution due to the limitation from the RHoS and WEEE directives, since their luminous efficacy depends on the mercury content. As a matter of fact, these two directives will set a limit for fluorescent lamps efficacy development. However, LEDs are still in a stage, where further development can be achieved in questions of efficacy. Nevertheless, the task is not easy and many other aspects have to be addressed such as materials, resources or chemicals consumed. Therefore, when reducing $CO_2$ emissions, the other aspects need to be taken into account, so we achieve an overall reduction of $CO_2$.

### 3.4 Consumer acceptance and cost

On the other hand, even if we find some innovations that comply with the necessary environmental improvements, there are still two issues that need to be considered, since is not always for sure that those innovations will be accepted by the consumer and that they will reach the market. We, therefore, need to consider what will be the mechanisms that can help us in that process. To do this is not an easy task, since the other problem to consider is that the stake holders in this sector have a number of habits and long traditions of using systems based on fossil fuel and that environmental technologies are not always seen as sufficiently "profitable" compared to conventional technologies. Therefore, we need to identify the main possibilities for a strategic implementation also from a socio-economic angle.

The life cycle analysis can provide us here with the material status of the available technologies.

However, environmental improvements have not always the sufficient driving power to make stakeholders switch to the new technologies, since the patterns of production and consumption are very much constrained in the pre-established relationships between producers and stakeholders roles in our current society

Thus, what we need to consider here, is what kind of business opportunities have the future illumination systems with a minor ecological footprint to substitute conventional technologies. When looking at the material dimension, practitioners of the LCA suggest taking as a base of comparison the service provided by the product, hereby defining a functional unit (see Table 1).The aim is to quantify the product or service with respect to volume and time, looking for possibilities of change on the product, in this case the lamp. However, this definition is still product-oriented. From this, one derives solutions that mainly focus on the materials and energy. Having the focus on either the life cycle of the lamp or in the life cycle of the electricity.

The functional unit according to Wenzel and Caspersen, (1999) should be defined considering both, the obligatory properties and the positioning properties. However, when it comes to the real life practice, the obligatory properties are the ones that define the functional unit since, as the definition of ISO points out, it has to be quantified. The functional unit is defined as the quantifying performance of a product system for use as a reference unit, (ISO 14044, 2006).

**Table 1.** Functional unit. Adapted from Wenzel and Caspersen (1999).

| Obligatory properties | Positioning properties |
|---|---|
| Supplying 500 lumens to a working area in typical Danish office | - Not blinding effect<br>- Avoiding overheat<br>- Optimal spectral composition of light for a working space (colour of light)<br>- Esthetical component of the room<br>- Flexibility possibilities (regulation of intensity)<br>• *-Reducing $CO_2$ emissions*<br>• *- Indication of "green responsibility"* |

When analyzing the possibilities for future illumination systems, it is important taking into account parameters such as efficiency but also parameters such as colour temperature, spectral composition and noise (non oscillating light) from the new alternatives. It can be argued, that it is also possible to quantify these, however, our point here is, that they are properties that are in relation to consumer's preferences and depend of the consumer's perceptions. These being subject-related, it is very difficult to quantify these as material bases, and they are often left aside of the analysis. In Table 1, we differentiate the Obligatory properties from the Positioning properties of an illumination system.

One way of providing more focus on the new positioning properties and one way of considering with the same weight the relevant illumination devises in conjunction with the electricity consumption and production is using the concept of Product-Service Systems suggested by UNEP (2000). A Product-Service systems, can be defined as the result of an innovation strategy, shifting the business focus from the design and selling physical products only, to selling a system of products and services, which are jointly capable of fulfilling specific client demands. (UNEP, 2000:4) While the responsibility under a Life cycle perspective lays on the design phase or on the production phase, the Product-Service Systems perspective seeks to distribute the responsibility through the entire production chain given an equal weight to the consumption phase.

In this way, the focus is not on selling separate products, but "selling the utility, through a mix of products and services, while fulfilling at the same client demands with less environmental impact" (UNEP, 2000: 3).

In order to narrow down to our study object, we will see to what extent LEDs and perhaps an addition of solar optical fibre illumination can contribute to enhance the possibilities of providing an integrated functional solution to meet the client demands.

Efficiently reducing ecological footprint: In our research it is considered with a twofold perspective. On one side we look at this from a footprint perspective: fewer hazardous materials and less resource consumption. With resource consumption beside materials, we also refer in high degree to the reduction of fossil fuels. On the other side, they have to be cost-competitive and provide a competitive service. This from an eco-innovation perspective can be achieved with the process of optimization of resources and thereby reducing the costs (Lovins, 2008).

According to Huber (2003) it is important to consider other parameters than technological ones to provide realistic solutions. Thus, from the socioeconomic side, one of the parameters in the past to select Edison's lamps was the number of watts that the lamps used. As a matter of fact, it is not about buying watts, what it is about is buying a certain number of lumens, with a very high quality and colour of light defined by the consumer side. History has shown us that even when florescent lamps have been accessible for a long time, they had a very hard time in getting accepted by the consumer, and still there are many consumers that do not like this technology. Therefore, it is not only a question of researching and finding new ways of illumination for our surroundings, but it is important to consider, what will it take for the consumers to adopt or accept the new technologies focusing in an new definition of the final service utility. Therefore, some of our main considerations, when it comes to social and economic parts are: the service and how do we provide that service, so we can design or re-design the future alternatives.

One of the interesting possibilities to consider with respect to future office illumination systems is the fact that most office spaces are used during daytime, which means that there actually often are plenty of daylight outside. It is actually many times so much that the office space has to be shielded behind curtains in order to allow for the working tasks to be performed. This points to the possibility that one could aim to apply some kind of solar collector, which either could produce electricity for use inside the offices, or one could use fiber illumination systems to move the sunlight into darker areas of the office buildings. With regard to the first, it is relevant to have in mind that photo-voltaic collectors and modem LED based illumination preferably could work on a separate low-voltage system.

Concerning the fiber illumination systems, it is highly relevant to point to the challenges that the fibers cannot be installed just in the same manner as normal electric wires (the fibers may not be bend so hard as electric cables). Furthermore, the fiber loss has to be considered. In order to illustrate this, we have performed a characterisation of a commercially available fiber illumination system including 20 meter long (polymer) fiber bundles to transport the collected sunlight.

Measurements were performed outside during sunny summer days in Denmark. Results are illustrated in the chromaticity diagram, shown in Figure 3, where the reference point (Ref) corresponds to the light coming from the sun and the point Test corresponds to the light coming from the fiber bundle output. The chromatic distance (DC) of the light coming from the fibers is 31.10-3, which is far above the limit of 5.4.10-3 given by the International Commission on Illumination (CIE). This observed “decolouration” is one of the challenges that future fiber illumination systems have to find solutions to.

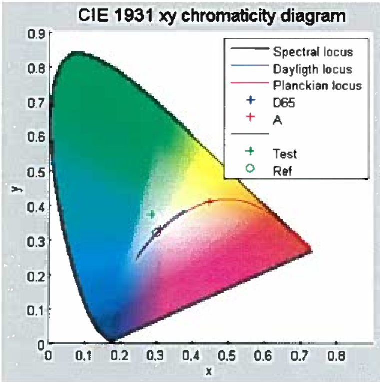


**Figure 3.** Chromaticity diagram measured on a commercially available fiber illumination system.

Other of the parameters for a selection of lamps beside the qualitative ones is the price. Considering the whole system one should consider then the entire price of the service and not only the price of the bulb. Therefore, technologies that present the highest potential of energy saving will have to be economically viable in the entire life cycle. Thus, we will consider the concept of total economy, which is related also to a systemic approach, since it considers not only the price of the lamp, but also the price of the whole service along the entire life cycle.

Regimens and practices

When talking about regimes and practices, one of the basic issues is the way in which the people will accept the new technology or the new service. Here it is, according to Rogers (2003), important to predict the reactions of people to an innovation. Not only making a differentiation of type of adopters, but also considering beliefs and past experiences of potential adopters. One of those experiences in relation to illumination devises, have been the colour of the light and the intensity of the light, and, therefore, setting LEDs on the market with lower performance than expected by consumers might give the consumers a negative experience, and the reaction will be not to trust those devises anymore (or at least for a very long time). Therefore, it is important to find out what can make the innovations in the new service or devises more acceptable for the consumers, and how to ensure a proper diffusion of the innovation.

We further consider that innovation is an iterative process, where it is necessary sometimes to take the already existing knowledge and technology as stand point and look for further improvement both based on what we know and/or in something completely new (Andersen P.D., et al, 2006). For example with LEDs, one can see that the technology have been there for some time - especially for the car industry and decoration purposes. However, it is just recently that their development in direction towards, TVs., Computer screens and general illumination systems have taken place, especially with the white LEDs - the last one being just a few years old. Therefore, one has to consider that LEDs for general illumination are still in the first or perhaps second stage of their technological development curve (see Figure 4), which represent still big opportunities for further applications.

The support refers to the political and regulations framework that can make it possible for the innovations to reach the market. Here, it is important to consider all the phases in the research and development of the innovation curve (see Figure 4), in the implementation of new ideas, or in its commercialization. Different to the linear and traditional approach of innovation, where research is only thought in connection with completely new ideas or in the beginning of the invention; We consider that, research should be pursued in all the phases and, therefore, differentiated forms of support should be pursued for each of the phases.

It is important to consider as well, that the implementation of new technologies will require adequate relationships and conditions that facilitate their fast and broad dissemination. To each of the phases of the diffusion of innovation different institutions are attached. Finding the corresponding institution network can enhance the possibilities to make the diffusion more effective (Kjær T., and Andersen J., 1993). Therefore, it is important to find out what the current Danish scientific and research base is for the illumination sector (research and development institutions as well as sector networks).

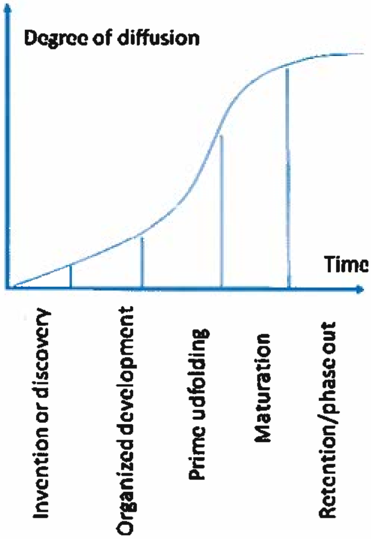


**Figure 4.** Innovation phases or innovation life cycle (Huber 2003). One can say that white LEDs are still in the stage of organized development or prime unfolding phase.

Though getting the product to the market is traditionally a process thought of as an exclusive job for the industry, environmental-innovation theories (Andersen et al., 2006) suggest that research, development and demonstration is not enough to support completely new technologies to a competitive level in the commercial market. Therefore, market oriented policy instruments should support this phase. The reason for improving the policy instruments for environmental technologies is, (different to other technologies), that environmental technologies are highly capital-intensive and this makes investment to seem less attractive for the venture capitals. Extending the span of life of the products (for example) will mean investments with long time horizons even less attractive. Nevertheless, it could be a good “business” for the governments. Though the investment return is not measured in money, it could be capitalized in cleaner environment and security of energy supply (Andersen et al., 2006:25), which are very important in order to reach the climate goals and energy sufficiency. Furthermore, besides solving the climate and energy problems, there is also the potential to create jobs and development in the region, spreading the benefits to all other sectors functioning as engine of economic development. Thus, finding the policy instruments necessary to support the environmental innovations still can represent a win-win situation for the governments, since this support could attract more venture capital into the region strengthening the entire cluster competition.

## CONCLUSIONS

One important point when designing low-carbon technologies with a minor ecological footprint is considering the best available technologies in terms of a life cycle perspective. This in relation to the photonic sector can be supported by regulations and studies made by the Eco-design directives or from relevant lifecycle assessments.

It is important as well to rethink the functional unit both in its product-oriented dimension (material dimension), but giving the same weight other relevant intersecting products that together provide the final utility. This perspective may allow seeing the possibilities that might not be directly measurable but are intrinsic to the new function(s) in the technological development of low carbon technologies and their potential business opportunities.

It is highly important to consider the consumer demands focusing in the right sector to be able to deliver a competitive service both in terms of quality and price.

The high level of competitiveness on the market will be the same if compared with conventional technologies. Therefore, when designing eco-innovations one has to be able to identify the potential market or policy instruments that can support the innovation through all the innovation phases until the product or service can reach the market.

The success of such strategy is complex and requires a close cooperation from trans-disciplinary fields, but if this point is achieved it could be one of the possibilities in itself.

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# Articles 2

# Possibilities and Challenges designing low-carbon-energy technologies - The case of the lighting sector

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***Abstract:*** *Though there is broad consensus that one of the solutions to the current environmental challenge will be based on the use of low-carbon technologies, and even though there is a big potential to turn to a more sustainable design and innovation, there are several elements that need to be taken into account to be able to achieve efficient reductions of energy and $CO_2$ emissions and at the same time design a product attractive for the consumer, in terms of price, level of service and aesthetical demands, to ensure its strategic implementation. This paper takes the Danish office lighting sector as a study object and discusses the question: What are the main possibilities and challenges when designing low-carbon illumination technologies?*

*To answer this question, we use a systemic approach including environmental, economic, energy and political issues using relevant concepts from the Ecological Footprint, concepts and tools from Life Cycle Assessment, and relevant elements from eco-efficiency theoretical frameworks. Often systemic approaches tend to be driven by completely rational models. However, our main contribution is to consider a more holistic approach that also includes socio-psychological aspects such as consumers' demands (aesthetic disposition, habits and different light tastes and needs). This is done by integrating relevant elements from eco-innovation and Service –Product System frameworks. Our empirical material is based on iterative interviews with relevant actors and experts within the Danish illumination sector and a consumer (user) research that included qualitative interviews and a quantitative survey. Furthermore, as a central part, our research included the design, fabrication and test of a new hybrid illumination system based on optical fibres and Light Emitting Diodes (LEDs) with the cooperation of a trans-disciplinary team.*

***Keywords:*** *Day light, Low-carbon Technologies, Consumer oriented design, holistic design, hybrid lighting, light transport systems*

## 1. Introduction

The total electricity consumption across the EU-27 countries showed an absolute increase of 28.7% between the years 1990 and 2005. The average electricity use per capita in the EU-27 is almost 2.5 times the global average. Total world consumption of marketed energy is projected to increase by 44% from 2006 to 2030 (EIA, 2010). These growing tendencies for electricity consumption still take place despite the emergence of almost countless numbers of energy saving devises. The production and consumption of electronic devises is at the same time growing at high speed. The amount of resources to follow up this consumption and production at a global scale is leaving a huge ecological footprint, and EU has an important share of this. The European Commission decision about banning the incandescent lamps has opened for a huge debate on whether we had a technology ready to take the place of the Edison bulb in terms of price and light quality.

One of the main constrains about banning incandescent lamps is that the world cannot continue increasing the consumption of electricity, because the levels of $CO_2$ are already surpassing the limits of a sustainable ecological footprint. When referring to a sustainable footprint, we are referring to the energy sources available to produce energy (today primarily fossil fuels) and the impact on the resources necessary to absorb their emissions and also to the materials and chemicals' impact on the environment (Wackernagel. M., 2005).

## 2. Methods

We have as stand point a problem-oriented design and innovation approach, which opens for three different possibilities:

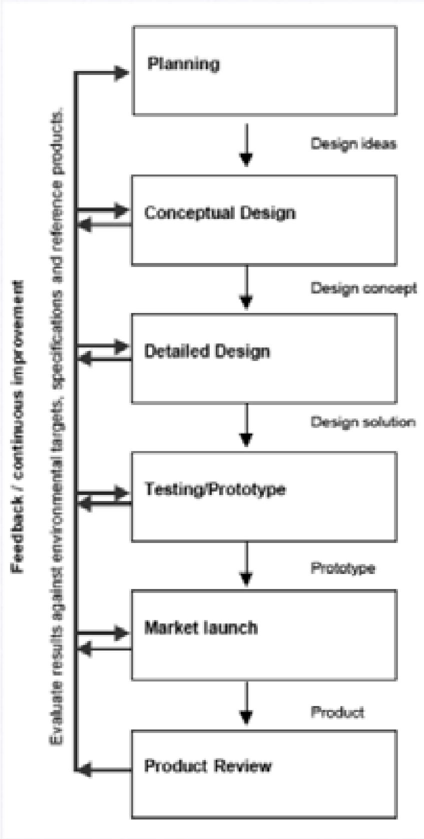
1. We take a holistic approach that ensures a relevant innovation avoiding partial solutions using a systemic approach.
2. We pursue a combination of the technological and the social solutions, where all the aspects of the production chain are considered, though we narrow our solutions to the most problematic stages. Even when this approach has its basis on the technological system, we take it further to the implication of the social aspects, so the new technology can be implemented, and;
3. We try to obtain a synergy between the eco-design and system design, by pursuing several benefits: such as reducing climate impacts, reduction of energy based on fossil fuels in combination to socio-economic aspects such as local business development.

Our conceptualization of design is a combination between product design and system design. For example:

- Using Eco-design (ISO 1462) or design for the environment as shown in Figure 1, taking as a stand point the life cycle or the production chain as precondition for the new design,
- Using a System-Design, the design takes into consideration the intersection of combined production chains to pursue an optimal advantage or effect, for example switching the focus from being only product oriented to also being service oriented. In this case, it is not only the effect of the lamp but all the other inputs that are also relevant in order to deliver the illumination service, for example, electricity and how it is produced, and,
- Using the design concept from Eco-innovation - derived from the EU's program (COM(2009) 519), which seeks a combination of the two previous conceptualizations.

Our empirical material was based on iterative interviews with relevant actors and experts within the Danish illumination sector. Furthermore, as a central part, our research included the design, fabrication and test of a new hybrid illumination system based on optical fibres and Light Emitting Diodes (LEDs) (Elforsk Projekt nr. 341-043) with the cooperation of a trans-disciplinary team. This prototype was tested with our consumer (user) research.

The total life cycle cost of the three systems was calculated using DEEP's LCC tool (http://deep.iclei-europe.org). This tool was chosen for its simplicity to assess the total energy consumption both for the initial and future cost.




The system was installed in one of the main buildings at Roskilde University. We also designed a consumer test based on qualitative interviews in order to identify the most important functions and qualitative parameters that an ideal illumination system should have to be accepted by the consumer from the own users point of view in the office sector (ten face-to-face random in-depth interviews with university staff were carried out). The most important factors form the qualitative interviews were then used to design a consumer quantitative test letting volunteers from university staff test our system (a total of 35 persons). We most stress that the test was designed to explore further considerations to support our design decisions rather than making a scientific statistical research. Thus, the results of the test have been used to further re-design and develop new hybrid lighting systems from which three new patents are in process of registration.

***Figure 1;*** *Eco-design, life cycle framework (source. Adapted from ISO 1462)*

## 3. Tackling the climate and energy challenge

Rising electricity consumption in the illumination sector is very problematic, since the production of electricity in most countries is mainly based on fossil fuels, and, therefore, the production of $CO_2$ will increase as the consumption grows. Furthermore, the increasing urbanization process in the world is demanding more illumination services and the levels of illumination services in industrialized countries are still too low compared with the current standards and demands of the consumers. Thus the main challenge is to reduce the $CO_2$ emissions, considering that the consumers will not accept to reduce the quality of the service (this might explain why even when there are energy-saving alternative bulbs available, the electricity due to illumination is still growing). On one hand it is necessary to design technologies that maintain or even improve the service of illumination using less energy – or using less energy based on fossil fuels. On the other hand - and maybe even more important - will it be to ensure the consumer and user acceptance. With an effective implementation we mean completing the innovation cycle: from designing a new product or service and ensuring all its way to the market.

According to the European Assessment for Energy-using Products (EuP) for the illumination sector, the best available technology today for the office sector is the tri-phosphate fluorescent lamp using electronic ballast. However, even implementing this technology (which is considered as the best available technology) the consumption of electricity compared to what was used in 1990, will be requiring *25%* more energy and producing *66% more* emissions of persistent organic pollutants in 2020, while emitting almost *30%* more $CO_2$ than in 1990 (Van Tichelen,P., et al., April, 2007). (*Note that the different percent values are due to a changed relative distribution between the sources of power used in the electricity production*).

## 4. Environmental impacts in the life cycle

In order to find an environmental solution to the energy consumption problem in this sector, we needed to determine in which process of the life cycle of the illumination technologies the biggest environmental impact occurred, and what kind of process should be improved to reduce those impacts.

Thus, we chose to analyze this problem from a life cycle perspective. To achieve this objective, we made use of latest life cycle assessments that had detected and measured the main impacts caused by incandescent, fluorescent and LED lamps in Europe (Van Tichelen,P., et al., April, 2007 and OSRAM, November 2009). These assessments were important to find the stages, where we needed to make a new design. The biggest environmental impacts showed to be in the use phase. This helped us to focus on the specific efforts and eco-design demands in this specific stage, see Figure 2.

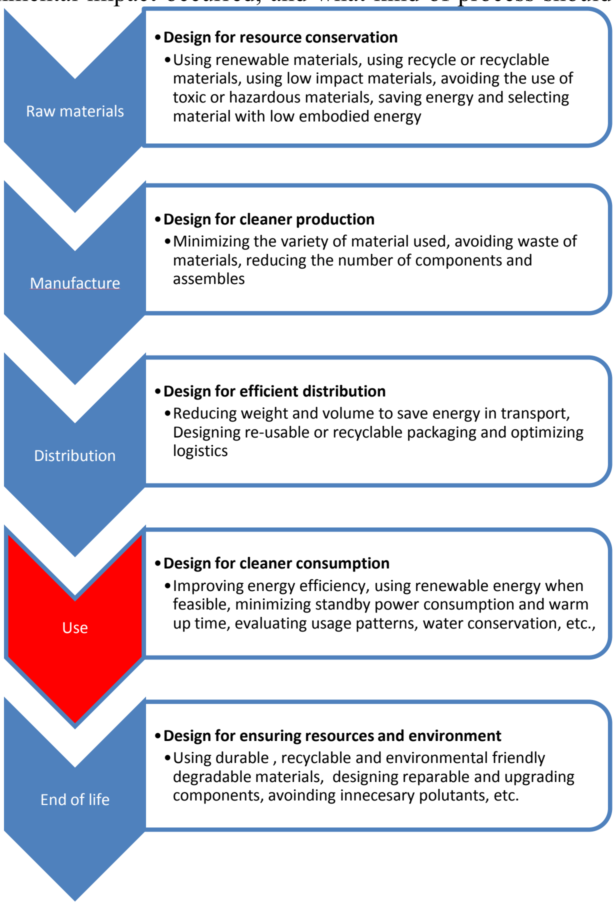



***Figure 2;*** *Eco-design single issue approaches. (Source: Adapted from Coles, R. 2002)*

## 5. Improvement potentials in the product-service system

One of the main tendencies in the illumination industry has been improving the energy efficiency in the lamps, having the most representative technologies to be: linear florescent lamps (LFLs), and lately the light emitting diodes (LEDs). Looking at the Product-Service System we realized that electricity consumption in the use phase is actually causing the biggest environmental impact, when delivering the service of illumination. A Product-Service System can be defined as the result of an innovation strategy, shifting the business focus from the design and selling physical products only, to selling a system of products and services, which are jointly capable of fulfilling specific client demands (UNEP, 2002:4).

Using this approach we realized that one of the main limitations for further improvements in relation to the environmental impacts is that this sector is mainly focusing on the lamps efficiency, but it is still ignoring the importance of looking at the entire Product-service system, and thereby providing solution to improve the overall illumination service. Using a systemic approach, we noticed that the most important environmental load was due to the consumption of electricity especially when this is produced mainly by fossil fuels, so it became our objective to analyse how to reduce the energy consumption and losses, while delivering the *service*. Accordingly, we considered that in order to provide illumination, one part of the problem relied on the electronic device performance, but the other part on how the electricity is produced, see Figure: 3.

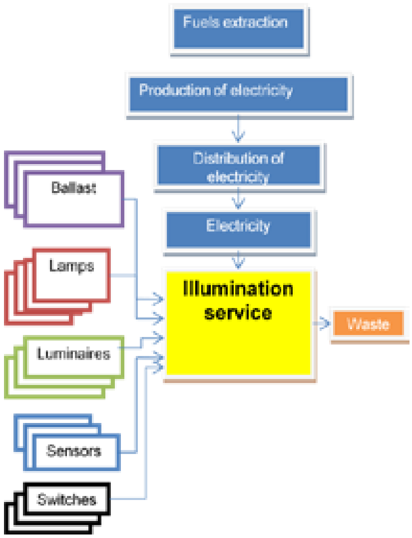



***Figure 3**: Illumination Product-service system.It considers not only the lamp but also all the other necessary inputs to deliver the whole service of illumination*

## 6. Efficiency challenges

Considering an illumination product-service system makes it necessary to see efficiency under three different perspectives. In general, efficiency is considered as the amount of inputs in relation to the outputs. As electricity is being one of the main inputs, we focused on it. Even if the system can convert 100% of electricity to light, it does not mean that all that light can be appreciated by the human eye. So, it is important to consider different types of efficiency (see Figure 4 and Box 1). Schubert defines three different kinds of efficiency: *Internal quantum efficiency*, *the external quantum efficiency,* and the *power efficiency*.

However, though we in a given area can produce a certain number of photons, it is not sure that we can get them all out of the device. To know how much the output really is, we need to look at the *external quantum efficiency,* which measures how effective the process is, for example comparing the number of electrons that come into the system and the number of photons that one actually gets out of the device. The third category: *power efficiency*, tells us how much electric power was needed to produce a given amount of optical power. This is useful to see, how much electric power was lost in the process, and finally, how much electric power one needs to produce one photon. (Schubert E. F., 2007: 86 and 87).

Though, it is important to know how much optical power one can get, it is also important to know how much a human eye can see from that light, since the human eye only can perceive certain frequencies of the light. The *luminux flux* tells us how much visible light the human eye can really see. Thus, in order to measure how efficient a given source (the lamp) is to produce light that the human eye can see, we need to measure it in terms of *luminous efficacy* (Schubert E.F., 2007:284-285).

Traditionally, this sector has focused on analysing, how much electricity we use per photon (External quantum efficiency) with a high luminous efficacy (so the users can see the light or have a better service of illumination, red circle). This comparison is what Schubert (2007:284-285) calls *Luminous efficacy.*

However, development tendencies show that the number of office square meters will increase, and, thereby, the consumption of illumination devises. Increasing the office space will result in an increased consumption of energy.
Thus, from the technology point of view, the most relevant alternatives will be those with potential to further increase luminous efficacy, and at the same time can reduce the consumption of electricity.

***Box.1***

***The internal quantum efficiency*** **refers mainly to the input of electrons compared to the number of photons produced in a given area**

*The external quantum efficiency,* measures how effective the process is, for example comparing the number of electrons that come into the system and the number of photons that one actually gets out of the device.

*Power efficiency* tells us how much electric power was needed to produce a given amount of optical power.

*The luminous efficacy* measures how efficient a given source is to produce light that the human eye can see

Schubert E. F., 2007

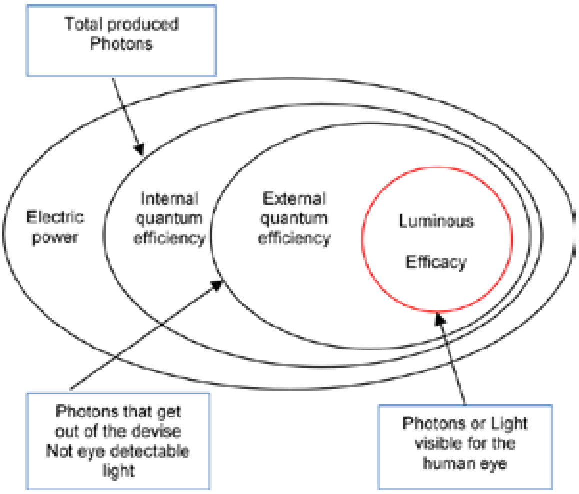



***Figure 4*** *Illumination service – the different types of efficiencies*

During our research we could establish that one of the main technological limitations is set by physical limits to increase the luminous efficacy with the current available technologies (Fluorescent lamps and LEDs) but on the other hand, we saw the possibility of including technologies that could make use of renewable sources of energy such as day light in a more useful way than windows do at the present. This was the result of looking at current consumption patterns in the office illumination sector in Denmark. By doing this, we could establish that 38% of the electricity due to illumination is used from 7 am. to 5 pm. when there is sunlight available.

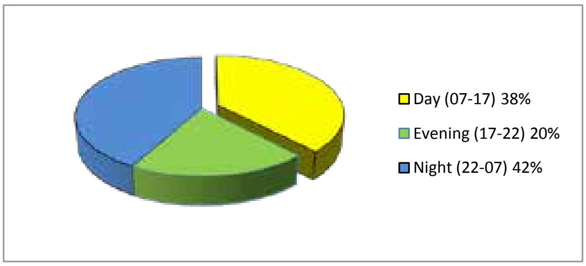



***Figure 5:*** *Annual average consumption of electricity for lighting. 133 work places are considered for this average in Denmark. Source: Elsparefonden*

This opened for a variety of further technological possibilities especially those contributing with direct light and/or solar energy. In other words, we saw the possibility of using hybrid lighting as one of the potential innovations. From the great variety of daylight transport systems, we chose to focus on fibre optical solar systems. We initially wanted to test a *hybrid system* and compared the energy saving with an illumination system based on linear fluorescent lamps as the one, recommended as the best available technology by the EU Eco-design Preparatory Studies for office lighting, and the best available technology within LEDs. However, though we made an extensive search for this kind of products, there were few companies on the market making an advertising of such systems. Moreover, when we contacted them, only Sunlight Direct Inc. answered, and we were told that we could not have this product during the year of our test, 2009-2010. Not finding this product on the market, we proceeded to design and make our own prototype. This was done with the cooperation of the Technical University of Denmark (DTU Fotonik), designers from

DesignSkolen Kolding, and the assistance of IBSEN – Electrician installation contractor company. To design our prototype, we used a solar light transport system based on optical fibre from the company PARANS (notice that the PARANS systems are not hybrid), and therefore, we designed a system that could integrate both electric illumination (artificial light) in combination with natural light (daylight transported through fibres). For these purposes, a switch on/off system was designed and special hybrid lighting luminaries were designed as well.
Though one of the main concerns in general is the question of what should replace the incandescent lamps, especially when one looks at the household sector, the question has to be differently formulated for the office sector. In the office sectors, there will be other challenges. Here the question is what will replace the inefficient linear fluorescent lamps (LFLs). The problem here is that the limitation in relation to mercury content will set a very strong barrier to further increase the luminous efficacy of LFL, and this will cause problems fulfilling the Danish standards of providing 500 lumen per $m^2$ in working areas(DS 700:2005). Living up to the required Danish standards will just mean a severe increase of electricity consumption and thereby potential disposal of mercury in to the environment.
Lately, the LED technology has been pointed out as the favourite to replace even LFLs. Though the EU preparatory studies for the eco-design directives for office lighting (Van Tichelen,P., et al., April, 2007) considered that LEDs were not ready yet in relation to colour of the light, lumens per watt and price, the further developments over the last three years has made it possible to consider this technology as viable solution for the future in relation to colour rendering and temperature of the light. In relation to price, the tendencies show that LEDs prices are still high compared with conventional devises.

## 7. Possibilities

It is very important to consider that the EU preparatory studies for the eco-design directives for office lighting (Van Tichelen,P., et al., April, 2007) pointed out, that some of the main possibilities in this sector can be achieved by including better sensors, improving the level of maintenance of the illumination system and most importantly including natural day light. What is important from this recommendation is that, exactly because this EU preparatory study consider the whole illumination service and not only the lamp' life cycle, it made it possible to see further possibilities beyond those of the lamps.
These possibilities consist not only of increasing the efficiency of the lamps, but also of making the systems easier to maintain clean, include more sensors both for dimming the light, when there is more day light available and for detecting movement. By doing this, savings between 50% and 80% of the total electricity consumption may be achieved (Van Tichelen,P., et al., April, 2007 and Verhaar, H., March, 2010).

Considering the day light, we can envision further possibilities. One very well known possibility is the use of windows. Some of the current responses to these challenges had been emphasising on the use of more windows, however, recent studies show that when including more windows, the load of heat or cooling increases the overall energy demand of the buildings heating and air-condition systems (Asdrubali,F., *et al*, March 2010: 260).
In practice, the use of windows results in additional electricity use for lighting, because the users blind the windows and turn on electrical light (see Pictures 1, 2 and 3).

***Pictures 1, 2 and 3***: *From left to right the pictures show a classroom at a university, an office in a research institution and a meeting room in a county building. The three pictures were taken when there was full sunshine outdoors during summer 2009 in different public spaces. Notice than in the three cases the artificial light is on*!

Furthermore, the impact of constructing new buildings with more windows is relative small as the number of new buildings represents a very small percentage of the whole building mass in Denmark. Though it is very important to construct new buildings in a more sustainable way, one of the biggest challenges in this sector is how to include more daylight in the already existing private and public office buildings in the service sector without glaring or increasing the heat or cooling loads inside the buildings worsening the environmental working conditions.

Therefore, we focused on light transport systems that were flexible, and easy to install in already existing typical buildings. We found these possibilities in solar optical systems. Though light transport systems are already known, little attention has been paid to them; however, they can open very interesting possibilities for future illumination system applications. Thus in cooperation with a trans-disciplinary team we designed a hybrid illumination system (see Figure 6). This was done with basis on a commercial solar transport system from PARANS and using commercial LEDs and with financial support from the Danish Elforsk program.

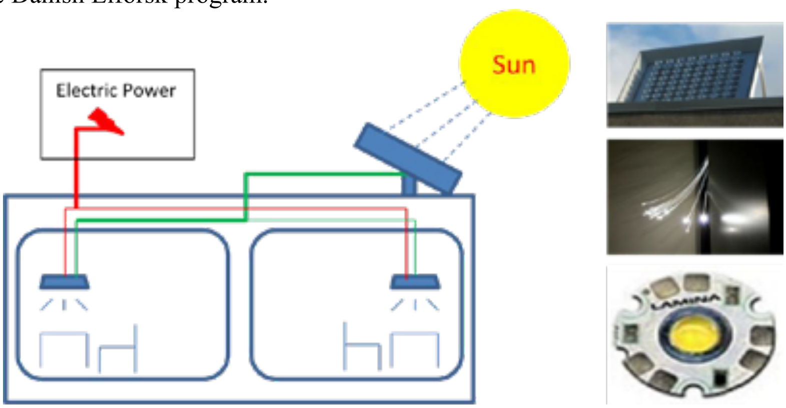


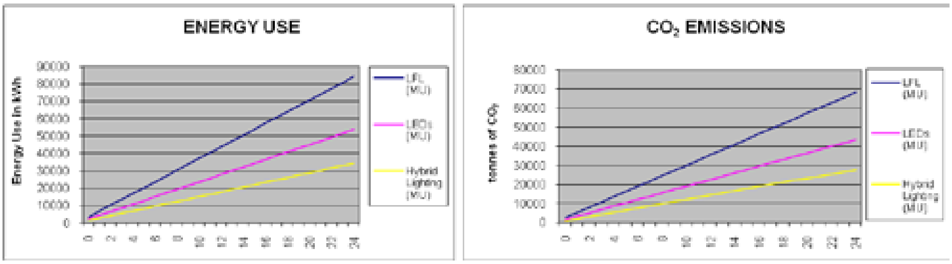

***Figure 6***: *Hybrid illumination system, at the right solar collector, optical fibers and LEDs*

The main idea was to produce a hybrid illumination system utilizing electric power and direct sunshine to provide a high quality and constant reliable illumination service. Hybrid lighting systems are a combination of four technologies: collecting natural light, generating artificial light, transporting and distributing light to where it is needed, and controlling the

amounts of both natural and artificial light continuously during usage. The overall idea is not new; the Department of Energy of USA (DOE) in collaboration with the Oak Ridge National Laboratory has published a large number of articles pointing out the advantages of hybrid solar fibre optical systems in terms of energy savings. However, when we started this project (in 2009), it was not possible to purchase a hybrid illumination system based on fibre optic technology.
On the current market it was only possible to buy solar systems based on fibre optic technologies (for example Parans and those from Himawari - notice that though these are solar optical fibre illumination systems, they cannot be called hybrid, since they do not combine both artificial and natural light - they only transport natural light). When both systems are installed as parallel systems they only add an extra cost and no energy savings are obtained. The main principles behind our design are:

- In order to harvest energy savings, electric power is switched of, when the sun is shining with a sufficiently high intensity to provide a pleasant indoor light intensity.
- Electric power is switched on, when it is dark or cloudy.
- The system can use standard electricity supply either from renewable or non-renewable networks (smart grid) working even when it is overcast

Designing and testing our hybrid system, however, pointed to very interesting results. First at all, we calculated that considering all the inputs of energy and outputs in lumens for our 3 comparison cases - LFL, LEDs and LEDs/solar optical transport system (hybrid system) - the energy savings and thereby the $CO_2$ savings to be 59% as showed in figure 7 and 8.




***Figures 8 and;*** *Energy consumption and $CO_2$ emissions considering a multiple user office for the three options for a Multiple User office using the DEEP's LCC tool (http://deep.iclei-europe.org)*

## 8. Consumer acceptance and price

As with any kind of environmental innovation, consumers' acceptance and price are decisive for any technology to be implemented (Kjær T., and Andersen J. 1993). Even finding some innovations with the necessary improvements, there are still two issues that need to be considered, since is not always for sure that those innovations will be accepted by the consumer and that they will reach the market. It is, therefore, important to consider what will be the mechanisms that can help in that process. Consequently, we needed to ask: if the new hybrid system could compete in price with our base case? And on the other hand we had to identify who decides what illumination system should be bought to satisfy the demand for public buildings?

**Price**

In order to assess the cost, we used DEEP's LCC tool (http://deep.iclei-europe.org). This tool was chosen for its simplicity to assess the total energy consumption both for the initial and future cost. It takes into account the costs, such as materials, installation cost, etc. and evaluates them in terms of Net present value. The comparison of the base cases are as shown in Figure 9

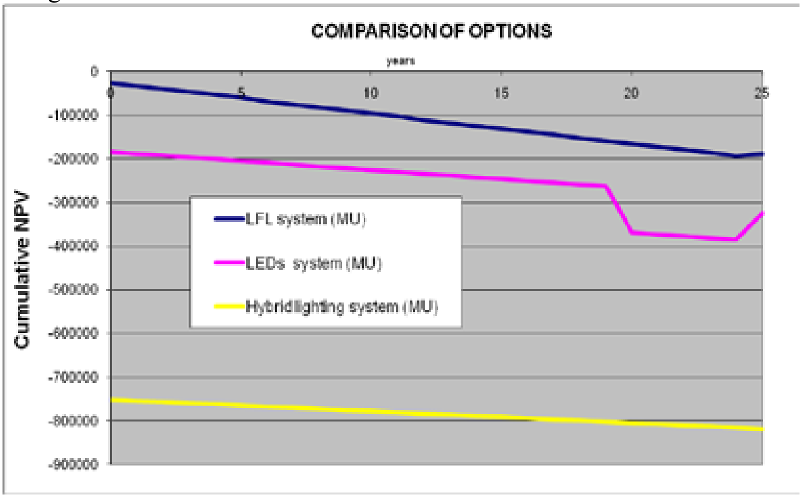



***Figure 9;*** *Comparison of options in terms of Net Present Value. Here we assumed a current discount rate of 3% (Denmark National bank, 25. March. 2010, ref 2010-14E), a "On - peak electric tariff price escalator" of 3% as an average value for the different energy sources (Bolt J., 2009,) and a carbon factor of 0.801 kgCO2/kWh (DONG energy., 2008,). We further consider that the life time for the hybrid system will be 25 years as the LEDs will be less used. The emission factor reported by the EU commission is 0.041 kgCO2/kWh, however, we do not consider this value as it is representative of an average of all kinds of energy sources (renewable and non-renewable). We choose to consider 0.801 kgCO2/kWh, since it is more representative for the marginal energy produced by non-renewable sources.*

As can be noticed from Figure 9, the main barrier for this design is the price of the system tested. The life cycle cost is almost 8 times higher that the LFL system, and 4 time higher than the LED system. Thus, even when the hybrid system is the option with the lower $CO_2$ emissions, the price will set a limitation for its implementation. Taking the whole life cycle of the hybrid systems we assessed that the complexity of the electronic system to drive the lenses in the solar collector system, the quantity of material used and the installation cost were the factors contributing to this barrier. Therefore we suggested getting back to Eco-design single issue approaches (Figure 2) and to look into the materials and manufactures stages in order to improve the design.

**Who decides what illumination system should be bought to satisfy the demand for public buildings?**

To do this is not an easy task, first of all, because when it comes to office lighting, there are several stakeholders that influence the decision making about which type of technology should be adopted. So in order to establish whose habits and long traditions had to be considered we needed to identify the role of these stake holders clearly. For this specific study we identify, 1) *regulators*, 2) *services providers* (consultant firms, light designers, architects, engineers and urban developers), 3) *consumers* (those who pay for the service) and 4) *Users* (those who use the service but not necessarily pay for it, usually employees).

As mentioned before, the systemic approach gives a good insight in the quantitative and political demands from the main stake-holders; however, the more subjective parameters are not focused in this framework. We, consequently, consider it important to look at the service itself instead of only on the product. This requires looking at the subjective preferences or properties that are in relation to the function. This can be done by looking for the potential that are there, when providing the illumination service for example temperature colour, spectral composition and noise (non oscillating light), symbolic value (prestige and aesthetic).

When looking at the material dimension, practitioners of the LCA suggest taking as a base of comparison the service provided by the product defining a functional unit (see Table 1). The aim is to quantify the product or service with respect to volume and time, looking for potential improvements in the product, in this case the lamp. However, this definition is still product-oriented. In our opinion, even when it is suggested to look at the subjective properties the functional unit is always evaluated in a quantitative way, e.g., how many units of this product we need in order to substitute the other one. This approach does not tell about the potential but only about the limitations. It is also complicated to evaluate which solution has the biggest potentials in terms of implementation, when the two options have exactly the same quantitative impacts.

| **Obligatory properties** | **Positioning properties** |
|---|---|
| Supplying 500 lux to a working area in typical Danish office | - Not blinding effect<br>- Avoiding overheat<br>- Optimal spectral composition of light for a working space (colour of light, warm light)<br>- Esthetical component of the room<br>-*Reducing $CO_2$ emissions*<br>- *Indication of "green responsibility"* |

***Table 1;*** *Functional unit*

Shostack, L., (1977), was one of the first authors suggesting that in order to see possibilities that can reach the market, one should pass from being product-oriented to be service-oriented. This requires being able to see the tangible dimension (materials), but also to see the intangible dimension (characteristics of the service).

The functional unit according to Wenzel and Caspersen, (1999) should be defined considering both the obligatory properties (tangible dimensions) and the positioning properties (intangible dimensions) of a product or a service. However, when it comes to the real life practice, the obligatory properties are the ones that define the functional unit since, as the definition of ISO points out, it has to be quantified (see Box 2).

We consider that the concept of the functional unit, though it makes an effort to include both dimensions, it often only focuses on the obligatory properties. In the case of providing illumination service, this has meant that the lamps (and not the service) are always compared in terms of watts and lumens (obligatory properties-definition). However, we would like to focus on the *possibilities* in the photonic sector, and, therefore, it is important to see the relation properties (intangible dimension) as well.

Box 2

**The functional unit** is defined as the *quantify* performance of a product system for use as a reference unit, (ISO 14044, 2006).

In different conferences and seminars, where we have participated during this research, it has been emphasised that, it is important taking into account parameters such as efficiency, but also parameters such as temperature colour, spectral composition and noise (oscillating light intensity). It can be argued, that these are also possible to quantify, however, our point here is, that they are properties that are in relation to consumer-users' preferences and depend on their perceptions. These are subject-related, and it is therefore very difficult to quantify them under material bases and they are often left out of the analysis. Furthermore, the positioning properties are most of the time described from the producer and service provider point of view and there is seldom a dialog with the consumer. Furthermore, the user is not included in defining these parameters. The perception differences can actually be very big, if the user is not included in defining them. As example, Table 1 shows the consideration that we as a design group made a priori in the beginning of this project, while, Table 2 has been filled in after the user quantitative and qualitative test.

One of the main issues when especially architects and light designers discuss "quality of light" is that the light should be warm and therefore so close to the light from incandescent lamp as possible. During the development of this study we met some architects that express their disappointment with the new regulations, since after their opinion nothing could substitute the incandescent lamp. To our surprise, when we asked the users in the office sector, they considered that if the light was soft and warm they will fall asleep in their offices.

| Obligatory properties | Positioning properties |
|---|---|
| Supplying 500 lux to a working area in typical Danish office | - It should be possible to read, write<br>- It should be possible to work in a computer without having light reflections<br>- It should be possible to see peoples' face while holding meetings<br>- The light has to be so close to daylight as possible (indirect sun light) both in colour and intensity<br>- Avoiding overheat<br>- Coming from a comfortable angle (no blinding)<br>- The lamps has to be beautiful (aesthetic)<br>- Flexibility possibilities (regulation of intensity)<br>- Reducing $CO_2$ emissions<br>- It should not contain mercury<br>- Nice to know when one is using daylight (indication of "green responsibility") |

***Table 2***, *Functional unit* after the user test.

One way of providing more focus on the new positioning properties and also considering with the same weight the relevant illumination devises in conjunction with the electricity consumption and production is using the concept of Product-Service Systems suggested by UNEP (2000). While the responsibility under a Life-Cycle perspective lays on the design phase or on the production phase, the Product-Service Systems perspective seeks to distribute the responsibility through the entire production chain given an equal weight to the consumption phase and not only focusing on the design phase. In this way, the focus is not on selling separate products, but "selling the utility, through a mix of products and services, while fulfilling at the same time client demands with less environmental impact" (UNEP, 2000: 3). Identifying and considering all the main stakeholders (including the users, if they are different from the consumers) with the same weight of importance is vital to achieve a more strategic design and implementation of low-carbon technologies.

**Testing our first prototype at Roskilde University in one of the main buildings**

To hear the opinion from our focus users, we installed the hybrid system that was specially designed for this project using the solar collector system from Parans and several luminaries were especially designed with the hybrid system. On basis of our explorative qualitative interviews with the users, we formulate a questionnaire. The questionnaire worked as the document test for reading and writing tasks, and we provided a transportable computer on the table. The test population was volunteers that passed by and accepted to test the system. The system was set in one of the rooms nearby the central cafeteria of Roskilde University in order to be tested by students and staff of the whole university, see Picture 4, 5, 6, 7




***Picture 4, 5, 6, 7;*** *from left to right: installation of the sol collector, installation of the optical fibers, installation of the luminaries, and disposition of the room.*

**Quality to perform office work tasks**

From Figure 10 we can conclude that there was actually a broad acceptation that the service fulfilled the criteria established by the users. However, the hybrid system still needs to provide more lumens to perform the writing and reading tasks especially in the work task area.

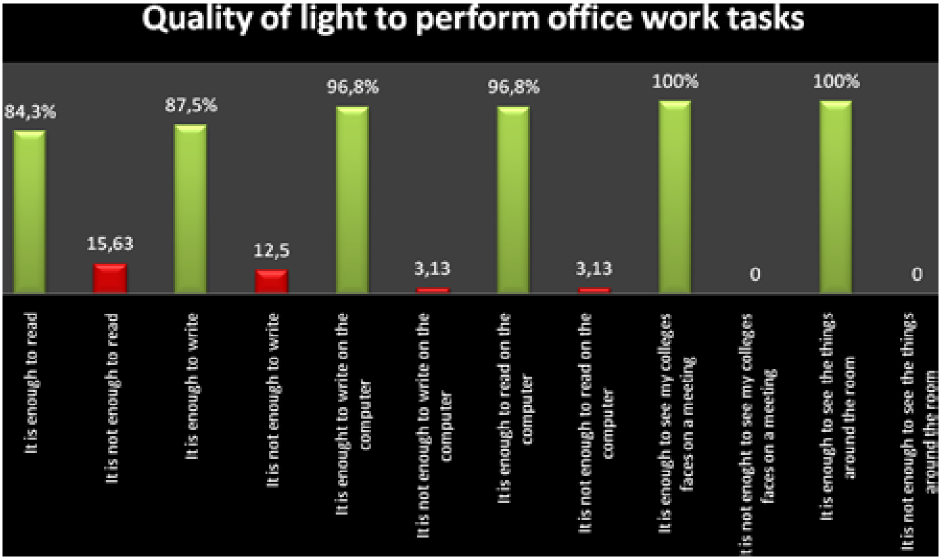


***Figure 10;*** *Quality of light to perform office work tasks*

However, we can argue that the age group that had more problem to read actually is the ages from 60-70 (Table 3), which, indicates that the difficulty to read may be due to age rather than bad illumination. Writing and reading from the computer seemed to be much better, but even considering that the computer had its own illumination - still the level of satisfaction was higher. In relation to holding meetings, the illumination system provided by the hybrid system was good enough, since this activity do not necessarily require too much writing and reading. From these answers, we could conclude that for general lighting purposes provided by the system, the light intensity can be accepted, but for work task area, the system should provide the possibility to increase the intensity according to the user physiological demands.

| **Age of respondents** | **The light is enough to read** | | | **% persons who answer yes** |
|---|---|---|---|---|
| | Yes | No | Total | |
| 20-30 years old | 9 | 1 | 10 | 90.0 |
| 30-40 years old | 8 | 1 | 9 | 88.8 |
| 40-50 years old | 0 | 1 | 1 | - |
| 50-60 years old | 7 | 1 | 8 | 87.5 |
| 60-70 years old | 3 | 1 | 4 | 75.0 |
| Total | 27 | 5 | 32 | |

***Table 3;*** *Ability to read using hybrid lighting by age groups*

**Light dynamics**

In relation to our test, 91% of the respondents answered that they have experienced variation with the light, see Figure 11. This occurred, when the sky was overcast and when the sun started to shine again or vice versa. 9% of the test persons did not experience variation with the light, and this might be because there was full sunshine or full overcast during the full period of the test. Most of the people experienced variation of light - independent of age see Table 4.

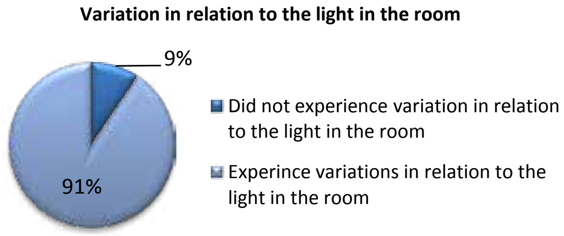



***Figure 11***; *Variations in relation to the light in the room*

| **Age of respondents** | **Did you experience variations in relation to the light in the room+** | | |
|---|---|---|---|
| | YES | NO | Total |
| 20-30 years old | 9 | 1 | 10 |
| 30-40 years old | 8 | 0 | 8 |
| 40-50 years old | 1 | 0 | 1 |
| 50-60 years old | 7 | 0 | 7 |
| 60-70 years old | 3 | 2 | 5 |
| Total | 28 | 3 | 31 |

***Table 4;*** *Variation of light in relation to age of the respondents*

As we mentioned before, there are some losses of the red spectrum in relation to fiber optic lighting and this was observable in our test since, the designers used warm white LEDs. As indicated in our qualitative interviews, light dynamic was within the parameters that our focus group considered important, and we asked for the reason considering again three parameters: pleasant/unpleasant, ugly/indication of daylight and natural/unusual to see, if they liked the light emitted by our system.

| Age of respondents | **Did you like light dynamics** | | | | | | |
|---|---|---|---|---|---|---|---|
| | No, unpleasant | No, ugly | No, unusual | Yes, natural | Yes, pleasant | Yes, indicates day light | Total |
| 20 - 30 years old | 0 | 0 | 1 | 1 | 4,5 | 2,5 | 9 |
| 30- 40 years old | 1 | | 0,5 | 2 | 2,5 | 2 | 8 |
| 40 - 50 years old | 0 | 0 | 0 | 1 | 0 | 1 | 2 |
| 50 - 60 years old | 0 | 2 | 0 | 1 | 1 | 3 | 7 |
| 60 - 70 years old | 0 | 0 | 1 | 1 | 0 | 3 | 5 |
| Total | 1 | 2 | 2,5 | 6 | 8 | 11,5 | 31 |

***Table 5;*** *Acceptance of the light in relation to age. 1 of the respondent did not answer this question. When one respondent marked more than one answer, we used equally large fractions as value. Some respondents both liked and did not like the light; therefore, we consider the answer in each point as half point for each answer.*

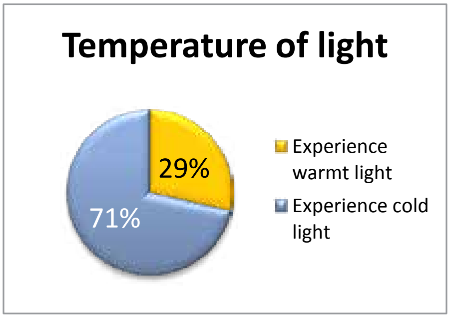
As it can be seen in Table 5, most people liked light dynamics from the test system especially those in the group from 20 -30 and the group from 30 – 40. The main reason to like the light dynamics is that they found it *pleasant and because it indicates the use of day light*. From this, we can conclude that even when there was light with two different colors, *it is not a big limitation* for the user to accept or like the system as it was tested. However, for further tests and to have a full and broader acceptance from all ranks of users, the system should be as close to the natural light (day light) spectrum as possible considering

the qualitative interviews and this should be important both for the LED color selection as for the light coming from the optical fibers.
The preference of light dynamics in relation to office lighting showed to be independent of gender - see Table 6.

| **Gender** | **Did you like light dynamics?** No, unpleasant | No, ugly | No, unusual | Yes, natural | Yes, pleasant | Yes, indicates day light | Total |
|---|---|---|---|---|---|---|---|
| Female | 0 | 0 | 0 | 3 | 5,5 | 3,5 | 12 |
| Male | 1 | 2 | 2,5 | 2,5 | 2,5 | 8,5 | 19 |
| Total | 1 | 2 | 2,5 | 5,5 | 8 | 12 | 31 |

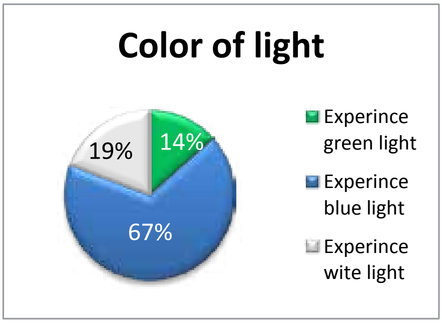
***Table 6;*** *Acceptance of light dynamics in relation to gender. 1 of the respondent did not answer this question. When the respondents marked more than a single answer, we used equaled fractions as value. When the respondents both liked and did not like a certain property, we considered the answer in each point as half point for each answer*

**Temperature, color and quality of light**




When the users were asked, if the experienced warm or cold light, they answered that, they had experienced more cold light. This might be due to the system was operating with full sunshine most of the time and the LED light took only proportionally less over - see Figure 12.

***Figure 12;*** *Temperature of light*




In relation to the color of the light, to our surprise, 67% of the users indicated that they experienced blue light. As we mentioned before one of the characteristics from the Parans solar system is that the spectrum of the light is dominated by the green part of the scale. However, it is interesting to see that what a user perceived as cold light is related to blue color.

***Figure 13;*** *Color of the light*

We allow the respondents to mark more than one option in relation to the quality of light. When the respondents marked more than one answer, we used equally large fractions as value. 70,93 % of the respondents answered that the light did not blind them, however, we recommend that the design of the lamps consider this more in the future, since still almost a third of the test users meant otherwise - see Figure 13.

As it can be seen in Figure 7, less than the half of the test users meant that the light was distributed evenly on the room, this was due to the fact that some of the lamps electric systems failed during the test period, and were working only with natural light, so when it was overcast only the rest of the lamps worked, and they were only partially illuminating the room. It is important to remember that a number of the lamps were prototypes developed in a 5 week project by the student of Design School Kolding and not commercial examples. The lamps were fragile to the touch of the users (and although we did ask them not to touch the lamps, many of the test users could not avoid to take the lamps in their hands to try to understand the system). For commercial versions, we strongly recommend to make the lamps more robust.

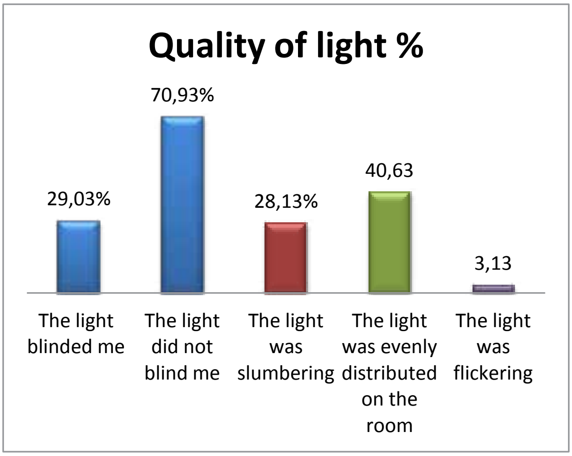



***Figure 14;*** *Quality of light*

**Influence of the armature design**

In this question, the objective was to see to which degree the design of the lamps in the test room influenced the acceptance of the lamp and we cross this information with the age of the respondents to see the correlation. As it can be appreciated in Table 7, the design of the lamp influences the acceptance of our focus group mostly from 50% to 75% but the acceptance of the lamp seem to be more correlated to males than to females. From this we can conclude that it is important to continue giving the correspondent importance to the aesthetic aspects, when designing the improved models.

| Gender | How much does the lamp design influence the user? | | | | |
|---|---|---|---|---|---|
| | 0 - 25% | 25 - 50% | 50 - 75% | 75 - 100% | Total |
| Female | 3 | 1 | 3 | 5 | 12 |
| Male | 2 | 3 | 11 | 3 | 19 |
| Total | 5 | 4 | 14 | 8 | 31 |

***Table 7;*** *Influence of the lamp design to accept the Hybrid lighting system. One of the test persons did not answer to this question.*

## 9. Conclusions

One of the main limitations in the lighting service sector has been that the focus has tended to be only on the lamp, while the way in which electricity is produced has the biggest environmental load. In order to overcome these challenges, we considered the entire line of elements as a whole using a broader holistic approach. Considering the whole Product-Service System allowed us to see the potential to use hybrid lighting to achieve reductions of primary energy and thereby energy based on fossil fuels and green house gas emissions. The results of our life cycle energy assessment in the use phase showed that using hybrid fibre lighting systems have the potential to save 59% of primary energy and thereby the corresponding $CO_2$ emissions. Using DEEP's LCC tool to assess the total life cycle cost of

the three systems provided with a practical and important insight of improvement potential and also a cost-benefit overview . It also helped us identifying the crucial inputs that constitute the main cost barriers. Here we identified that the collector and it installation price should be reconsidered for further design improvements. These elements are considered in our new designs in process to be patented.
The main limitation for these systems is still their initial high cost. However, looking at the material and production processes to redesign them could bring the price down and thereby make them more price-competitive in the entire life cycle cost. An explorative consumer (user) test, even not strongly scientific based, provided us with a relevant and useful insight of the challenges and design potentials to make this technologies more consumer acceptable and see their potential to provide users with a better light quality. At the same time we foresee the potential for a great variety of aesthetical applications.

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# Articles 3

# Barriers and possibilities for the emerging alternative lighting technologies

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## Abstract

Final electricity consumption grew across the EU-27 at an average annual rate of 1.7 % between 1990 and 2005 showing an absolute increase of *28.7 %*. The average electricity use per capita in the EU-27 is almost 2.5 times the global average and 3.5 times that for China. These are some of the facts that set a big question mark on how the $CO_2$ emission goals can ever been achieved for 2020 even if we are talking about a reduction of 20%. Therefore, when we, on one hand, know that 20% of the world electricity consumption is due to illumination and on the other hand, that 1.6 billion people do not have access to this service yet, it is obvious that this is a very important sector to target. Most of the electricity consumption due to illumination is today mainly produced by fossil fuels. Therefore beside $CO_2$ emissions, the shortage of resources will press the development of new technologies that can cope with this challenge in the future. Furthermore, even with the emergence of energy saving devices, the global ecological footprint is still rising. In this article, we discuss the main challenges that the emerging illumination technologies will have to deal with, if we really aim to achieve more sustainable solutions to climate change in this sector.

*Keywords*: Electricity, Lighting, Energy Policy, Post-fossil fuel technologies

## Introduction

The year 2007 was another important step-stone for the discussion of Climate Change. Giving the Nobel price to Al Gore and the intergovernmental Panel on Climate Change, it was once more emphasized that the effect of human activities on the climate change is an urgent matter to address for all countries.

However, climate change has been on the political agenda for *at least three decades*. Some of the pioneering formal efforts of politically addressing climate change can be traced back to 1979 in the first "World Climate Conference" organized by the World Meteorological Organization (WMO).

In 1992 climate change was formalized in the Rio Convention, during the Earth Summit, addressing three interlinked issues, namely climate change, biodiversity and desertification. In those days, the measures for reduction of emission started as voluntary agreements setting non-mandatory limits.

As the emission continued rising so did the discussions about how to solve the problem. In 1997, with the Kyoto Protocol, limitations of green house emissions were listed for developed countries and economies in transition. The emission-reduction commitments were set at a 5% below 1990

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levels to be reached between the years 2008-2012. Once the discussion turned to have binding agreements, the process of action turned slow and burdensome. From 1997 to the year 2000 the negotiations were almost stagnated. The most notable result of these discussions during this period was the rejection of the Kyoto Protocol made by the USA. After a long way of negotiations (almost 8 years), the Kyoto Protocol entered into force on February 2005.

In 2002, EU agreed to cut 8% of green house gases (GHG) in average from 1990 emission levels over 2005 to 2012. Some of the main concerns, and specially those stated in the 2006 report from the European Agency "*Energy and environment in the European Union*" [EEA 2006:5] were the pressure that the production and consumption of energy was setting on the environment including climate change, impacts on natural ecosystems and human health among other impacts. Consequently, this report suggested European policies to pursue the following three goals [EEA 2006:5]:

- security of supply
- competitiveness
- environmental protection

The EU announced again in 2007 - as part of the European Union policy - a cut in $CO_2$ emissions by at least 20% by 2020. To reach this goal, the EU aims to increase the use of renewable energy sources, to limit global temperature changes to no more than 2°C above pre-industrial levels. Another of the strategies includes improving the EU's energy efficiency by 20% [EU 0170107]. EU also is willing to achieve a cut of 30% under a new global climate change agreement when other developed countries make comparable efforts [EEA 5/2008]. The report "Greenhouse gas emission trends and projections in Europe 2008" predicts that the EU 27 emissions under the current EU energy measurements will increase 1% between the years 2006 to 2010 and that the goals for the year 2020 will not be reached [EEA 5/2008:3].
The future scenario is not clear yet, since on one side, the EU-Secretariat, in its Climate Development and Climate Strategy's review stated that in order *to not exceed the $2^0$C, the EU will have to bring down the $CO_2$ emissions as much as 60%* in 2050 to reach the levels of 1990 [Folketingets EU-Sekretariat, 2008].

## Climate Change Challenge

According to the IPCCs "Fourth Assessment Report" from 2007, avoiding the global temperature to rise more than a range between 2-2.4 degree Celsius, requires that the total concentration of GHG in the atmosphere keeps between 445-490ppm ($CO_2$-equvalents) [IPCC 2007: 67]. Nevertheless, it has been pointed out by several sources that the concentration of GHG already reached the 445 ($CO_2$-equvalents), and therefore, if the goal is no more that 2-2.4 degree Celsius, the emissions have to top in 2015 and the reduction have to be from 50 to 85% in 2050 in relation to 2000. [IDAs Maj 2009 and Danish Climate Commission April, 2009].

Though the EU's official 20% goal is presented as being very ambitios, taking into consideration that a reduction at a global plan has to be of *up to 50-85%,* talking about an even 30% is still very conservative. The reductions of 20 to 30% have been criticized for their limited impact. On one side, some experts and politicians who agree that even the reduction of 20% would not be enough to cut down emissions to the desired level and *that the efforts from EU will only contribute to reduce from 2 to 3% of the world's total $CO_2$ emissions* [EU, Sustainable Energy Week, 2008]. On the other side, the European Commission's New Energy and Climate Change Strategy pointed out that cutting *30%* in developed country emissions by 2020 will only reduce the half amount of global emissions necessary to reach 1990 levels. It has been stated that the Climate is already altered by 0.7% and what we have left to reach that 2% for the year 2020 is in reality only 1.3% [Danish Commission on Climate Change Policy., April, 2009]. This reveals that the current goals have been and still *are* very conservative, and further, that the efforts within this targets have not solved the problem at all, and everything indicates that humanity *is going to* experience an average temperature increase of $2^0$C sooner than expected. The consequences of this conservatism has derived in the situation that today *instead to prevent* Climate Change we have to think in how we adjust to what it cost not to have paid the necessary attention to the warnings. Consequently, this stresses that we still have "solving policies" instead of "preventive policies". In the same way, the production of new illumination devises should be preventive. Thus, we need to increase the energy efficiency and to pursue high levels of energy savings much more seriously than we do today.

## Availability of fossil fuel resources

Worldwide, the oil reserves-to-production ratio is estimated at *41.6* years, the world natural gas reserves-to-production ratio is estimated at *63* years. However, the *EU* gas domestic production proved reserves at current production rates are estimated to only be secure between *14 to 15* years from 2008. The coal reserves-to production ratio is *133* years. [BP June 2008 and COM 13-11-2008] however, using coal is problematic in relation to GHG.

The EU's energy production can hardly support the half of its needs. EU's current import dependency was almost 54% in 2006. Most of this dependency was due to oil, which comprised 60% the bulk of the total EU energy imports. The imports of gas accounted for 26% and solid fuels 13%. Further pressures added to the availability of the reources are due to the geographical and political situation of the main oil suppliers (see Figure 1). The main suppliers are OPEC countries, followed by Russia and the Middle East countries. The fact that main suppliers are from the OPEC countries means that they will require themselves the resources to continue developing.

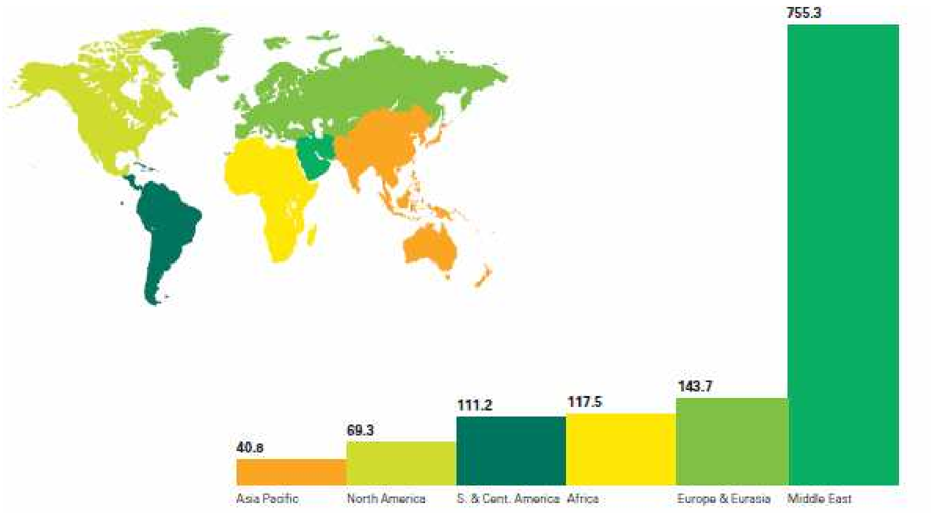


***Figure 1.*** Proved oil reserves at end 2007 (Thousand million barrels). Source [BP June 2008].

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The uranium world proven reserves are estimated to last for 100 years at the current production rate. However, the European Union only counts with 1.9% of the world current reserves. Therefore, uranium is a non-strategic resource, if EU is looking for being energy self-sufficient [COM 13-11-2008].

Electricity in Europe accounts for 70% of the $CO_2$ emissions. Therefore, it is strategically important to direct the efforts to this sector. Equaly imperative is it to find alternative sources of energy, *and also find alternatives to save energy in a more strategic way*. It was not a surprise that the theme for the Danish political election campaign of 2007 was the uncertainty of supply of fuels - especially considering the geographical situation of these resources. Currently 61% of the electricity is produced with fossil fuels [EIA, January 2009]. Being the case that electricity security supply depends of fossil fuels makes it imperative to reconsider the way we are using the resources, while we have them. It also makes it necessary to plan strategic alternative technologies and energy sources. Therefore, the illumination sector has to consider that the availability scenery of resources is changing, and we have to design products for a post-fossil fuel era. Meaning with this that the supply using conventional plants might not be the same and the supply sources might be very different from what we currently know today. The traditional electric grid and the voltages of supply might also be re-adapted for a new generation of illumination devises.

## Other important environmental impacts

The European Environment Agency suggests in the document Europe's Environment - The fourth Assessment: "The challenge to energy policy is thus to meet concerns about energy security and affordability at the same time *as to reduce environmental impacts*" [EEA, 2007: 323]. These environmental impacts are not only the ice melting in the poles, but in a high degree desertification, shortage of water resources in some geographical areas, floods in other regions, the pollution of rivers and soils with hazardous substances, that at the same time contaminate food chains and damage human health, etc., etc., etc.

Using the concept of ecological foot print ( see box 1), the World Wildlife Foundation and the Global footprint Network organizations were, already in 2005, suggesting a more sustainable development, understanding this as: "Improving the quality of human life while living within the capacity of our supporting ecosystem" [Wackernagel. M., 2005: 3]. This report also warned the European Union about the Earth already exceeding the carry capacity limits. It also stated that *Europe was by then using more than double of its own carry capacity*.

Box.1
The ecological foot print: is the total area required to produce food and fibre that it consumes, absorb its waste, and provide space for its infrastructure. People consume resources and ecological services from all over the world, so their footprint is the sum of these areas, wherever they are on the planet. The foot print can be compared with nature's ability to renew these resources".
[Wackernagel. M., 2005]

Adding to this already established reality, the emergence of giant energy consumers such as China and India [Pamlin and Szomolányi 2006] will cause an extra pressure on the Earth ecological *footprint* (see Box 1.1). This increasing population will demand to cover their basic material needs. According to the State of the World Population report [2007]: "By 2008, for the first time, more than half of the globe's population, 3.3 billion people, will be living in towns and cities. The number and proportion of urban dwellers will continue to rise quickly. Urban population will grow to 4.9 billion by 2030" [Obaid 2007: 6].

Thus, besides dealing with the European ecological foot print surplus, we will have to seriously consider the other's parts of the world ecological foot print, if we really want to avoid a greater accelerated deterioration of our natural resource base.

The initiatives for alternative sources of energy as well as the reduction of energy consumption have been plenty but, any way, not enough to reduce as much as needed for the ecological foot print. Considering a scenario of business as usual our world carry capacity will be seriously diminished (see Figure 2) in a very close future. Not considering the necessary resource base will affect the possibility to produce better technological solutions and we will enter in an energy and resource vicious cycle.

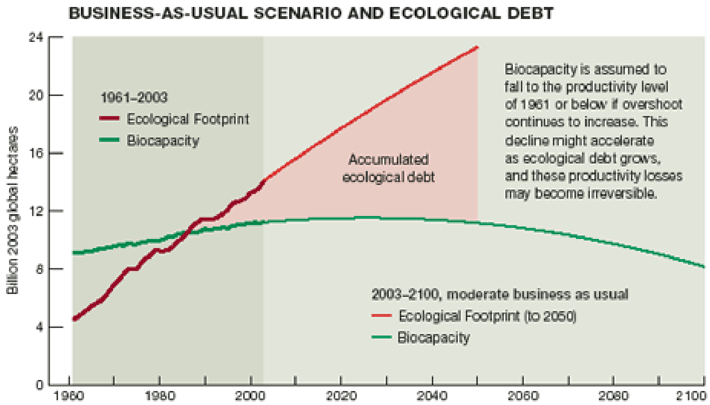


***Figure 2.*** Humanity's footprint- business as usual. Source: WWF 2008,

## Lighting technologies and their environmental impact

In the first meeting of stake holder consultation about "Energy efficiency requirements for light bulbs and other energy-using products on track for adoption" it was stated that there is a big potential in saving $CO_2$ emissions phasing out inefficient products. The amount of saved $CO_2$ could ascend to 180 Mt representing *a quarter of the reduction target by 2020*. From this, 15 Mt could be achieved by switching to more efficient light bulbs" [EU., June 2007]. This concern has driven countries such as Australia, as one of the first of the world, to phase out the incandescent bulb for the year of 2009 and suggest using compact fluorescent lamps. Following this example, China and USA have plans to do the same. The 8th of December 2008, the European Union announced the phasing out of incandescent lamps and favored the Compact Fluorescent lamps (CFLs) as the current most efficient lighting sources [EU-ECO-design, 2008].

## More than $CO_2$ in current illumination devises

The Danish Environmental Agency stated in a communication of the 29th of March 2007 *that though there was an EU-restriction against CFL due to their mercury content*, the restriction was withdrawn *due to the lack of suitable alternatives* to the incandescent lamps. It also stressed that the

RoHS-directive[2] recommends that the content of Mercury should not exceed 0.1 of the weight %, however, for the case of the CFL the limit was set up to 5 mg of mercury per lamp. It added that EU's eco-label "Flower" allowed to use mercury as well, however, the level of mercury should not exceed 4mg of mercury per bulb [Miljøstyrelsen 29 / 03 / 07]. Nevertheless, the emergence of lighting devises such as Light Emitting Diodes (LEDs) could question, if this is the wisest decision to switch to CFLs. Mercury is hazardous, because it is quickly absorbed into the body via skin contact or inhalation. Mercury can cause damage to the central nervous and reproductive systems as well as neurological and kidney damage. If the CFLs are not properly disposed, the mercury in form of gas will be distributed in the air affecting directly human's health, or it will settle into soil and nearby water bodies, ultimately contaminating food chains. Therefore it is important to find other illumination technologies that the one based on mercury.

## A holistic thinking

Technology will without doubt be *part* of the solution. However, the production of the new technology has to be addressed in a more holistic way, so in trying to solve one problem we do not create another one. With this philosophy, each of the phases necessary for the acquisition of raw materials, manufacturing, use of the product, and disposal of the product have to be assessed. This is what is also called cradle-to-grave thinking or lifecycle approach (See box 2).

There is a need for technological innovation, but this innovation has to be based on more knowledge about *all the environmental impacts* of a product or service. This approach is useful, since it allows us to see the environmental impact during the different stages of the product from its raw materials to the consumption phase. Checking the entire life cycle helps to make decisions about the materials and energy use to produce a solution to ameliorate the emission of $CO_2$ and avoid materials that might have a negative impact on the environment or at least as small a foot print as possible. Despite the relevance of such approaches, much of the assessments on energy consumption still focused on the carbon-footprint and, therefore, most of the times in the usage phase. This paradigm might leave aside the materials and even worse, hazardous substances that might be used during the whole production chain giving a wrong view of the whole picture. This has the consequence that the products might reduce some $CO_2$ emissions, but they will create other extra burdens to the environment.

> Box 2
> "The International Standard ISO 14044 (2006) defines life cycle as the "consecutive and interlinked stages of a product system, form raw materials acquisition or generation from natural resources to final disposal" [ISO 14044 2006].

[2] "The RoHS Directive stands for '"the restriction of the use of certain hazardous substances in electrical and electronic equipment'. This Directive bans the placing on the EU market of new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants" (http://www.rohs.gov.uk/)

## New illuminations technologies and its socio-economic impact

Technological innovation can many times become an opportunity to boost local and regional economies. At least it is what one can read in the European directive 2006/32/EC, when this directive expresses that the challenge of reducing $CO_2$ emissions also arises as an economic opportunity. In this directive, it is underlined that this challenge is at the same time an opportunity to boost the Community's innovativeness and competitiveness as indicated in the Lisbon Initiative (See Box 3).

Box 3
"With the establishment of the Lisbon Agenda in 2000, the European Union set itself the strategic goal of establishing a **competitive, innovative and knowledge-based European economy**, capable of sustainable economic growth with more and better jobs and greater social cohesion by 2010. [www.eib.org].

The opportunity of boosting the Community's innovativeness and competitiveness might be the answer to the concern that gave the basis for the formation of the High Level Group of European executives from *research organizations and industry* encouraged by the European Commission. They reported that there has been a "loss of manufacturing activities from Europe to lower wage economies - and the realization that this deindustrialization is inevitably accompanied by loss of *productive* employment" [EC 2004: 8]. Thus the problem becomes even more challenging: Can we find solutions to reduce the energy consumption footprint at the same time that we ensure sustainable and productive livelihoods in Europe?

The sustainable livelihoods term (see Box 4) was coined at the end of 1980ies. The term was used as a development concept. The thinking behind this term points out to strategic planning and implementation and it is, therefore, meaningful to use, if one is looking for creating better jobs and greater social cohesion. With the sustainable livelihoods background thinking, one should be able to achieve a more sustainable development, since it supposes to provide:

- "a more realistic understanding of people's livelihoods and the factors that shape them,
- basis to build a policy and institutional environment that support peoples livelihoods and support the development that builds on the local and regional capitals and,
- opportunities to improve their livelihoods or in the case of Denmark sustain the level of wellbeing.

Development in this sense should conduct us, to enhance the local and global assets on which livelihoods depend and, at the same time, obtain net beneficial effects on other livelihoods without undermining *their local* and *global* resource base - or in other words reducing as much as possible our ecological foot print on the planet and in a high degree making use of local resources.

Box 4

"A livelihood comprises people, their capabilities and their means of living.
A livelihood is environmentally sustainable when it maintains or enhances the local and global assets in which livelihoods depend, and has net beneficial effects on other livelihoods. A livelihood is socially sustainable which can cope with and recover from stress and shocks, and provide for future generations". [Chambers & Conway, 1991]

Thus, talking about sustainable production and consumption, one can say that it is not only necessary to reduce the consumption of energy but also do it in a way that the materials needed to produce such solutions leave the minor footprint in the process of production. As energy based in fossil fuel will be scarce, the future illumination technologies should be based on local renewable energy sources. Furthermore, an advantageous European production strategy should be the one that targets a production with a great dematerialization of new products in order to produce alternative solutions to the increasing green house effect with the minor local and global ecological footprint. At the same time, this dematerialization (see Box 5) will help enhancing the resources from which European jobs or livelihoods depend.

> Box 5
>
> Dematerialization is defined as.
>
> "(The)…reduction of environmental pressure by reduction in the use of materials, combined with a constant need fulfillment. On the macro-level this can be translated into a reduction of environmental pressure from materials at a certain level of economic growth" [Goedkoop et al., 2000]

The point here is that the new technological solutions cannot continue isolating problems such as the emission of $CO_2$ on one side without considering the whole ecological impact. We cannot continue only focusing of the end-use ignoring the whole process of production and the imminent disposal, as we cannot allow us to think in innovation without thinking on how to make sustainable livelihoods of such activities. These problem are interlinked and require and integral analysis and solutions.

The EEA states two important issues: *one* that "Most impacts of electricity use result from its production rather than consumption" and *two* that "For many smaller electric and electronic goods, the most critical environmental impacts arise from disposal rather than usage, because of their high content of heavy metals and other hazardous substances. This waste category now represents one of the fastest-growing waste fractions in the EU" [EEA 2007:3328]. However, when it comes to the Danish strategies, it is still emphasized that the use-phase is where actions need to be taken. The fact is that offering *more efficient* appliances that seems advantageous in the use-phase has leaded the consumer to acquire *more appliances*. Therefore, though there are in the market more "energy efficient" appliances, still the energy generation is increasing. Consequently, it is important to consider strategies that also include raw materials used and their consequent disposal to reduce consumption or to make consumption more rational along all the production chain.

## Cost-competitive challenge

Under green house gasses policies the world electricity prices could be 22% higher than those in 2007 [DOE/EIA., March 2009: 3]. In Denmark the prices of electricity have risen constantly since 1997 (see figure 3). Despite the goals set by the EU, the $CO_2$ taxes has remained constant. However, applying stricter GHG policies the prices could be much higher.

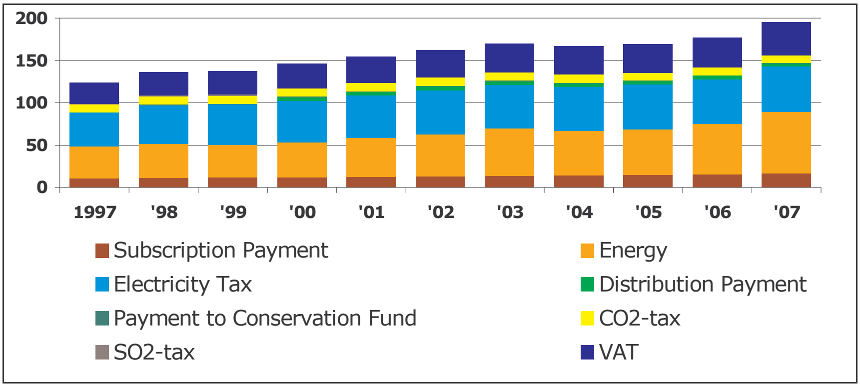


***Figure 3:*** Electricity Prices for Households in Denmark (per January, 2007) in Danish cents. Source: Association of Danish Energy Companies

Production prices also encompass the price of energy used. Until know this has been considered as a marginal cost since the prices of energy in the production sector has remained lower than those for the households. However, the prices of energy and especially of electricity for the industrial sector may be higher in the future as well. Thus, considering not only the consumption phase but all phases in the production process and end of life cycle has to be one of the main concerns of the actors involved in the production, consumption and discharge of illumination devises.

## Consumer accept of new technologies

Another effort has been encouraging "energy efficient technologies". However, as Figure 4 shows, consumers in the EU-15 *are not* switching with the same speed to more efficient lighting devises as is the case with the ownership of more efficient dishwashers.

Our own empirical material coincide with the assessment made for the Oak Ridge National Laboratory [Ashdown, *et al.*, 2004], in relation to the consumer willingness to buy saving lamps. Despite the investment recovery is in a short time (3-5 years), the consumers are resistant to change easily to saving lamps. Therefore, beside ethical parameters esthetical ones should go hand in hand.

Thus, one can say that in order to achieve realistic reductions of green-house gases, the future lighting technologies have to provide *exceptional service* to be accepted.

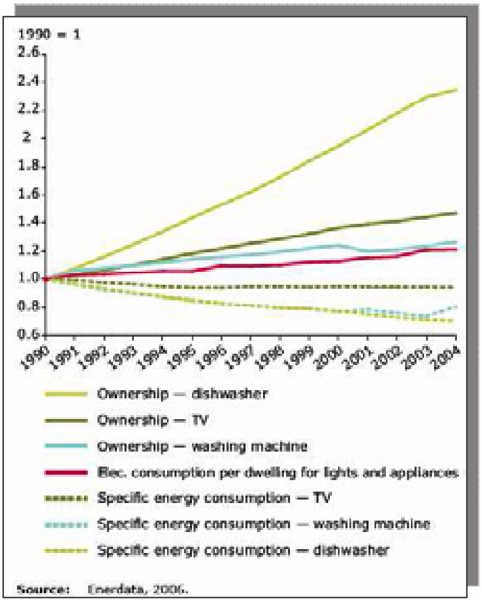


***Figure 4:*** Trends in *energy efficient ownership* and overall energy consumption of selected household appliances, EU 15.

Still, the illumination sector is one of the most strategic areas to get $CO_2$ reductions and achieve economic advantages. According to Kage [2006] *"Since U.S. Department of Energy figures reveal that about 22 percent of electricity used in the United States goes toward lighting, converting to LED bulbs would have a profound economic and environmental impact" (Kage., 2006).* In the same article it is argued that if 25 percent of U.S. were converted to 150-lumens-per-watt LEDs , USA would eliminate the need to build *133 coal-burning power stations* and reduce carbon emissions in the atmosphere by *284 million tons*. USA accounts for a third of the world's current lighting energy consumption. Taking into account the utility costs, by replacing conventional bulbs all over the world by LED bulbs, the world could save to the year 2025 US$345 billion [Kage., 2006]. However, from most of these data it is uncertain to know, whether the savings are calculated based on the use-phase or from cradle to grave considerations.

### *Conclusions*

The illumination sector present great opportunities to both achieve green house gas emissions reduction and a strategic sector for a post-fossil fuel era. It also represents a huge market if one considers the 1.6 billion people who still do not have access to electric light. There are, however, many challenges that the production of new emerging illumination technologies has to consider, these are listed as followed:

- The challenge of reducing the ecological footprint (materials, toxic substances, emission of $CO_2$, etc.) of current and future options;
- The challenge of being cost competitive with the incandescent lamp in its life-cost cycle;
- The challenge of making use of the current European photonic industry assets to enhance productive jobs;
- The challenge of integrating the esthetical design combined with engineering and social disciplines
- A main challenge considering the already mentioned ones, is finding new methods to achieve a more holistic approach related to sustainable development of environmental technologies.

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# Articles 4

# In which sectors could new illumination technology strategically reduce $CO_2$ emissions?

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**Abstract**

Illumination is responsible for the consumption of 19% of the total electricity consumption worldwide. Efforts to reduce the consumption of this energy fraction are, therefore, increasingly taking the attention of many governments. Denmark, as one of the leader countries in environmental actions, is engaged in several actions to reduce its $CO_2$ emissions. The problem severity demands a capacity to react quickly and efficiently to better reach the international goals. Traditionally, the efforts have concentrated on the residential sector. Consequently, the aim of this paper is to contribute to the discussion on where the effort shall be strategically directed. We look at the international tendencies with specific focus on Europe and chose Denmark as a representative example to illustrate the way in which the policies focus on the residential sector instead of the commercial and services sectors. This paper conclude that the available statistics so far show that in Europe the commercial and service sector is responsible for the highest electricity consumption due to illumination. The same pattern repeats in Denmark. Therefore, this paper argues that in order to achieve even more optimal solutions, a more detailed differentiation of data shall be pursued by the electricity companies. It is suggested that detecting the right sector will give possibilities to better target actions with higher impact potential.

*Keywords*: Electricity, Lighting, Technology, Energy Policy.

## Introduction - Lighting technologies

In 2005, global lighting accounted for approximately 19% of the total electricity consumption [1]. The consumption of this electricity was responsible for the emission of 6,000 Mt $CO_2$ [2]. In Europe, the green house gas emissions related to energy are rising again after they have shown a minor improvement (decrease of emissions) in the 1990s, stressing the long-term reduction targets [3]. About 55% of the green house gas emissions are due to electricity consumption. The given explanation for the rising emissions is that they are the result of a flexible end-use (meaning that final electricity consumption in the usage phase is uncontrolled), *a growth in the services sector,* and an increase in the ownership of electrical appliances [3]. Furthermore, the report "Energy and Environment in the European Union-Tracking progress towards integration" stated that: "Two to three units of energy input are needed for producing one unit of electricity from fossil fuels with the rest being lost in the process, unless the heat is recovered in a combined heat and power process. This implies that the rise in electricity consumption results in a disproportionate increase in environmental pressures, particularly greenhouse gas emissions [3]. Therefore, finding strategies to reduce the environmental impact of the energy used for illumination is highly relevant. Even more important is it to focus on the right sector – meaning the sector, where the largest potential for green house gas emissions exists. This is stressed, since the European Environment Agency (EEA) has pointed out that the growth in *the tertiary sector* has been one of the causes of the increasing emissions related to electricity consumption, where lighting has had an important share. At the same time much of the efforts and campaigns have been directed to the households and towards the public sector.

All sectors use illumination; from commercial, residential, and industrial to the public sector. However, most of the ongoing research organised by the European Commission has been directed to the residential sector [4]. A similar strategy has taken place in Denmark [5-8], where the focus on energy used for lighting is set on the household and public service sector.

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**Total energy consumption in Denmark**

Numerous efforts have been done in Denmark to break the tendency of increasing total energy consumption. The result is that the total energy consumption in the household sector has been slowed down from the late eighties (see Figure 1). The graphics shows the sectors, where Denmark has concentrated the main efforts, namely on the households and lately in the industry sector. The example of Denmark conduct us to have two reflections, one that efforts and actions pay back, but at the same time, that policies have to be readjusted periodically, taken into consideration the new challenges that emerge. In this article, it is also argued that a deeper differentiation and detection of the main electricity-using devises shall be done in order to make our efforts more strategic and effective.

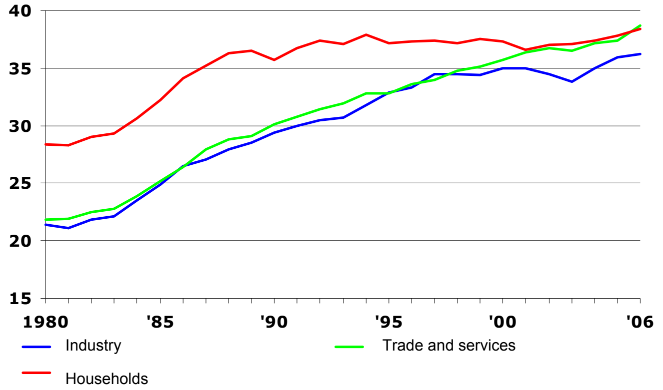


***Figure 1,*** **Total electricity consumption by sectors in Denmark Source: Energi Styrelsen (www.ens.dk/sw15175.asp)**

**Worldwide Electricity consumption due to lighting**

Though the household sector represented an important fraction of the total electricity consumption due to lightning in 2005, the *tertiary sector* was responsible for the largest proportion of electrical energy used for *illumination* in the same year, using 1,140 TWh. This consumption represented *43%* of the worldwide grid-based electricity used for lighting, which in the same year corresponded to about 2 650 TWh of electricity or 31% of the total world electricity composition in the year of 2005[1] (see Figure 2).

In the OECD countries (2005), *the tertiary* sector was responsible for the consumption of 34% (688.2 TWh) of the electricity for lighting followed by industry, which accounts for 20% (405 TWh). At the OECD level, the residential sector consumption represented 14% (283.5 TWh) of the electricity used for illumination [1].

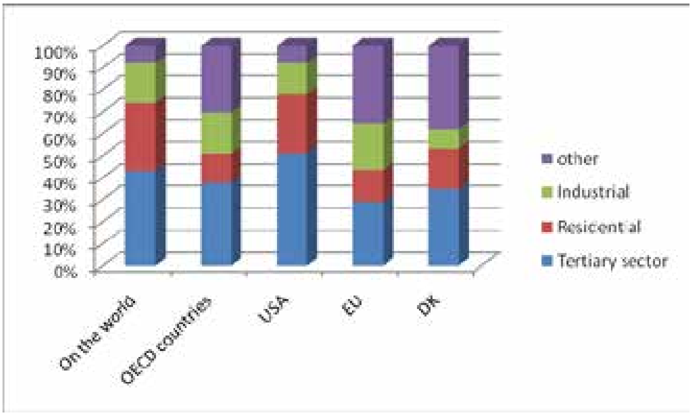


***Figure 2. -* Overview of the electricity due to illumination by sectors in different regions of the world**

Worldwide, OECD and EU electricity consumption due to lighting share by sector [15]

Electricity use for illumination by sectors in USA [18]

Electricity use for illumination by sectors in Denmark [5]

**Electricity consumption due to lighting in the United States of America**

In the USA for the year of 2002, 22% (765 TWh) of the *electricity was used for illumination*. From this consumption, *more than half* of the energy due to lighting was consumed in *the commercial* sector (51% or 391 TWh), (see Figure 2). One has to observe that the residential consumption was 27% (208 TWh) of the electricity used for lighting, and though it represented a considerable fraction, it was still much lower than that of the commercial sector. The industrial share in the same year was for 14% (108 TWh) [18]

**Electricity consumption due to lighting in the European Union**

Thought the residential sector only accounts for 13% of the total electricity consumption due to lighting in the EU, still several sources agree that the strategies have tended to focus more on the residential sector [4 and 9]. Furthermore, the total electricity consumption in the residential sector in the EU-25 has grown by 10.8% in the period 1999-2004, whereas the electricity consumption in *the tertiary sector has grown by 15.6%* [15]. Taking into account EU-27 countries' tertiary sector in 2004, the total electricity consumption due to lighting was of *175* TWh representing 26% of the total electricity consumption in this sector. Whereas the residential sector electricity consumption in the same year was of *102* TWh [15]. According to Waid and Tanishima, "There has been no systematic survey of industrial-sector electric lighting in the European Union and the best data available are from individual site audits and occasional national survey information" [1:235]. Therefore, the estimation from the IEA Light's labour's Lost report [1] is used in this reference. Thus, it is considered that the electricity consumption due to lighting in the industry sector in EU is of 100.3 TWh in 2005 accounting for approximately 8.7% of the total industrial electricity consumption.

**Electricity consumption due to lighting in Denmark**

The last year, when "Dansk Energi" (the Danish energy association financed by Danish electricity companies) published information about the electricity consumption due to lighting in *all sectors* was in 2001 [5]. In the subsequent editions, Dansk Energi concentrated on the households sector and the information of the other sectors was omitted [5-7 and 10-13].

The tendencies in Denmark were, however, very much like those in the rest of the EU until 2001 (upon the available data). In Denmark the fastest growth of electricity consumption due to illumination happened in the trade and service sectors, where the consumption of electricity increased in the period from 1992 to 2001 by 17.3% followed by the Industry sector (with a 16.3% increase) and the public sector (with an increase of 14.3%), while the electricity consumption in residential buildings only increased 1.4% [5]. Yet the whole attention was, however, set on the households and public sectors and not on the sectors that really show a big impact on the electricity consumption such as the tertiary sector [10-13]

**Consumption of electricity due lighting in Denmark in absolute numbers**

The Households in Denmark used 17% of the total electricity consumption for illumination devises in 2001 and 12% in 2007 [5 and 7]. This amount seems high in relative terms, however, one has to consider that the other sectors also play an important role and they should not be ignored. In 2001, industry consumed 7% of the total electricity due to illumination. Trade and commerce used 33%, services 24%, and the public sector used 31% of the respective electricity consumption, for illumination.

Table 1 shows the distribution in % of the electricity by end-use of different sectors in Denmark. Due to the relative data one is tempted to think that trade and the public sector are the major consumers of electricity for illumination and, therefore, interesting sectors to be subject of further research.

| End-use | Industry | Trade/commerce | Services | Public sector |
|---|---|---|---|---|
| **Lighting** | **7** | **33** | **24** | **31** |
| **Diverse** | 12 | 9 | 15 | 20 |
| **Electronic** | 2 | 2 | 13 | 5 |
| **El-heating** | 1 | 3 | 8 | 5 |
| **Cooling** | 7 | 30 | 10 | 3 |
| **Engines** | 28 | 10 | 3 | 6 |
| **Process heating** | 8 | 2 | 6 | 3 |
| **Pumping** | 9 | 1 | 5 | 11 |
| **Special blowing** | 6 | 3 | 0 | 2 |
| **Pressure air** | 11 | 2 | 2 | 2 |
| **Ventilation** | 10 | 5 | 13 | 11 |
| **Total** | 100 % | 100 % | 100 % | 100 % |

***Table 1,*** *The* % of electricity used, distributed by sectors and end-use for the year 2000 [5].

However, most of the data referring to illumination energy consumption is given in relative terms. Therefore, aiming at finding the explanation of why the households and public sectors are the sectors in focus for the Danish authorities, I calculated the absolute consumption of electricity due to lighting taken the percentages given above and comparing with the total electricity consumption in each sector to see if that was the reason, why the policies have concentrated in the residential and public sector (see Table 2). Yet, if one looks at the absolute amount of energy used by sectors one can realize, that the sectors using more electricity due to lighting is clearly the commerce, services and the public sector (see table 2).

| Direct Energy Content (GWh) Climate Adjusted | Final Electricity Consumption (GWh) in 20011 | % of electricity consumption due to lighting2 | Absolute electricity consumption due to lighting (GWh) |
|---|---|---|---|
| **Industry (manufacturing and construction)** | 10259,17 | 7 | 718,14 |
| **Trade (Wholesale and retail sale)** | 3324,722 | 33 | 1097,16 |
| **Service (private)** | 4264,722 | 24 | 1023,53 |
| **Public sector (public service)** | 2587,222 | 31 | 802,04 |
| **Residential (single family and multi-family houses)** | 10261,11 | 17 | 1744,39 |

***Table 2,*** Absolute electricity consumption due to lighting by sectors in Denmark 2001. Sources: own calculations based on
***1:*** *Danish Energy Authority [14]*
***2:*** *The* % of electricity used, distributed by sectors and end-use for the year 2000. [5]

Usually, trade- and service segments are considered as the tertiary sector and, therefore, if one adds the consumption of the two categories, the total consumption of electricity due to lighting is of the magnitude 2,121 GWh. This corresponds to the 28% of the total electricity consumption, which has to be compared to 1,744 GWh used for lighting in the residential sector. This means, at the same time, *that tertiary sector uses 22% more electricity* for lighting than the residential sector.

One of the explanations of why the EU plans are focusing on the residential sector might be that when one looks at the *energy in general [15]*, the residential sector seems to be one of the main consumers. When looking at the electricity consumption, some EU reports sometimes aggregate data, adding the consumption of household with the consumption of electricity from the service and trade sectors [16] and these gives as well troubles in identifying which of the three sectors is the real major consumer.

With the available information one can say that it is necessary to focus on the commerce and service sectors and search for options that can provide sustainable solutions that besides reducing the $CO_2$ emissions also will be able to create a reduction of the entire ecological footprint of lighting appliances.

Furthermore, most of the light used in the trade and services sector is consumed coinciding with the peak electrical demand and it contributes to a building's internal heat generation, increasing air-conditioning load. Therefore, in order to direct the efforts in a more strategic way, a more consistent and detailed data base is necessary.

There are already some measures that will take place for the public sector, for example Legislation already requires: "that by January 2009 at the latest all large public buildings in the EU display energy performance certificates for the visiting public to see" [15]. However, plans for the tertiary sector are very much absent.

**Potential energy savings**

There are a lot of possibilities to save energy in the commercial sector. Different to industry, the commercial sector uses spots, halogen and standard reflectors (see picture 1) that are less efficient than CFLs for example and, much less efficient than LEDs spots. Therefore the author of this paper agrees with the status report made for the Institute for the Environment and Sustainability (JRC) which predicts that there will be more savings from the commercial sector than the residential sector [17]. For example the JRC's status report points as a realistic scenario compared with business as usual scenario for the year 2015 savings of 16 TWh/year for the residential sector, while with the same scenario the potential savings are *36TWh/year in the commercial lighting* [17] ( a little bit more that the double). But this in my opinion will only be possible, if the same focus given to the residential sector is set on the commercial sector.

***Picture 1***: Typical picture of illumination by spots in commercial facility in Denmark

## Conclusions

Lighting is a very important sector to address in order to achieve savings of electricity and consequently $CO_2$ emissions. In the European Union, however; there is quite limited and somewhat inconsistent statistic information available about this - especially *by sectors* in absolute terms. The information given by relative terms is also inconsistent, because the residential sector has been prioritized neglecting the other sectors. In order to direct the efforts in a more strategic way, it is very important that systematic information is provided. With the available information, however, it is possible to say that the efforts are still mainly directed to the residential sector, since it was an important sector and the easiest way of achieving electricity savings. However, though the household sector should not be forgotten, today the major challenge in EU and Denmark, considering the use of electricity due to lighting, lays in the service and trade sector. Missing the implementation of targeted efforts can result in decreases of electricity consumption with little or at least non-optimal impact. Therefore, in order to achieve the necessary reductions of energy and $CO_2$ emissions, the information about consumption of electricity due to lighting by sector has to be more consistent, clear and accessible in order to direct the efforts in a more strategic way. Detecting the right sector will give possibilities to better target actions with higher impact potential. The photonic sector should, therefore, also have a close look of the geographical and contextual situation to make a common effort to confront this global challenge and demand such information.

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