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LONG-TERM SCENARIOS FOR GLOBAL ENERGY DEMAND AND SUPPLY

FOUR GLOBAL GREENHOUSE MITIGATION SCENARIOS

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with contributions from **Bernd Kuemmel and Peter Meibom**

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Long-term scenarios for global energy demand and supply:
Four global greenhouse mitigation scenarios
Bent Sørensen (with contributions from Bernd Kuemmel and Peter Meibom)
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Abstract: The scenario method is used to investigate energy demand and supply systems for the 21st century. A geographical information system (GIS) is employed to asses the spatial match between supply and demand, and the robustness of the scenario against changes in assumptions is discussed, for scenarios using fossil fuels without carbon dioxide emissions, nuclear fuels with reduced accident and proliferation risks, and renewable energy from local and from more centralised installations:

• The year 2050 demand scenario is based on a very high goal satisfaction in all regions of the world, for the middle UN population projection. All energy efficiency measures that are technically ready and economic today are assumed in effect by year 2050. An increased fraction of total activities are assumed to occur in non-material sectors.

The four supply scenarios are:

• A clean fossil scenario, with new fuel cycles avoiding or retaining greenhouse gases for deposition or other uses not leading to atmospheric release.

• A safe nuclear scenario, with new fuel cycles minimising proliferation possibilities and risks of large accidents, and aiming at delivering energy for other energy use sectors besides that of electric energy, without long-term waste storage.

• A decentralised renewable energy scenario, based upon building-integrated solar systems and dispersed installations for utilising wind and biomass energy, the latter being based on integrated production of food, energy and bio-feedstock for industry.

• A centralised renewable energy scenario, placing solar collectors or wind turbines in areas of non-arable land, or off-shore in large farms. Biomass plantations would be placed on areas of land where competition with food production is considered minimal.

Technical, economic and implementation issues are discussed, including the resilience to changes in particularly demand assumptions, and the type of framework that would allow energy policy to employ any of (or a mix of) the scenario options.

Results are presented as average energy flows per unit of land area. This geographically based presentation method gives additional insights, particularly for the dispersed renewable energy systems, but in all cases it allows to identify the need for energy transmission and trade between regions, and to display it in a visually suggestive fashion.

The scenarios are examples of greenhouse mitigation scenarios, all characterised by near-zero emissions of greenhouse gases to the atmosphere. All are more expensive than the present system, but only if the cost of the negative impacts from the current system is neglected. As options for global energy policy during the next decades, the clean fossil and the renewable energy options (possibly in combination) are the only realistic ones, because the safe nuclear option requires research and development that most likely will take longer time, if it can at all be carried through successfully.

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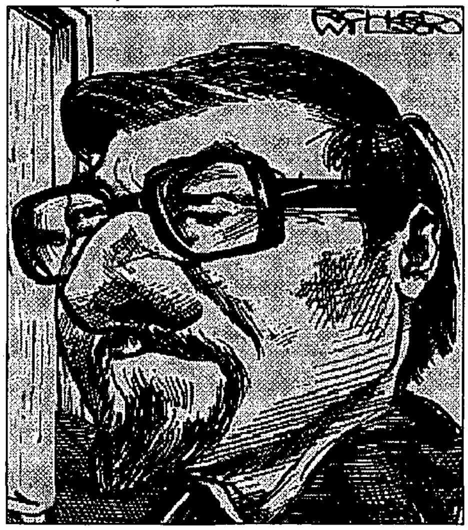

Richard Wilson's drawing of Bent Sørensen presenting NGO demands to the UN Conference on New and Renewable Energy in Nairobi 1981.

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PREFACE

The present project was completed over a three-year period, from 1996 to 1998. Bent Sørensen assigned 50% of his time to the project during all three years, after having defined the basic scenario structure and outlined the demand and supply scenarios in previously published work. He is alone responsible for the present text, Appendix C and D excepted. Bernd Kuemmel was attached to the project during the spring of 1997, working on data gathering and construction of a preliminary fossil scenario. Peter Meibom worked on the renewable energy scenario during the fall 1998 and spring 1999, particularly the population model and the alternative biomass model described in Appendix D. This work was deliberately duplicated, because of the central importance of the food and energy connection and because it was considered the least well explored territory. By deriving the results along two very different paths (either following the energy flow through all conversion steps, or doing the evaluations using weight of wet and dry matter in harvest and only making the transition to energy units at the end), the consistency of assumptions and results was secured. The entire effort thus involved some 3 man-years. This is quite remarkable, because models of a similar complexity being worked on during the 1970ies and 80ies typically required the full-time work of 20-50 scientists to reach a similar level of documented scenario detail. It shows how useful recent advances have been in easy database access and provision of tools for combination of formats, all in electronic form, along with the graph generation tools developed for geographical information systems. In many cases, Internet databases were found, downloaded, changed to the formats used in this project and subjected to the necessary scenario calculations, using simple Basic or C programmes, and finally entered into the scenario presentation software to display the new results, all in the matter of a day or two. This allowed extensive cross-checking of results using data for a given quantity derived from different sources, before selecting the final one. Preliminary versions of parts of the scenario work have been presented at numerous occasions, and we thank colleagues for engaging in very interesting discussions on our assumptions and the methods used.

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Keywords: Sustainability, Energy efficiency, Energy demand, Scenarios, Greenhouse mitigation, Fossil energy, Decarbonisation, Nuclear energy, Accelerator-breeders, Renewable energy, Solar energy, Wind energy, Hydro power, Biomass energy, Hydrogen, Food production, Energy systems, Global energy modelling, GIS (Geographical information systems).

Chapter 1

INTRODUCTION AND METHODOLOGY

1.1 INTRODUCTION

A scenario for global energy demand and supply by year 2050 is constructed, based upon the following normative assumptions: Concern for human welfare and environmental sustainability leads to energy consumption patterns based on materials conservation and emphasis on non-material ("information society") types of activity. The energy system includes provisions for storage and transfer, in order to deal with the mismatch between supply and demand caused by the variability of access to important resources, or in case of renewable resources fluctuations in the source flows themselves, and variations in demand.

In the following sections, the characteristics assumed for the global 2050 society are sketched, with the purpose of deriving the associated energy demands. Then, for each supply options, the potential contribution of each major resource is discussed, and finally the actual supply is fixed to match demand on a global level, leaving spatial variations to be dealt with by energy trade and transmission, and time variations to be dealt with by energy management and active storage cycles.

The scenario year 2050 is selected sufficiently distant into the future to allow the assumption that the necessary changes in infrastructure and technology can be introduced in a smooth and gradual manner. The use of a geographical information system (GIS) makes it possible to express all quantities on an "energy flow per unit of land area" basis, a methodology which is particularly suited to describe the extraction and use of dispersed renewable energy flows. In a concluding section we deal with uncertainty of demand and economic factors that would determine or influence the implementation of the scenario considered. In appendices, the assignment of countries to regions used in the modelling framework is given, additional details of some of the fossil technologies used, and an alternative estimation method for one of the key renewable resources, that of biomass.

1.2 METHODOLOGY

The energy scenario is based on a general vision of the characteristics of the global 2050 society, but one that is more a description of some general conditions assumed created than an attempt to forecast any actual picture of the precise technologies and activities prevailing at the time. By necessity, the energy system is based on assumed developments of presently known technologies, but only as a means of proving the feasibility of the scenario: if better options emerge, as they almost certainly will, then they will be used, but the choice made at least constitutes a default to fall back on, and as such proves that there is a possible system of the kind envisaged, although not necessarily the optimum one.

The economic viability of technology choices made for the scenarios can be assured only within considerable uncertainties, because the final cost of emerging technologies can only be estimated.

However, in selecting the technologies to use in each scenario, best available judgements have of course been used to ensure that goals of economic viability can indeed be met, if the technical development and politically assisted creation of a suitable environment for implementation are indeed forthcoming as stipulated. It may in this connection be necessary to refer to inclusion of externality costs (i.e. indirect costs not currently included in market prices), in order to justify such an effort.

First some remarks on why scenario studies are relevant for discussing greenhouse policy options. For the purpose of assisting decision-makers, a way must be found of describing a given energy system in its social context, that is suitable for assessing systems not yet implemented. Simple forecasts of demand and supply based on economic modelling cannot directly achieve this, as economic theory deals only with the past and occasionally the present structure of society. In order to deal with the future, economic modellers may attempt to invoke the established quantitative relations between components and assume that they stay valid in the future. This produces a "business-as-usual" forecast. Because the relations between the ingredients of the economy, e.g. expressed through an input-output matrix, vary with time, one can improve the business-as-usual forecast by taking into account trends already present in the past development. However, even such trend-forecasts cannot be expected to retain their validity for very long periods, and it is not just the period of forecasting time that matters, but also changes in the rules governing society. These may change due to abrupt changes in technology used (in contrast to the predictable, smooth improvements of technological capability or average rate of occurrence of novel technologies), or they may be changed by deliberate policy choices. It is sometimes argued that econometric methods could include such non-linear behaviour, e.g. by replacing the input-output coefficients by more complex functions. However, to predict what these should be cannot be based on studies of past or existing societies, because the whole point in human choice is that options are available, that are different from past trends. The non-linear, non-predictable relations that may prevail in the future, given certain policy interventions at appropriate times, must therefore be postulated on normative grounds. This is what the scenario method does, and any attempt to mend economic theory also implies invoking a scenario construction and analysis, so in any case this is what has to be undertaken.

It is important to stress that scenarios are not predictions of the future. They should be presented as policy options that may come true only if a prescribed number of political actions are indeed carried out. In democratic societies this can only happen if preceded by corresponding value changes affecting a sufficiently large fraction of the society. Generally, the more radical the scenario differs from the present society, the larger must the support of a democratically participating population be. For non-democratic societies a scenario future may be implemented by decree, with the negative implications of such a procedure.

The actual development may comprise a combination of some reference scenarios selected for analysis, each reference scenario being a clear and perhaps extreme example of pursuing a concrete line of political preference. It is important, that the scenarios selected for political consideration are based on values and preferences that are important in the society in question. The value basis should be made explicit in the scenario construction. Although all analysis of long-term policy alternatives is effectively scenario analysis, particular studies differ in the comprehensiveness of the treatment of future society. For example, most of the current analysis makes normative scenario assumptions only for the aspects of society directly having a direct influence on the energy sector. Still the full, normative makeup of future societies will come into play, and notably for scenarios describing an ecologically sustainable global society (such as is attempted by the renewable energy scenarios), whereas scenarios aiming only at avoiding or coping with one particular problem, here the climate change induced by greenhouse warming, are often of the simpler kind.

Chapter 2

THE DEMAND SCENARIO

2.1. POPULATION

The most recent revision of the United Nations population study estimates a year 2050 world population of 9.4×10^9, in its middle variant (UN, 1996). The middle variant is most consistent with the assumption made here of significant advance in the economy of all regions of the world, and no devastating wars. Wars and hunger would diminish the estimate, whereas low degrees of development, coupled with ignorance and fundamentalism would lead to higher population numbers. The density distribution of the current world population is shown in Fig. 2.1. It is a 0.5°×0.5° data set that we have extracted from the 1994 5'×5' data set of CIESIN (1997) described by Tobler et al. (1995). In order to project the population density to year 2050, both the UN estimated totals for each country and the projected development in the degree of urbanisation are used (UN, 1997). Regional urbanisation trends are shown in Table 2.1 have been utilised in the following way: The rural population density is changed according to the projected development, and at first, the population densities of existing cities are changed (almost invariably increased) according to the projections. However, if this makes the city population density higher than the largest existing today (taken as 5000 cap/km^2 on the 56km × 56km grid used), the density is not allowed to grow any further. Instead, the extra population is distributed over neighbouring areas and this process is repeated until the density becomes lower than 5000 cap/km^2. The result of this model procedure is a realistic growth of urban conglomerates. Fig. 2.2 shows the resulting 2050 population density. Note that in some regions, the rural population decreases (as it has done earlier in currently industrialised areas), and that the concentration of populations in urban centres are often inconspicuous when illustrated on a world map.

Table 2.1. Summary of UN population and urbanisation projections (UN, 1996; 1997)

Region	Population 2050 million	Urban Pop. 2025 (%)	Urban Pop. 2050 (%)
Sub Saharan Africa	1795	52	68
West Europe, Japan & Pacific	601	85	88
East Europe, former USSR & Middle East	1151	73	83
Latin America, India & other SE Asia	3737	58	71
North America	387	85	90
China & other centrally planned Asia	1684	54	74
World	**9355**	**61**	**74**

2.2 ECONOMIC ACTIVITY AND ENERGY DEMAND

With respect to economic activity and energy demand, one expects the development to the mid-21st century to be dominated on one hand by efforts to "catch up" by currently poor countries, depending on several factors including issues of global equity in development and trade conditions. On the other hand, a determinant will be the nature of "new activities" being added to or replacing the current inventory of energy demanding undertakings. In recent decades, information-related activities have replaced materials-related activities, and this development has (due to the often smaller energy requirements of information-related activities and products) lead to a de-coupling of economic growth and energy demand: Energy demands have risen much less than measures of economic activity such as gross national products. The expectation is that this trend will continue, and due to technical requirements the energy intensity of e.g. computer-related activities will continue to decrease, while the number of installations will increase.

As an example of industrial growth rates, the overall activity growth in the European Union countries was a factor 5.6 during the last 60 years, from 2200 to 12370 1990-US$/cap. average GNP between 1930 and 1990. The growth was uneven (depression, World War II, reconstruction period, unprecedented growth 1956-1971, stabilising from 1973), but over the entire 60 years perhaps symptomatic of the technology progress achieved during this in the world history quite exceptional period. The likely European growth over the next 60 years will be lower, and high growth rates will be seen predominantly in certain Asian regions. The IPCC Second Assessment (IPCC, 1996) estimates in its high-growth scenario, that the growth in Western Europe will reach a GNP of 45300 1990-US$/cap. by 2050, as contrasted to 69500 1990-US$/cap., if the growth factor equalled that seen in the period 1930-1990. It would perhaps be a more realistic approach to estimate growth during the next 60 years as being at most the same in absolute terms as between 1930 and 1990.

A recent European study assumes the emergence of an information society with two thirds of the growth de-coupled from energy and use of materials (Nielsen and Sørensen, 1998), implying in simplistic terms that the growth factor for demand of energy services should be one third of the GNP growth. The relationship between energy and GNP is complex and depends both on attitudes and on technology developments. The ratio between energy and GNP growth 1930-1990 first declined from 1.5 to 1.0, then rose to 2.0 during the exceptional period and became negative after 1973. This is partly an effect of energy (and particularly oil) prices, but also technology requirements have played a role, by improving energy efficiency after 1975 in ways often exceeding a cost-driven transition. The change in delivered energy service may have been even lower (e.g. the improvement in service between bicycle transport and automobile transport is not always as big as the increase in energy use would suggest).

Based on factors such as the ones outlined above, the energy demand by year 2050 has been estimated for different regions in the world, using the following methodology (Sørensen, 1996; Kuemmel et al, 1997): Current energy supplied to the end-user (taken from statistics, such as OECD, 1996) is analysed with regard to the efficiency of the final conversion step, translating energy into a useful product or service. The net energy demand is taken as that used by the most efficient equipment available on the present market or definitely proven (e.g. available as a prototype). The assumption is thus that by 2050, the average of all equipment used will have an energy efficiency equal to the best currently marketed or nearly marketed. This would seem a fairly cautious assumption, as it neglects the certain invention of new methods and equipment working on principles different from those currently employed, and possibly improving efficiency by much more than marginal factors.

The overall consequence of these assumptions will in the current demand scenario be a global increase in end-use energy amounting to an average factor of 4.8, with much larger increases in the currently poor countries. The average 1994-2030 per capita growth factor for the demand scenario end-use energy is 2.7, and the consequences in terms of primary energy input will be different for the different supply scenarios, due to different conversion efficiencies in the intermediate conversions. The de-coupling implies that the GNP per capita growth to year 2050 will be substantially larger than the factor 2.7.

2.3 BOTTOM-UP ENERGY DEMAND CALCULATION

This section describes the basic methodology for estimating energy demand at the end-user. Energy demand futures are sometimes discussed in terms of changes relative to current patterns. This is of course a suitable basis for assessing marginal changes, while for changes over a time horizon of 50 years, it is not likely to capture the important issues. Another approach is offered by looking at human needs, desires and goals and building up first the material demands required for satisfying these, then the energy required under certain technology assumptions. This is a bottom-up approach based on the view, that certain human needs are basic needs, i.e. non-negotiable, while others are secondary needs, that depends on cultural factors and stages of development and knowledge and could turn out differently for different societies, subgroups or individuals within a society. The basic needs include those of adequate food, shelter, security and human relations, and there is a continuous transition to more negotiable needs that incorporate material possessions, art, culture and human interactions and leisure. Energy demand is associated with satisfying several of these needs, with manufacturing/constructing the equipment and products entering into the fulfilment of the needs, and with procuring the materials needed along the chain of activities and products.

In normative models such as an environmentally sustainable scenario, the natural approach to energy demand is to translate needs and goal satisfaction to energy requirements consistent with environmental sustainability. For market driven scenarios, basic needs and human goals play an equally important role, but secondary goals are more likely to be influenced by commercial interest rather than by personal motives. It is interesting that the basic needs approach is always taken in discussions of the development of societies with low economic activity, but rarely in discussions of highly industrialised countries.

The methodology used here is to first identify needs and demands, commonly denoted human goals, and then to discuss the energy required to satisfy them in a chain of steps backwards from the goal-satisfying activity or product to any required manufacture, and then further back to materials. This will be done on a per capita basis (involving averaging over differences within a population), but separate for different geographical and social settings, as required for the local, regional and global scenarios considered in Chapters 3-5.

The primary analysis assumes a 100% goal satisfaction, from which energy demands in societies that have not reached this can subsequently be determined. The underlying assumption is that it is meaningful to specify the energy expenditure at the end use level without caring about the system responsible for delivering the energy. This is only approximately true. In reality there may be couplings between the supply system and the final energy use, and the end use energy demand therefore in some cases becomes dependent on the overall system choice. For example, a society rich in resources may take upon it to produce large quantities of resource-intensive products for export, while a society with less resources may in-stead focus on knowledge-based production, both doing this in the interest of balancing an economy to provide satisfaction of the goals of their populations, but possibly with quite different implications for energy demand. The end-use energy demands will be distributed on energy qualities, which may be categorised as follows:

1. Cooling and refrigeration 0-50°C below ambient temperature.

2. Space heating and hot water 0-50°C above ambient.

3. Process heat below 100°C.

4. Process heat in the range 100-500°C.
5. Process heat above 500°C.
6. Stationary mechanical energy.
7. Electrical energy (no simple substitution possible).
8. Energy for transportation (mobile mechanical energy).
9. Food energy.

The goal categories used to describe the basic and derived needs have been chosen as follows:

A: Biologically acceptable surroundings

B: Food and water

C: Security

D: Health

E: Relations and leisure

F: Activities

- f1: Agriculture
- f2: Construction
- f3: Manufacturing industry
- f4: Raw materials and energy industry
- f5: Trade, service and distribution
- f6: Education
- f7: Commuting

Here categories A-E refer to direct goal satisfaction, f1-f4 to primary derived requirements for fulfilling the needs, and finally f5-f7 to indirect requirements for carrying out the various manipulations stipulated. Individual energy requirements are estimated as follows:

Space conditioning: biologically acceptable surroundings

Suitable breathing air and shelter against wind and cold temperatures, or hot ones, may require energy services, indirectly to manufacture clothes and structures, and directly to provide active supply or removal of heat. Insulation by clothing makes it possible to stay in cold surroundings with a modest increase in food supply (which serves to heat the layer between the body and the clothing). The main heating and cooling demands occur in extended spaces (buildings and sheltered walkways, etc.) intended for human occupation without the inconvenience of heavy clothing that would impede e.g. manual activities.

Space heating is assumed to be required if the monthly average temperature is below 16°C. This would give an indoor temperature above 20°C in a suitably constructed buildings, taking into account thermal mass (to smooth out day-to-night temperature differences) and indoor activities producing waste heat. Space cooling is considered necessary for monthly average temperatures above 24°C, again with consideration of optimum use of building thermal mass and devices such as smart solar window screens. The rate of energy provision for heating and cooling is calculated from the temperature difference ΔT by the simple formula P = C×ΔT (Sørensen, 1979), where C=36 W/cap/deg. assuming an average heated or cooled space of 60 m^2 per person (40 m^2 living space, the rest for work and public spaces). Just under 60% of the space heating covers heat losses through external walls, the rest is air exchange, partially through heat exchangers.

Figure 2.3 shows the measured seasonal temperatures (taken from Leemans and Cramer, 1998; the data are consistent with other sources such as NCEP/NCAR, 1998) and indicates the seasonal movements of the borders defining the onset of needs for space cooling or space heating. Figures 2.4 and 2.5 gives the energy per unit of populated land area required in 2050 for full satisfaction of heating and cooling needs, respectively. It is the quantity |P| defined above times the population density for 2050. Figure 2.6 gives the direct energy input to these processes in the actual 2050 scenario, along with that to other low temperature heat requirement (given in the row "other low-T heat" in Tables 2.4). The heat pump technologies assumed used in the scenario employs electricity as high-quality energy input and environmental heat (from air, soil or waterways) for the low-quality source. A fairly low average COP (coefficient of performance, i.e. ratio of heat output to electricity input) of 3.33 is assumed for the heat pumps, because many of them will be placed at high latitude locations (where the space heating need is largest). At these locations they will in most cases need soil sources and corresponding technology for the low-temperature source. Current technology uses pipes shot through the earth at frost-free depths by special machinery to extract this heat, and the rather low COP is an indication of the average current performance of such systems in cold climates. Table 2.6 gives both the heat pump electric energy inputs and the energy drawn from the environment.

Energy in and related to food and water

The energy in food currently supplied to end-users is given on a regional basis below in Table 2.5. It is seen that the ratio of animal and vegetable foods vary considerably between regions. The biological energy requirement is on average 120 W for an adult (Sørensen, 1979), so the average delivered seems adequate, but deficits occur in South Asia and sub-Saharan Africa. There is also a loss between delivered and consumed food, but this loss is presumably smaller in regions of food shortage. For the "full goal satisfaction" estimate it is assumed that the food supply has the regional distribution on foods of animal and vegetable origin shown in Table 2.6, including losses at the end-user of 20% for animal food and 30% for vegetable food (i.e. delivered energy times 0.8/0.7 equals end-use food energy). The losses would typically be vegetable stalks, husk and peeling residues, plus meat fat, skin or bones. They may contribute to energy provision through collection of household refuse, e.g. for biogas production. The actual 2050 scenario food energy delivered is given in Table 2.6. It corresponds to full satisfaction of needs except in Africa, but the ratios of animal and vegetable food still vary between regions, although less that today. This assumes a move towards what is considered a more healthy diet in the currently most meat-intensive parts of the world. The geographical distribution of vegetable and animal food product deliveries used in the 2050 scenario is given in energy units in Figs. 2.7 and 2.8.

To store the food adequately, the use of short and long term refrigeration is assumed to take place. The weight of the average per capita food intake is of the order of 2×10^{-5} kg/s, of which 0.8×10^{-5} kg/s is assumed to have spent 5 days in a refrigerator at a temperature ΔT=15°C below the surrounding room temperature, and 0.4×10^{-5} kg/s is assumed to have spent two months in a freezer at ΔT=40°C below room temperature. The heat loss rate through the insulated walls of the refrigerator or freezer is taken as 2×10-2W/°C per kg of stored food. The energy requirement then becomes

$$P \approx 0.8\times10^{-5}\times5\times24\times3600\times2\times10^{-2}\times15 = 1.04 \text{ W/cap. (refrigerator)},$$

$$P \approx 0.4\times10^{-5}\times2\times720\times3600\times2\times10^{-2}\times40 = 16.6 \text{ W/cap. (freezer)},$$

plus the energy needed to bring the food down to the storage temperatures, $P \approx 0.72+2.12 = 2.84$ W/cap. (assuming a heat capacity of 6000 J/kg/°C above 0°C and half that value below the freezing point, and a phase change energy of 350 kJ/kg). The energy is assumed to be delivered at the storage temperatures. Some energy could he regained when melting frozen food.

Cooking the food requires further energy. Assuming that 40% of the food intake is boiled at ΔT=70°C above room temperature, and that 20% of the food intake is fried at ΔT=200°C above room temperature, the energy needed to bring the food up to the cooking temperatures is $P \approx 3.36+4.80 = 8.16$ W/cap., and the energy required for keeping the food cooking is $P \approx 1.45+2.08 = 3.53$ W/cap., assuming daily cooking times of 30 minutes for boiling and 15 minutes for frying (some food cultures certainly use more), and heat losses from the pot/pan/oven averaging 1 W/°C for the quantities of food cooked per person per day.

Provision of water involves pumping and cleaning/purification. The pumping energy needs are negligible on a per capita basis and the treatment energy needs are small, but both are deferred to the industry sector considered below.

Security

Heating and cooling of buildings used by courts, police, military and other security-related institutions are included as part of the floor area accorded each person. The remaining energy use for personal and national security would be for transportation and energy depreciation of materials and would hardly amount to more than 1 W/cap., except for very belligerent nations.

Health

Hot water for personal hygiene is taken as 50 litres per day per capita at maximum T = 40°C above the waterworks' supply temperature, implying a rate of energy use averaging roughly P = 97 W/cap. Some of this could be recycled. Clothes washing and drying may amount to treatment of about 1 kg clothes per day per capita. Washing requirements are assumed to be 5 kg water/kg clothes, at T = 60°C (in practice often more water at a lower temperature), or an average energy of P = 15 W/cap. There is a trade-off between use of lower washing temperatures and use of more chemicals with potential environmental impacts. For drying it is assumed that 1 kg of water has to be evaporated (heat of evaporation about 2.3×10^{6} J/kg) per day per capita, at an effective temperature elevation of 80°C (the actual temperature is usually lower, but mechanical energy is then used to enhance evaporation by blowing air through rotating clothes containers). Local air humidity plays a considerable role in determining the precise figure. Condensing dryers recover part of the evaporation heat, say 50%. The energy use for the case considered is then 17 W/cap.

Hospitals and other buildings in the health sector use energy for space conditioning and equipment. These are included in the household energy use (where they contribute 1-2%).

Human relations

Full goal satisfaction in the area of human relations involves a number of activities, which are not independent on cultural traditions, habitats and individual preferences. One possible combination of energy services for this sector will be used to quantify energy demands.

The need for lighting depends on climate and habits regarding the temporal placement of light-requiring activities, as well as on the age of persons using the light sources. Taking 40 W of present "state of the art" commercial light sources (about 50 lumen per watt) per capita for 6 hours a day, an average energy demand of 10 W/cap. results. Still, the radiant energy from the light sources represents some ten times less energy, and more efficient light sources are likely to become available in the future.

Radio, television and telecommunication take some 40-80 W/cap. for say 3-5 hours a day on average, or an energy flux of 6-12 W/cap, other leisure-related appliances adding some 14-30 W/cap. (listening to music, computing, etc.). Current problems include stand-by power for much of the equipment involved, and that computer equipment, particularly screens and peripherals not being energy-optimised (cf. Sørensen, 1991). This is assumed to improve in the future, but an additional energy expenditure of some 30 W/cap. is included to account for new energy-demanding activities (like automated Internet-down loads and other unattended services). Social and cultural activities taking place in public buildings are assumed to be included above, as far as electric energy is concerned, and to be part of the floor area allocation per capita in regard to space conditioning.

Recreation and social visits entail a need for transportation, by surface or by sea or air. A range of 25-133 W per cap. is taken to be indicative of full goal satisfaction: The upper figure corresponds to travelling 11000 km/y in a road-based vehicle occupied by two persons and using for this purpose 100 litres of gasoline equivalent per year per person. This amount of travel could be composed of 100 km weekly spent on short trips, plus two 500 km trips and one 5000 km trip a year. Depending or habitat and where friends and relatives live, the shorter trips could be reduced or made on bicycle, and whether a yearly long trip is considered necessary for experiencing goal satisfaction is also varying among cultures and individuals. Hence the lower limit is some 5-6 times less than the upper limit. The total demand for transportation will be summarised in a subsection below.

Human activities, including economic activities needed to satisfy human and social goals.

Education (understood as current activities plus lifelong continued education required in a changing world) is assumed to entail building energy needs corresponding to 10% of the residential one, i.e. an energy flux of 0-20 W/cap. for cooling and 0-65 W/cap. for heating.

Construction is evaluated on the basis of one percent of structures being replaced per year. It would be higher in periods of population increase. Measuring structures in units of the one-person space as defined above under the heading "space conditioning", it is assumed that there are about 1.5 such structures per person (including residential, cultural, service and work spaces). This leads to an estimate of the rate of energy spending for construction amounting to 30-60 W/cap. of stationary mechanical energy and a further 7-15 W/cap. for transportation of materials to building site. The energy hidden in materials is deferred to industrial manufacture and raw materials industry.

Agriculture, including fishing, lumber industry and food processing, in some climates re-quires energy for food crop drying (0-6 W/cap.), for water pumping, irrigation and other mechanical work (about 3 W/cap.), electric appliances (about 1 W/cap.) and for transport (tractors and mobile farm machinery, about 6 W/cap.).

The ***distribution and service*** (e.g. repair or retail) sector is assumed, depending on location, to use 0-80 W/cap. of energy for refrigeration, 0-150 W/cap. for heating of commerce or business related buildings, about 20 W/cap. of electric energy for telecommunications and other electric appliances, and about 5 W/cap. of stationary mechanical energy for repair and maintenance service. Transportation energy needs in the distribution and service sectors, as well as energy for commuting between

home and working places outside home, depend strongly on the physical location of activities and on the amount of planning that has been made to optimise such travel, which is not in itself of any benefit. An estimated energy spending is in the range of 30-100 W/cap. depending on these factors. All the energy estimates here are based on actual energy use in present societies, supplemented with reduction factors pertaining to the replacement of existing equipment by technically more efficient types, according to the "best available and practical technology" criterion, accompanied by an evaluation of the required energy quality for each application.

In the same way, the energy use of the ***manufacturing industry*** can be deduced from present data, once the volume of production is known. Assuming the possession of material goods to correspond to the present level in the USA or in Scandinavia, and a replacement rate of 5% per year, one is lead to a rate of energy use in the neighbourhood of 300 W/cap. Less materialistically minded societies would use less. Spelled out in terms of energy qualities there would be 0-40 W/cap. for cooling and 0-150 W/cap. for heating and maintaining comfort in factory buildings, 7-15 W/cap. for internal transportation and 20-40 W/cap. for electrical appliances. Most of the electric energy would be used in the production processes, for computers and for lighting, along with another 20-40 W/cap. used for stationary mechanical energy. Finally, the process heat requirement would comprise 10-100 W/cap. below 100°C, 20-70 W/cap. from 100-500°C and 12-30 W/cap. above 500°C, all measured as average rates of energy supply, over industries very different in regard to energy intensity. Some consideration is given to heat cascading and reuse at lower temperatures, in that the energy requirements at lower temperatures has been reduced by what corresponds to about 70% of the reject heat from the processes in the next higher temperature interval.

Most difficult to estimate is the future energy needs of the ***resource industry***. This is for two reasons: one is that the resource industry includes the energy industry, and thus would be very different depending on which supply option or supply mix is chosen (being very different for the four global scenarios considered in Chapters 3-5). The second factor is the future need for primary materials: will it be based on new resource extraction as it is largely the case today, or will recycling increase to near 100%, for environmental and economic reasons connected with depletion of mineral resources?

As a concrete example, let us assume that renewable energy sources are used. The extraction of energy by a mining and an oil & gas industry as we know it today will disappear and the energy needs for providing energy will take a quite different form, related to renewable energy conversion equipment which in most cases is more comparable to present utility services (power plants etc.) than to a resource industry. This means that the energy equipment manufacture becomes the dominant energy requiring activity.

For other materials, the ratios of process heat, stationary mechanical energy and electricity use depend on whether mining or recycling is the dominant mode of furnishing new raw materials, so if ranges are estimated, then not all maxima are supposed to become realised simultaneously, and neither all minima. The numbers are assumed to comprise both those of the energy industry and for all material provision industries. The basis assumption is high recycling, but for the upper limits not quite 100% and adding new materials for a growing world population. The assumed ranges are 0-30 W/cap. for process heat below 100°C, the same for the interval 100-500°C, 0-250 W/cap. above 500°C, 0-170 W/cap. of stationary mechanical energy, 0-30 W/cap. of electrical energy and 0-20 W/cap. of transportation energy.

Total amount of energy for transportation

Energy for the transportation sector is by 2050 either electricity (trains and urban electric vehicles) or fuels (bio-fuels such as methanol, or hydrogen). The total net end-use energy for road transportation is summarised in Table 2.3. It only accounts for basic friction losses and assumes acceleration and potential energy (when climbing uphill) expenditures as partially reclaimed during breaking and downhill driving, and similar assumptions are made for other types of transport. It is therefore assumed that the energy delivered to the vehicle must be twice the end-use energy. For fuel-cell operation this accounts for typical conversion losses (fuel cell efficiencies of 50% are still considerably higher than the efficiencies around 20% characterising most current gasoline or diesel cars), and for electric vehicles, where the energy efficiency is well over 90%, the 50% "loss" may be considered to represent storage cycle losses in battery charging processes and discharges during extended parking. The delivered energy for transportation given in Table 2.6 is simply twice that obtained by multiplying the value from Table 2.3 by the goal satisfaction factor of Table 2.4. Its geographical distribution is given in Figure 2.9.

Total demand for electricity and other high-quality energy

In Table 2.6, the energy not related to space conditioning, food or transportation is labelled "Electricity etc.". It comprises medium and high temperature heat, refrigeration other than space cooling, stationary mechanical energy and dedicated electric energy. The reason for this coarse summation is the abundance of sources for producing electrical energy in most of the scenarios. In cases where a more detailed analysis is needed it will be given. No distinction is made between delivered and end-use energy, as the electricity to heat losses are zero and the electric appliance energy inputs are anyway estimated as electricity delivered, in our sources. The geographical distribution assumed in the 2050 scenario is shown in Fig. 2.10.

There is obviously a lack of accuracy in any estimate of future energy demands, and certainly in the one made here. This could make the estimates both too low and too high: new activities involving energy may emerge, and the efficiency of energy use may further increase by use of novel technology. Yet it is reassuring that the energy demands estimated for full goal satisfaction (for a choice of goals not in any way restrictive) are much lower than the present use in industrialised countries. It demonstrates that bringing the entire world population, including underdeveloped and growing regions, up to a level of full goal satisfaction is not precluded for any technical reasons. The scenarios constructed in Chapters 3-5 display this in the stated efficiency gains amounting to about a factor of four.

2.4 SCENARIO OF ENERGY DEMAND AT END-USER

The energy demand analysis will now be applied to the regions used in the present study (see Appendix A) to determine the actual end-use energy required by year 2050. First, a summary of the type of energy demand analysis described above is given for the current energy system in Table 2.2, spelled out on energy use categories (reflecting the different qualities of energy, from low-temperature heat to specific electric or mechanical energy for mobile use, and including human food intake as an energy input - a choice made because it is useful in analysing future renewable energy use with a supply system using bio-energy for both food and energy purposes). Note that the above definition of end-use energy differs from what some statistical sources denote "end-use" or "final" energy.

Table 2.3 then projects the net end-use energy per capita energy demands of Table 2.2 into a future situation, where all members of the future society (population about 10 billion) enjoy fulfilment of both basic and derived needs as defined in section 2.3 (and including some that are not anticipated now and therefore have been included only as an overall growth percentage). Spelled out in terms of GNP per capita this as stated above involves more than a tripling of current end-use energy even in Western Europe, Japan and the United States, and for the presently poor countries a lift to similar levels (only varying due to different needs for heating and cooling, due to different transportation needs depending on settlement densities, and due to the mix of industrial activities assumed for each region). The totals are based on the 2050 population estimates. Again the assumption is made that there be of no major wars or other oppression blocking the economic development and causing an uneven distribution of wealth between those benefiting from a "war economy" and those suffering destruction of their assets.

Finally, Table 2.4 shows the actual demand scenario to be used in the following system analysis (clearly, other scenarios can be defended, but the choice here is to use a single demand scenario together with several supply scenarios). The Table shows the assumptions made to arrive at the actual end-use energy demand in year 2050, expressed in terms of the closeness of different societies to the "goal society" of Table 2.3. Factors included in this analysis include starting level of educational skills, presence of repressive rulers and fundamentalist institutions, as well as indications of the current rate of development. The ideal energy provisions of Table 2.3 would then be multiplied with the fraction of goal satisfaction derived from Table 2.4, reflecting the different weight given in the regional development processes to personal comfort, industrial manufacture and transportation. Food energy is consistently treated on the same footing as other energy forms, which is convenient in scenarios using biomass both for food production and for energy purposes.

The extensive use of electrical energy in the supply scenarios described below allows the simplification of not distinguishing between stationary mechanical energy, necessary electric energy (i.e. where electricity is not performing tasks that could be performed as well by fuels) and high-temperature heat. E.g. in the renewable energy scenarios, it is assumed that all low-temperature heat and refrigeration is provided by electrically driven heat pumps. For heat provision, this regains the thermodynamical efficiency factor that would be lost if electricity was used for direct resistance heating. Why the alternative of using solar thermal collectors for low-temperature heat is not explicitly treated is explained in the supply section below. In the transportation sector, there is a possibility to work with either electric energy or bio-fuels, and for providing food, an important choice is between vegetable and animal constituents of the food mix delivered to the end-users. In the section on demand above, specific assumptions were made in these cases of choice.

The use of a common demand scenario allows a common quantity called ***delivered energy*** to be specified. It is the energy delivered to the end-user before his final conversion into goods or services. The delivered energy is essentially the "final energy" found in many statistical sources of historical data, and it is the quantity of interest from the energy supplier's point of view. Therefore it is convenient to keep track of this quantity throughout the construction of supply scenarios.

2.5 SUMMARY OF 2050 SCENARIO ENERGY DEMAND.

The total amounts of energy that have to be delivered to the end-users are shown in Table 2.6, split on regions and given both as totals and per capita energy flows. The geographical distribution is shown in Fig. 2.11. The average energy demand is 0.9 W/cap or three times the amount furnished today (cf. Table 2.2). This proves that the 2050 scenario does indeed assume a considerable lift in the activities depending on energy supply. In judging the fairly low absolute value it should be kept in mind, that the primary energy produced today (the global average of which is about 2 W/cap.) goes through a number of conversion processes before reaching the final consumer and being converted to end-use products or services. The central conversion processes have efficiencies of around 0.3 (fuel efficiency of average electric power plant plus transmission losses) to around 0.9 (fuel combustion in industry). A large part of the current losses from a primary average production of 2 W/cap. to an end-use energy of only 0.3 W/cap. is therefore associated with the final conversion taking place at the end user. This is consistent with our data indicating that end-use conversion efficiency is improved by a factor of 3-4, when the current equipment is replaced with the best available. In the 2050 scenario, the currently most efficient equipment is assumed to be used, and the delivered energy of 0.9 W/cap. The ratio of required primary production (see Chapters 3-5) and end-use energy is also smaller than the current one, particularly for the renewable energy scenarios.

Table 2.2. Analysis of end-use energy 1994.

Region: 1994 analysis of end-use energy	1. United States, Canada	2. W. Europe, Japan, Australia	3. E. Europe, Ex-Soviet, Mid. East	4. Latin America, SE Asian "tigers"	5. China, India, rest of Asia	6. Africa	Average / total	
Space	186	207	61	2	19	1	46	W/cap
Heating	52	116	41	1	48	1	260	GW
Other low-T	120	130	40	15	18	10	36	W/cap
heat	34	73	27	12	47	7	199	GW
Medium-T	40	50	30	10	10	5	17	W/cap
heat	11	28	20	8	26	3	97	GW
High-T	35	40	30	10	10	3	16	W/cap
heat	10	22	20	8	26	2	88	GW
Space	9	1	13	2	3	0	4	W/cap
cooling	2	1	9	2	8	0	22	GW
Other re-	29	23	14	2	2	0	7	W/cap
frigeration	8	13	9	1	5	0	37	GW
Stationary	100	130	80	25	5	4	34	W/cap
mechanical	28	73	53	21	13	3	191	GW
Electric	110	120	50	20	5	4	29	W/cap
appliances	31	67	33	16	13	3	164	GW
Transpor-	200	140	40	20	5	3	34	W/cap
tation	56	79	27	16	13	2	193	GW
Food	120	120	90	90	90	90	95	W/cap
energy	34	67	60	74	233	61	530	GW
Total end-use	**948**	**962**	**448**	**195**	**167**	**121**	**318**	**W/cap**
energy	**268**	**540**	**298**	**160**	**432**	**83**	**1781**	**GW**
Population 1994	282	561	666	820	2594	682	5605	million
Region area	20	15	28	26	20	31	141	million km^2

Regions are different from those employed in Table 2.1 and from those used in Sørensen (1996); see Appendix A for a list of countries included in each region. The assumption is that development patterns are similar in each of the regions constructed. Space heating and cooling are calculated on a geographical grid by the method described in the text. The other entries depend on population density and the goal satisfaction fraction given in Table 2.4 for 1994.

Table 2.3. Per capita end-use energy for "full goal satisfaction" and corresponding total end-use energy assuming the population estimates for year 2050.

Regions: / Energy quality:	1. United States, Canada	2. W. Europe, Japan, Australia	3. E. Europe, Ex-Soviet, Mid. East	4. Latin America, SE Asian "tigers"	5. China, India, rest of Asia	6. Africa	**Average / Total**
Space heating*	201	186	191	7	225	10	
Other low-temp. Heat	150	150	150	150	150	150	
Medium-temp. Heat	50	50	50	50	50	50	
High-temp. Heat	40	40	40	40	40	40	
Space cooling*	9	2	50	14	168	44	
Other refrigeration	35	35	35	35	35	35	
Stationary mechanical	150	150	150	150	150	150	
Electric applicances	150	150	150	150	150	150	
Transportation	200	150	200	150	150	150	
Food energy	120	120	120	120	120	120	
Total 2050 end-use e.	**1105 419**	**1033 545**	**1136 1181**	**866 1195**	**1238 4902**	**899 1834**	**1079 W/cap. 10076 GW**
Population 2050	379	528	1040	1380	3960	2040	**9340 millions**
Total area million km^2	20.1	15.4	28.3	26.3	20.1	30.9	141.1

* These rows are evaluated on the basis of temperature data in each GIS cell.

In the table, it is assumed that the distribution between regions of manufacturing industries and raw materials industries is proportional to the populations in each region. However, within each region there may be large differences. The same is true for variations in demand for space conditioning within regions induced by climate (for an assumed 60 m^2 of heated or cooled space per capita), and in the case of transport by major differences between population densities within settled areas. Except for these more detailed investigations, the numbers are as in Sørensen (1996).

Table 2.4. Fraction of "full goal satisfaction" assumed reached in 2050 scenario (estimated values for 1994 given for comparison, in parentheses).

Regions: / Energy quality:	1.United States, Canada	2.W. Europe, Japan, Australia	3. E. Europe, Ex-Soviet, Mid. East	4. Latin America, SE Asian "tigers"	5. China, rest of Asia	6. Africa
Space heating	0.9 (0.9)	1.0 (0.96)	0.75 (0.25)	0.67 (0.08)	0.63 (0.16)	0.15 (0.10)
Other low-temp. heat	0.87 (0.8)	1.0 (0.87)	0.53 (0.27)	0.6 (0.10)	0.67 (0.12)	0.13 (0.07)
medium-temp. heat	0.9 (0.8)	1.0 (1.0)	0.8 (0.6)	0.8 (0.2)	0.8 (0.2)	0.1 (0.1)
High-temp. heat	0.88 (0.88)	1.0 (1.0)	0.75 (0.75)	0.75 (0.25)	0.75 (0.25)	0.13 (0.08)
Refrigeration	1.0 (0.83)	1.0 (0.67)	0.4 (0.4)	0.5 (0.05)	0.33 (0.05)	0.05 (0.01)
Stationary mechanical	0.93 (0.67)	1.0 (0.87)	0.53 (0.53)	0.67 (0.17)	0.67 (0.03)	0.13 (0.03)
Electric applicances	1.0 (0.73)	1.0 (0.8)	0.53 (0.33)	0.67 (0.13)	0.67 (0.03)	0.1 (0.03)
Transportation	0.9 (1.0)	1.0 (0.93)	0.35 (0.20)	0.67 (0.13)	0.33 (0.03)	0.1 (0.02)
Food energy	1.0 (1.0)	1.0 (1.0)	1.0 (0.75)	1.0 (0.75)	1.0 (0.75)	0.83 (0.75)
Averages of the above	**0.93 (0.85)**	**1.0 (0.90)**	**0.62 (0.45)**	**0.68 (0.21)**	**0.64 (0.18)**	**0.20 (0.13)**

In distributing industrial manufacture on regions, it is assumed that robot technology provides a "backstop" wall against excessively low-salaried regions, but in any case, most regions are assumed to reach a high level of wealth before year 2050, implying that little low-salary advantage will be left by then. An exception is Africa, and at the same time a chance for this continent to catch up, if a viable manufacturing industry can be established. In the transition period 1990-2050, this role was regarded as assumed by regions 3-5.

Table 2.5. Current food delivery to end-users (Alexandratos, 1995)

Food supplies 1990	Total (W/cap.)	Animal food (%)	Vegetable food (%)
US/Canada/W.Europe/Oceania	166	53	47
Formerly Centrally Planned	164	44	56
Latin America	131	33	67
South Asia	108	21	79
East Asia	127	9	91
Middle East/N. Africa	146	21	79
Sub-Sahara Africa	102	10	90
World	**131**	**28**	**72**
Developing countries	120	16	84
Developed countries	165	32	68

Table 2.6. Energy delivered to end-user in 2050 scenario.

Regions: / Energy quality:	1. United States, Canada	2. W. Europe, Japan, Australia	3. E. Europe, Ex-Soviet, Mid. East	4. Latin America, SE Asian "tigers"	5. China, rest of Asia	6. Africa	**Average / Total**
Food based on animals	30 45 17	30 45 24	30 45 47	25 37 52	25 37 148	20 25 51	**23 %** **36 W/cap.** **339 GW**
Food based on grain & vegetables	70 119 45	70 119 63	70 119 124	75 128 177	75 128 506	80 114 232	**77 %** **123 W/cap.** **1148 GW**
Gross transportation energy	359 136	299 158	140 146	201 277	99 392	30 61	**125 W/cap.** **1170 GW**
Heat pump input for low-T heat and cooling	103 39	110 58	87 90	43 60	80 318	22 45	**65 W/cap.** **610 GW**
Environmental heat	240 91	256 135	203 210	100 140	186 741	51 105	**151 W/cap.** **1421 GW**
Direct electric and all other energy	420 153	424 224	245 255	288 398	283 1116	47 96	**240 W/cap.** **2242 GW**
Total delivered energy*	**1272** **482**	**1252** **661**	**838** **871**	**800** **1104**	**814** **3225**	**290** **591**	**742W/cap.** **6934 GW**
Population 2050	379	528	1040	1380	3960	2040	**9340 millions**

* Including heat drawn from the environment by heat pumps.

In Figs. 2.12 to 2.17, the energy demand scenario assumptions illustrated once more, but this time in a country-averaged fashion, which will be useful in comparing with the fossil and nuclear supply scenarios, that are created on the same basis. Here detailed area match between supply and demand would not give further insights, as it does for the renewable energy scenario, where much of the supply infrastructure is decentralised down to solar panels installed on individual buildings. For the fossil and nuclear scenarios, the underground or off-shore resources constitute a "centralised" supply which in any case has to be transported to the point of use, often in a different country.

Figure 2.12 and 2.13 give the required food delivery of vegetable and animal type, Fig. 2.14 and 2.15 the required energy delivery for transportation and low-temperature heat (expressed as input to heat pumps delivering that energy, but with suitable multiplication by the COP factor of 3.33 also useful in determining the need for direct heat delivery). Figs. 2.16 gives the remaining energy requirement, termed "electricity etc.", comprising dedicated electricity, stationary mechanical energy and medium and high temperature process heat, and Fig. 2.17 the total demand (cf. Table 2.6).

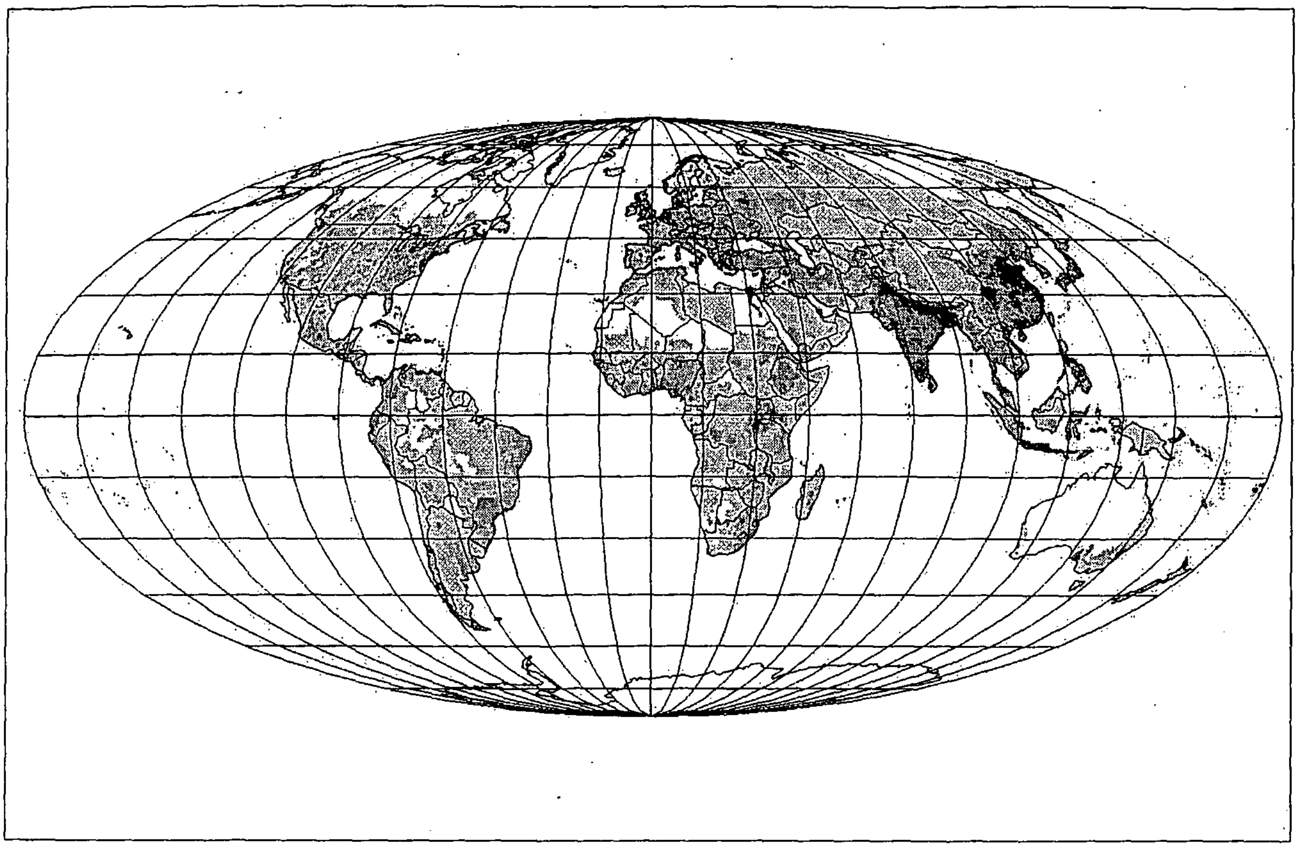
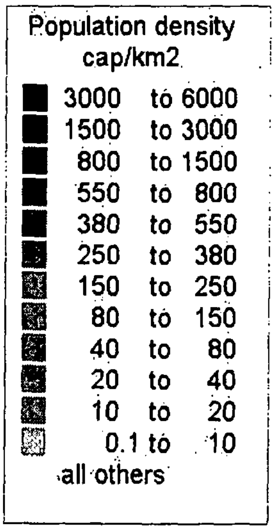


Figure 2.1a: Present population density: 1994 data (source: CIESIN, 1997; scale given in Figure 2.1b). This and all following geographical maps are employing the Mollweide equal area projection, consistent with our rendering of area-based densities of various quantities. This means that visual summing up over or comparison between different regions will be correct, in contrast to the situation for e.g. longitude-latitude square grids.

Figure 2.1b: Population scale (people per km^2, note that the scale is not linear).



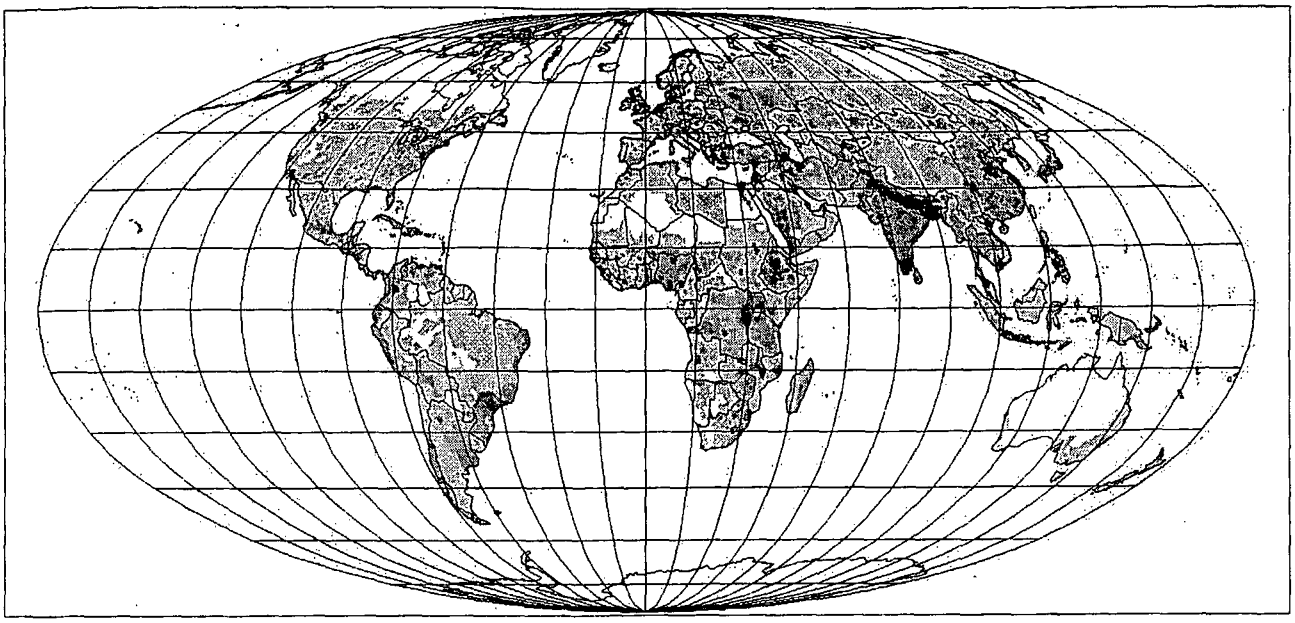


Figure 2.2. Population density assumed in 2050 (scale given in Figure 2.1b).

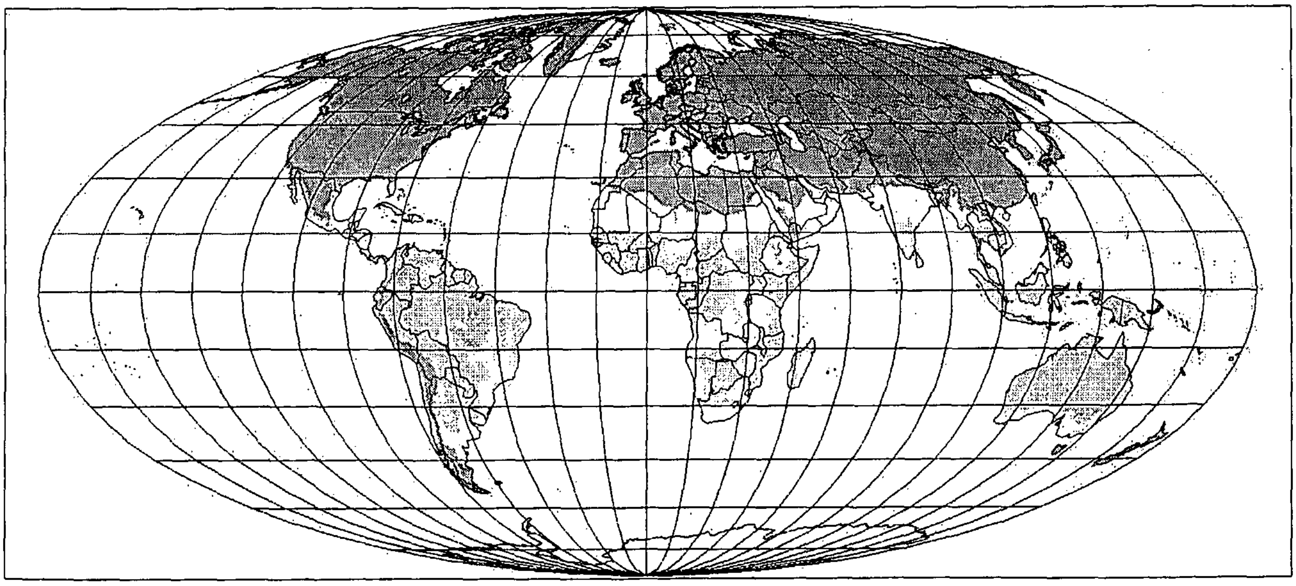


Figure 2.3a. January average temperatures indicating areas with space heating and cooling needs (source: Leemans and Cramer, 1998; the scale is given in Figure 2.3e).

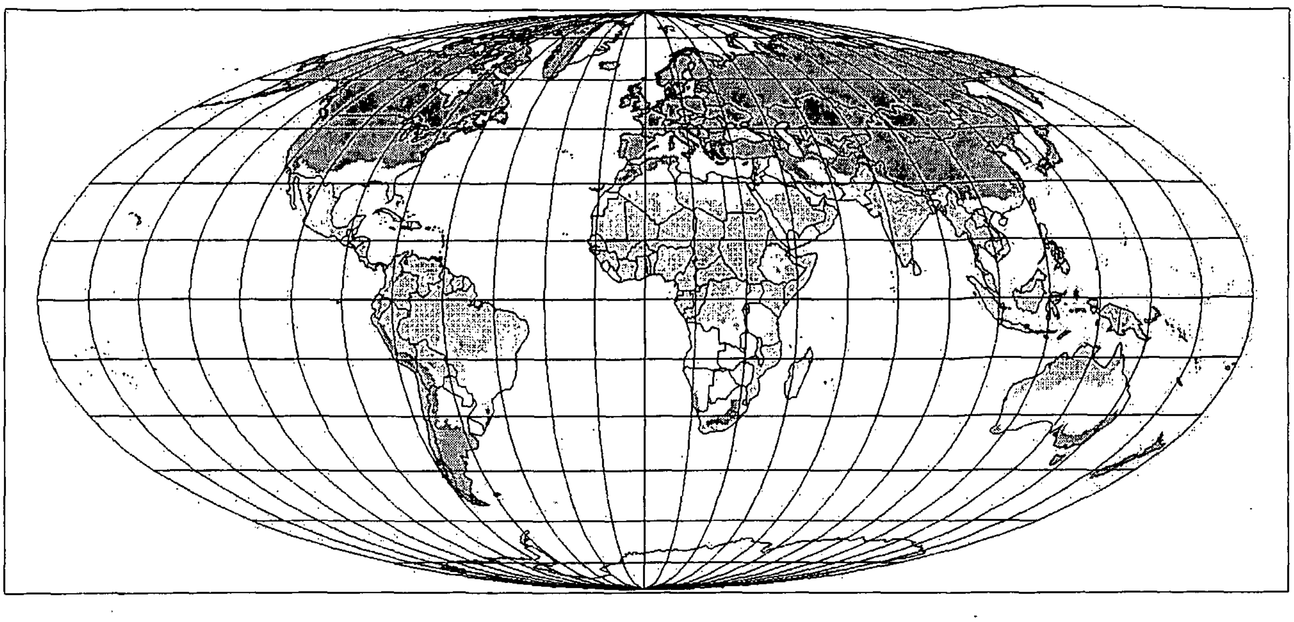


Figure 2.3b. April average temperatures indicating areas with space heating and cooling needs (source: Leemans and Cramer, 1998; the scale is given in Figure 2.3e).

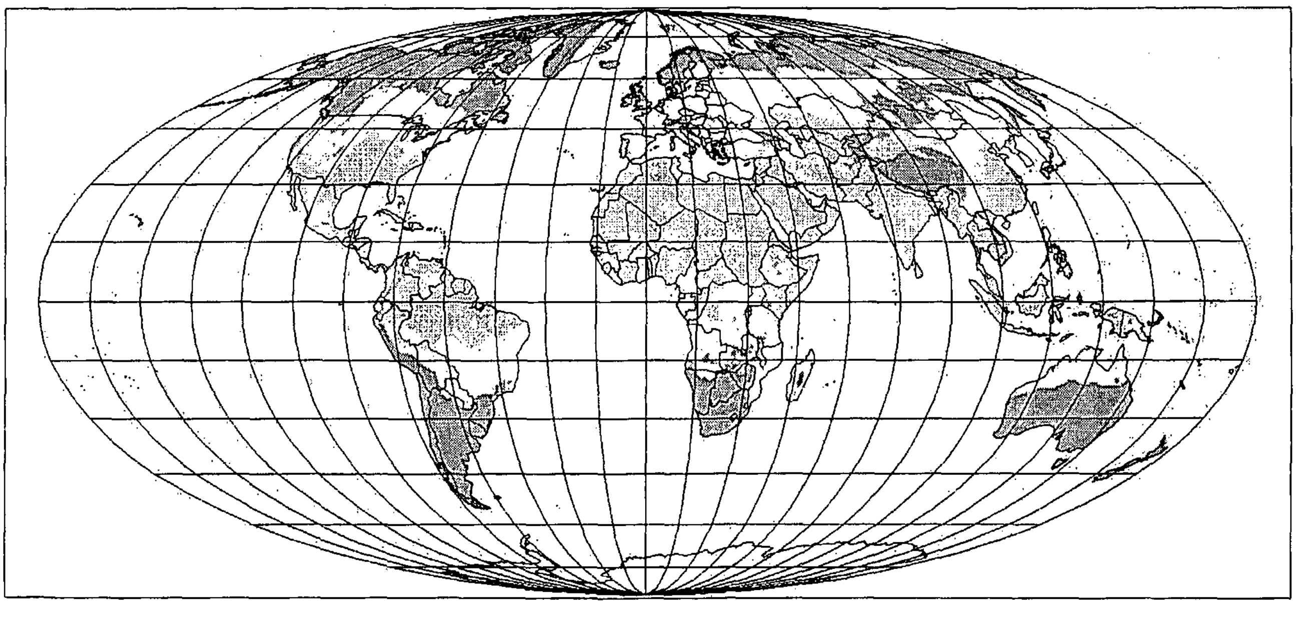


Figure 2.3c. July average temperatures indicating areas with space heating and cooling needs (source: Leemans and Cramer, 1998; the scale is given in Figure 2.3e).

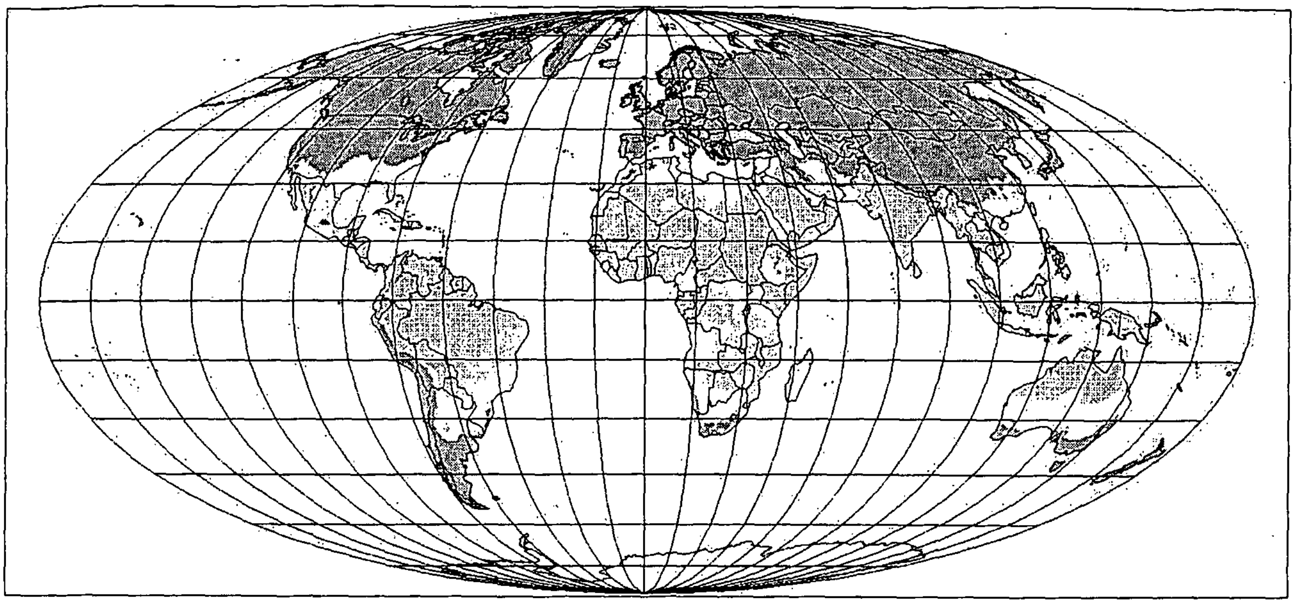
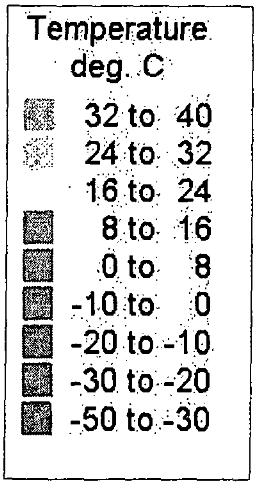


Figure 2.3d. October average temperatures indicating areas with space heating and cooling needs (source: Leemans and Cramer, 1998; the scale is given in Figure 2.3e).

Figure 2.3e. Temperature scale (deg. C)



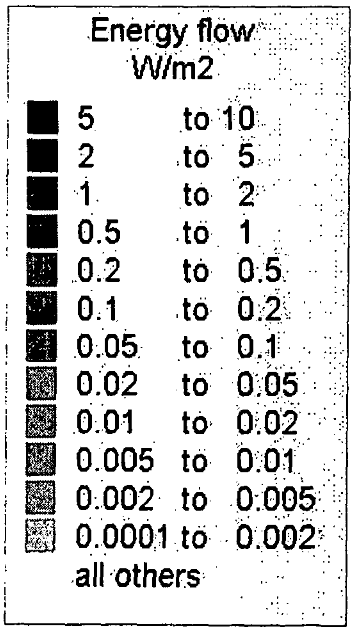


Figure 2.4e. Scale of energy flow (rate of energy capture, conversion or use, note that the scale is logarithmic) (W/m^2).

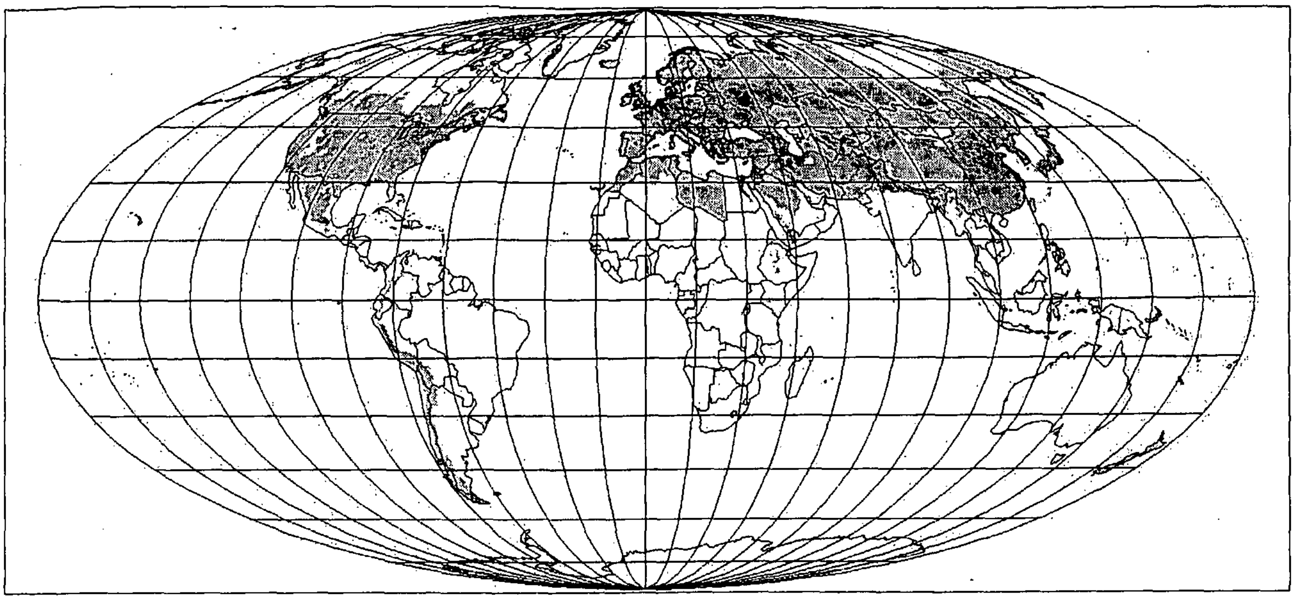


Figure 2.4a. January space heating energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

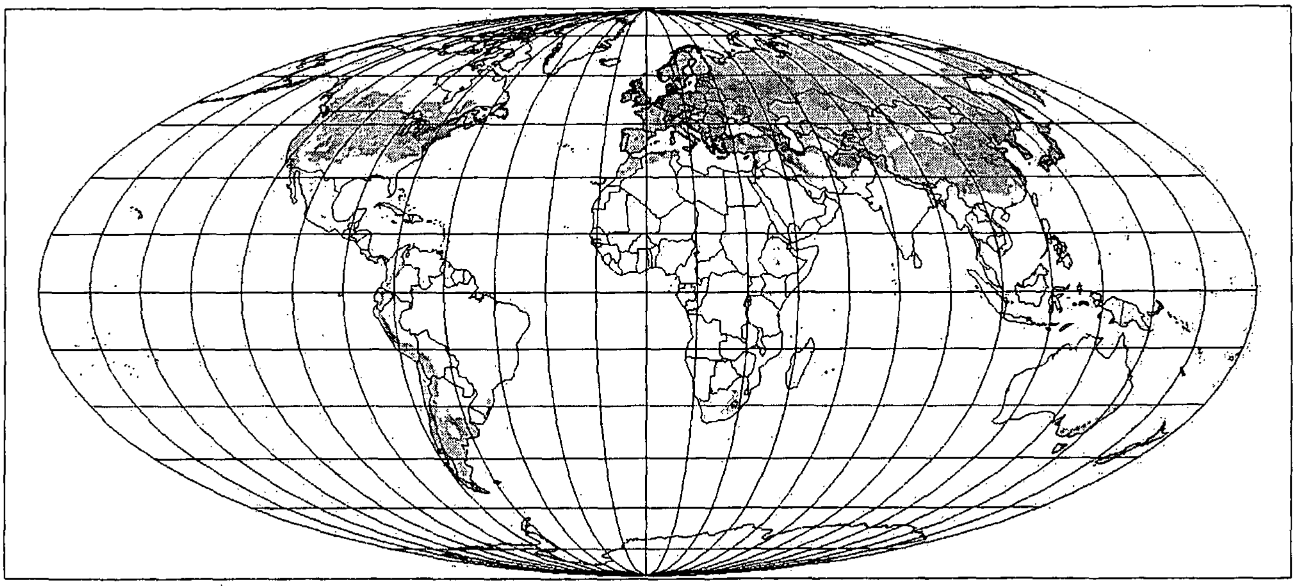


Figure 2.4b. April space heating energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

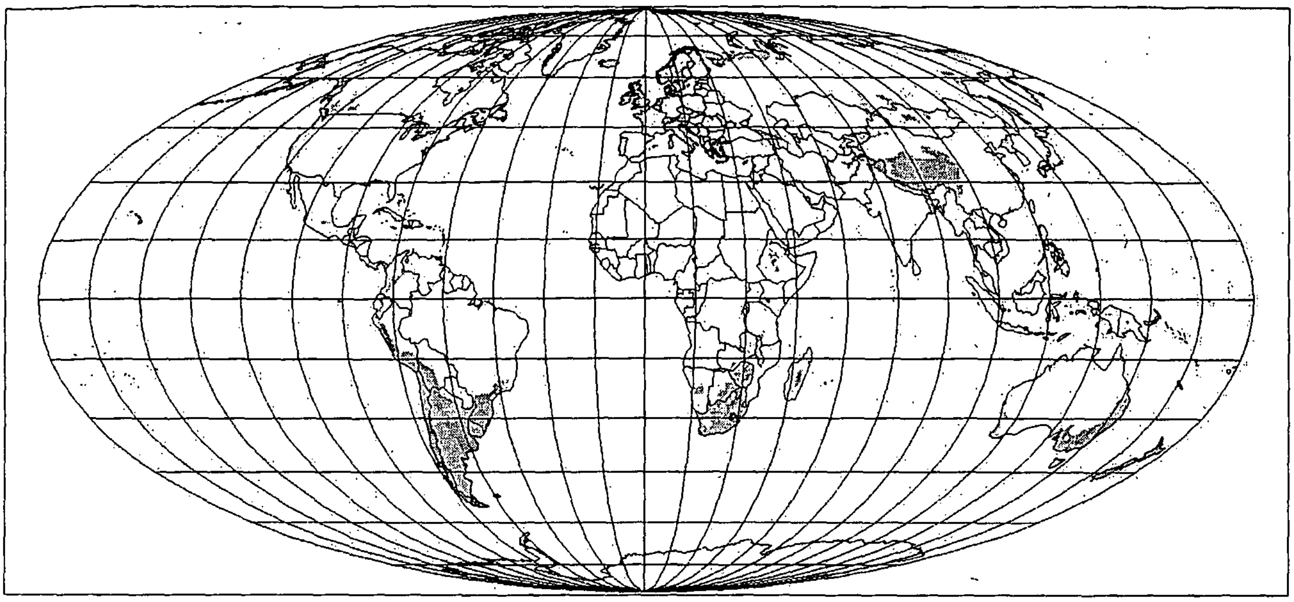


Figure 2.4c. July space heating energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

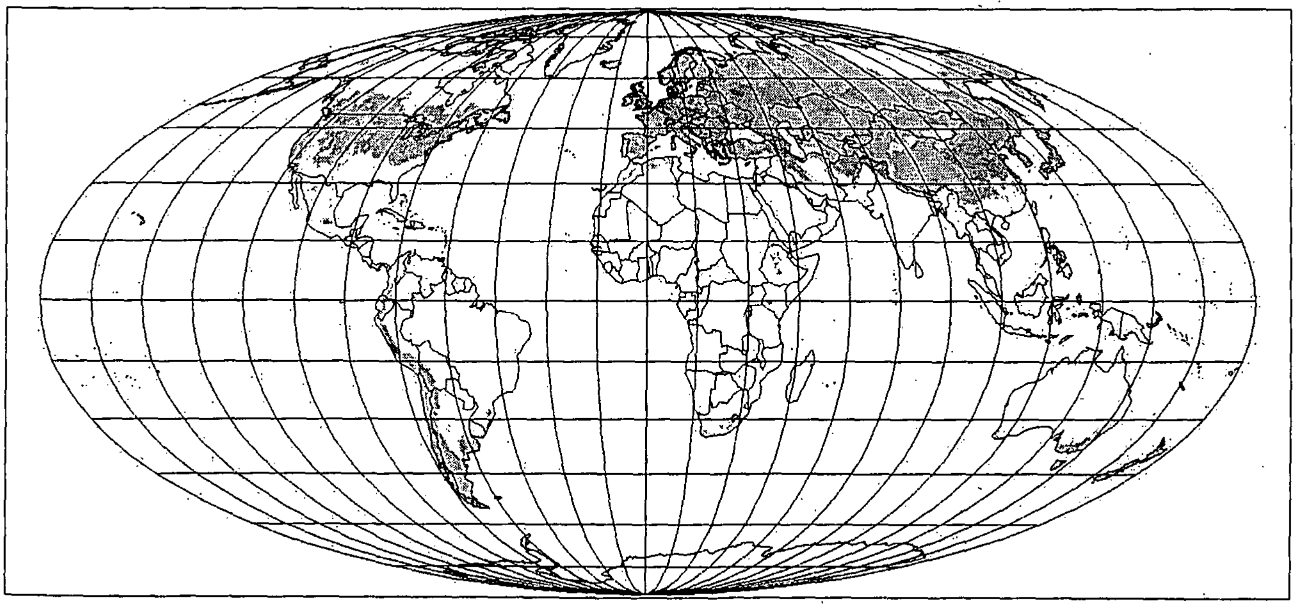


Figure 2.4d. October space heating energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

(Figure 2.4e appears on page 21).

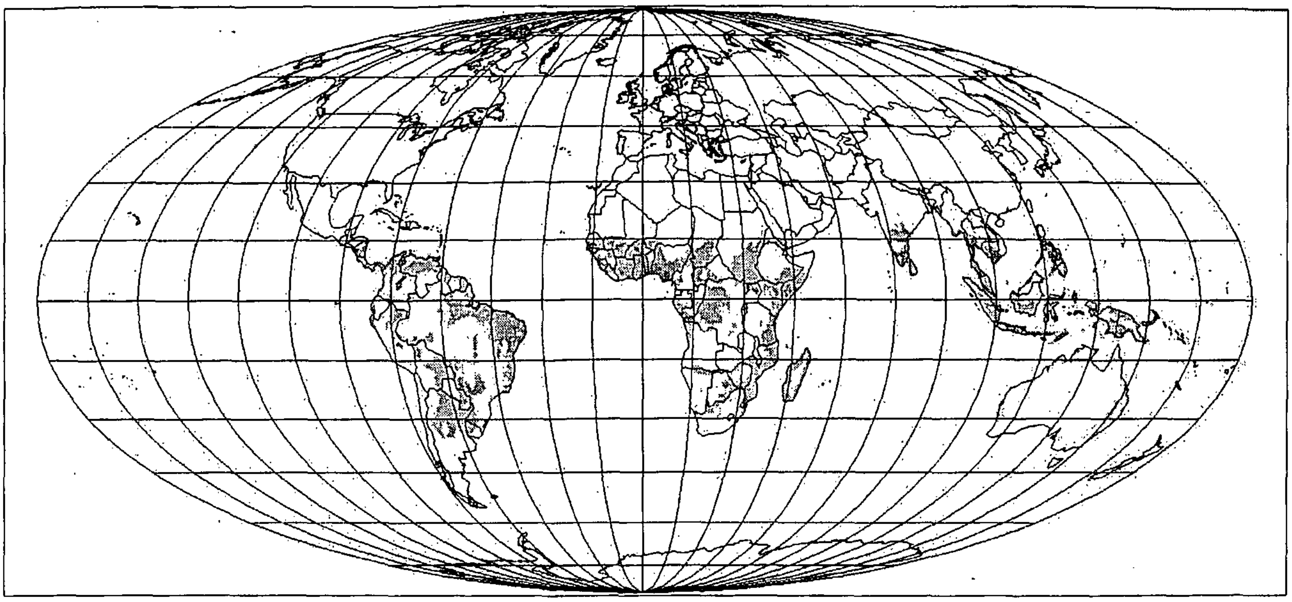


Figure 2.5a. January space cooling energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

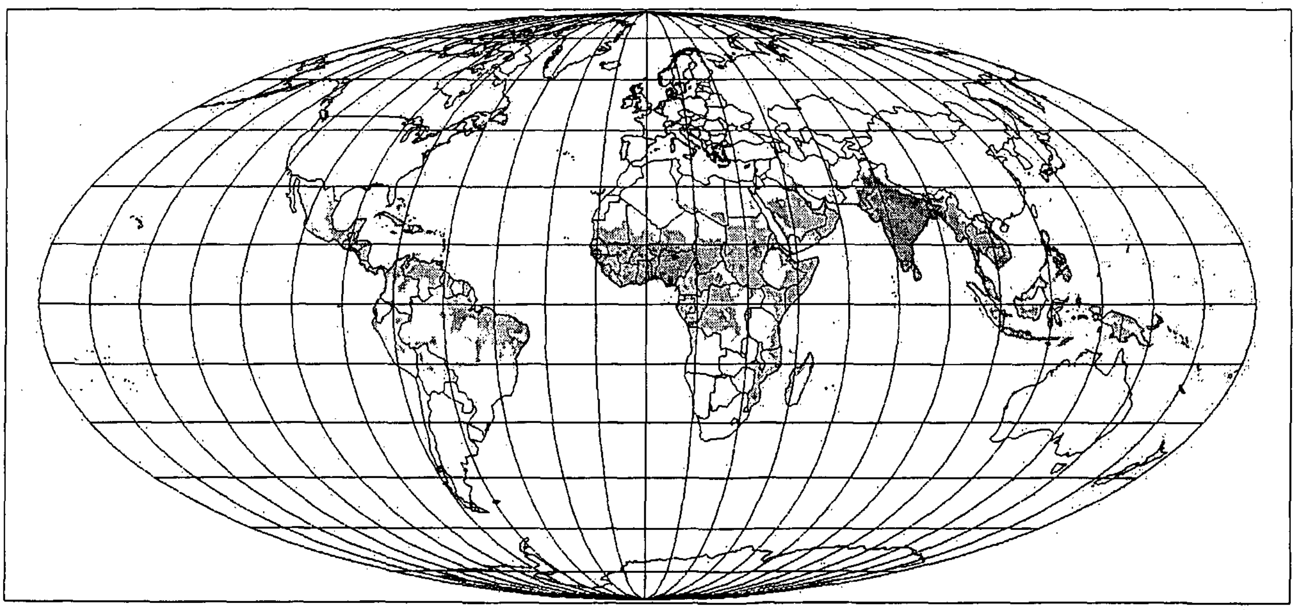


Figure 2.5b. April space cooling energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

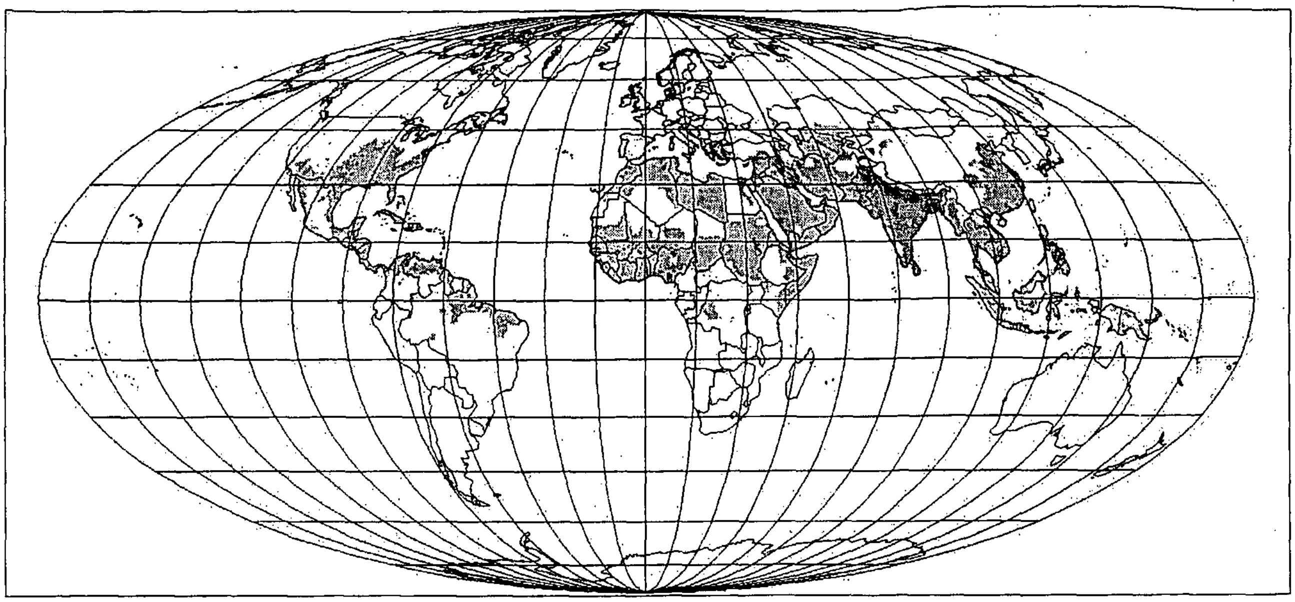


Figure 2.5c. July space cooling energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

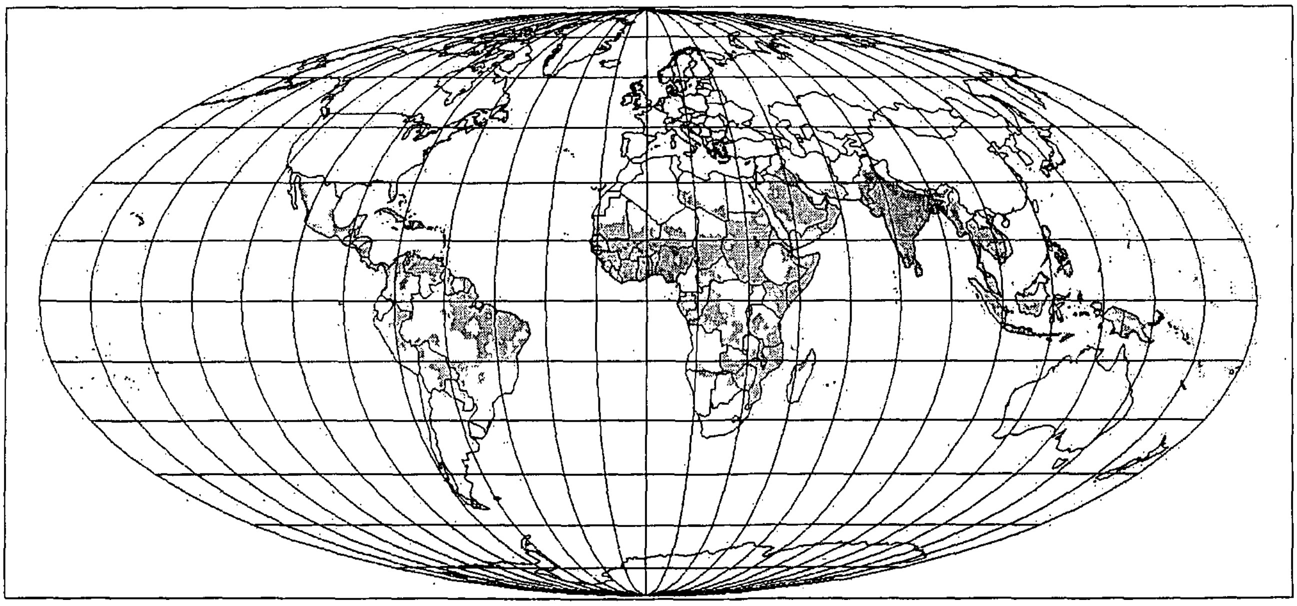


Figure 2.5d. October space cooling energy requirements for full satisfaction of indoor comfort needs (scale given in Figure 2.4e).

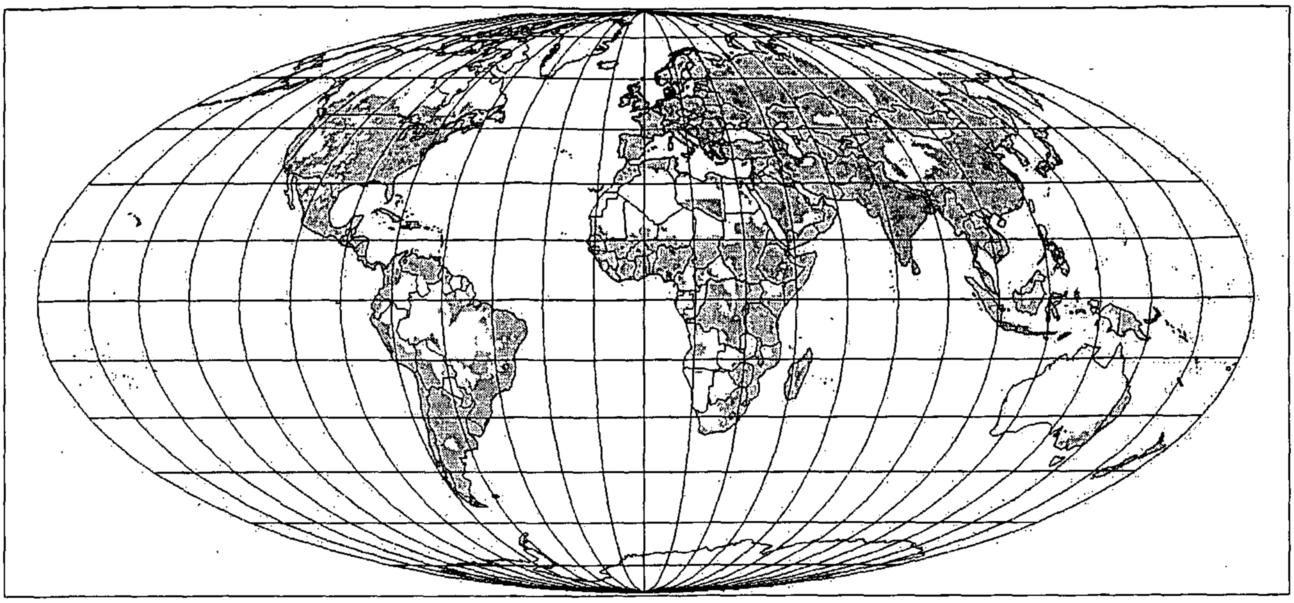


Figure 2.6. Annual average energy input to heat pumps producing space heating, space cooling and other low temperature heat, as delivered to consumers in 2050 scenario (scale given in Figure 2.4e). Annual averages in this and following figures are constructed from January, April, July and October data and may differ slightly from the 12 month averages.

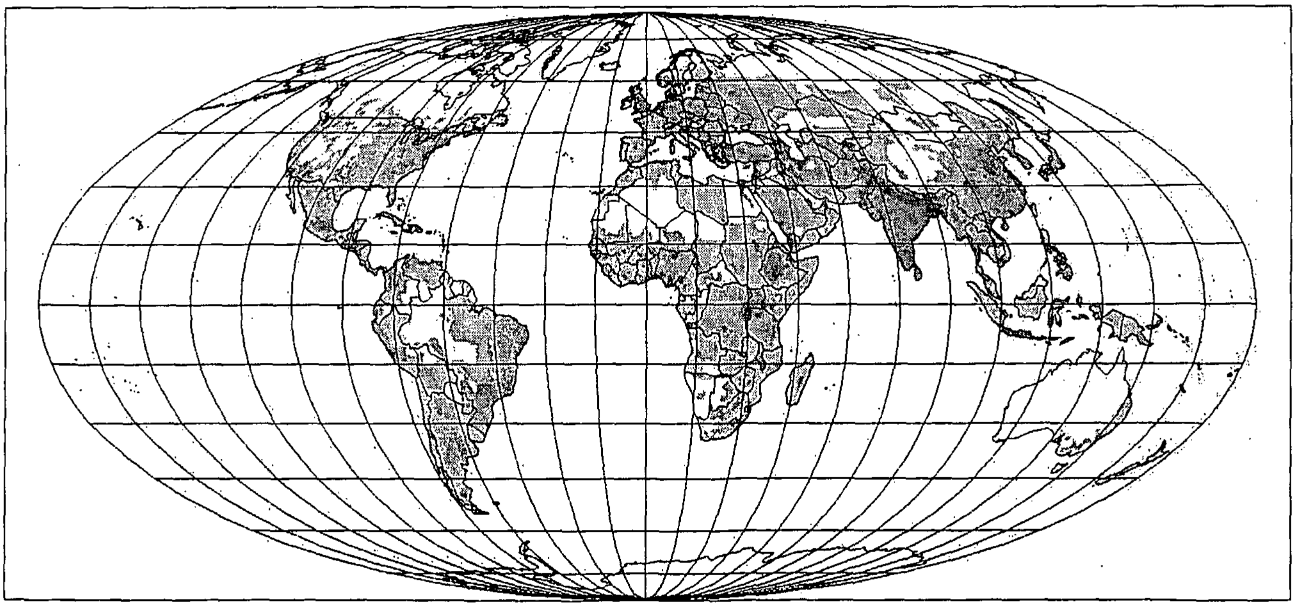


Figure 2.7. Gross energy content in food of vegetable type delivered to consumers in 2050 scenario (scale given in Figure 2.4e).

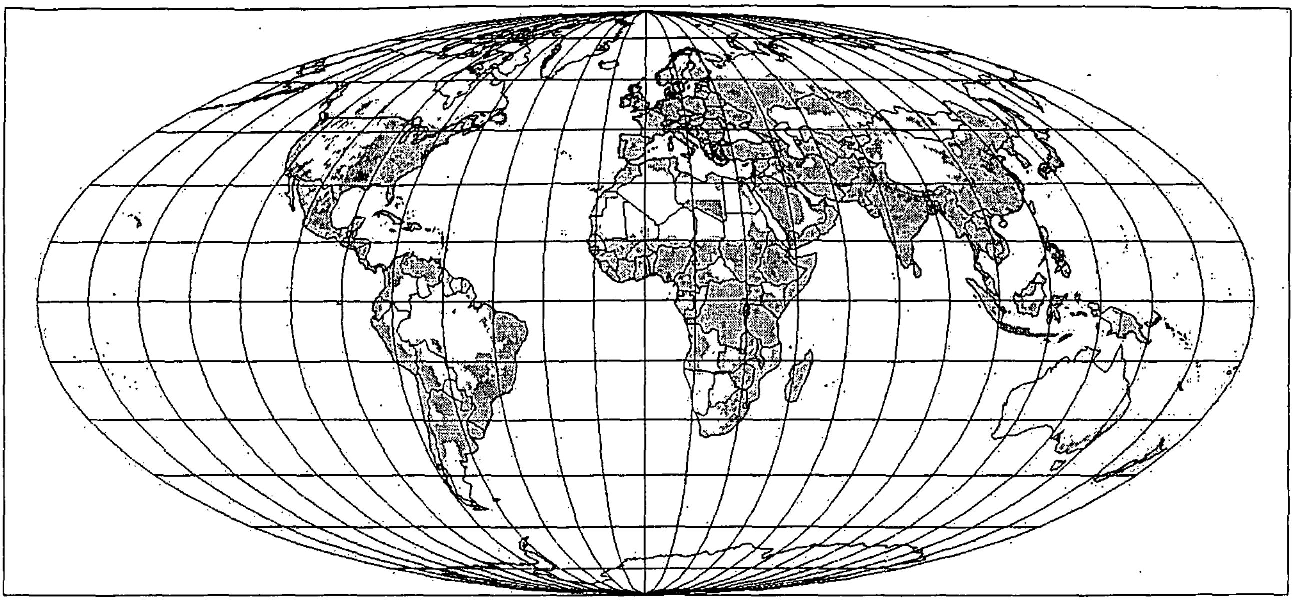


Figure 2.8. Gross energy content in food of animal type delivered to consumers in 2050 scenario (scale given in Figure 2.4e).

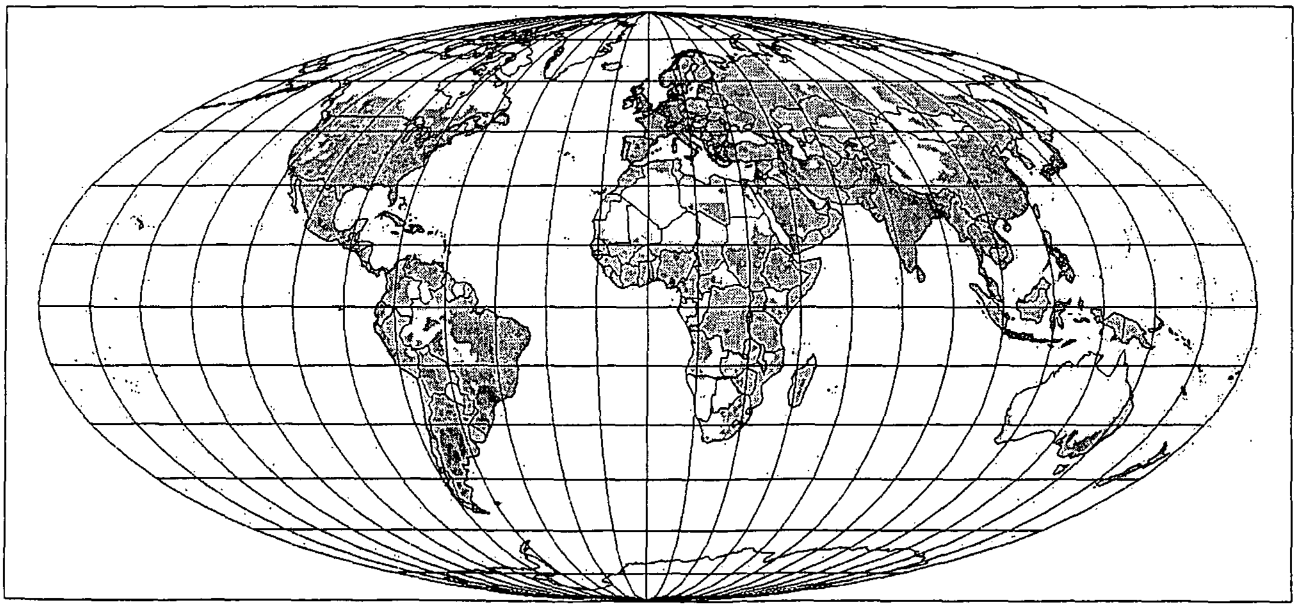


Figure 2.9. Gross energy demand at delivery to consumer, for all forms of transportation in the 2050 scenario (scale given in Figure 2.4e).

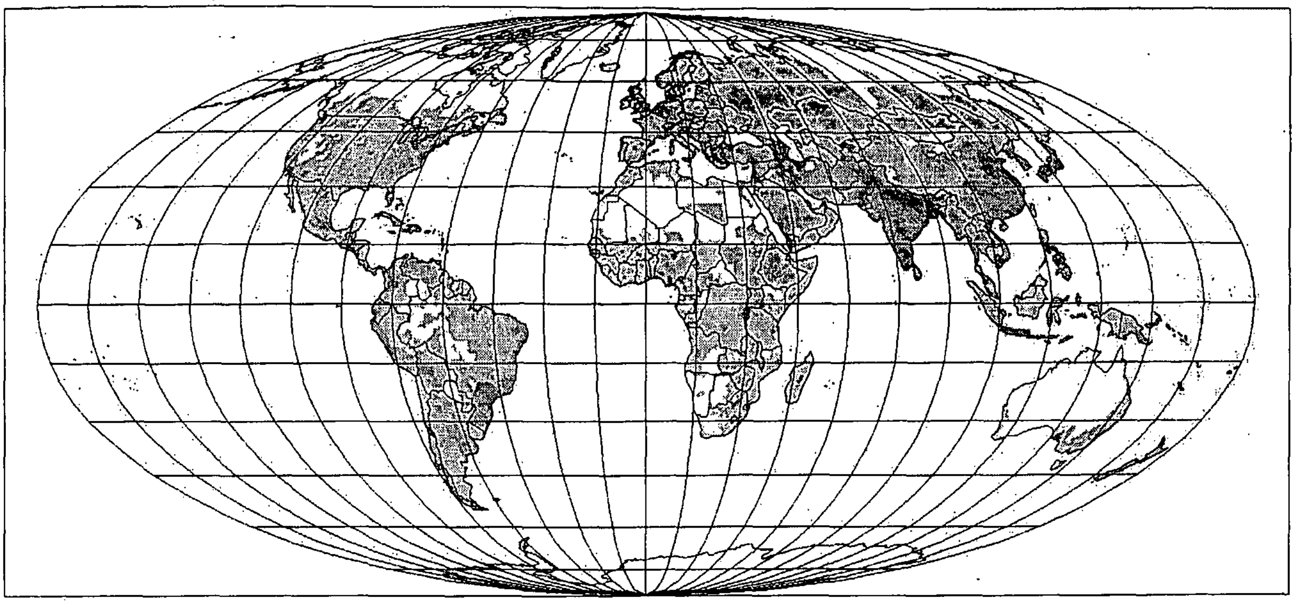


Figure 2.10. Energy demand at delivery to consumer, for electric energy including energy for dedicated electric appliances, stationary mechanical energy and medium- and high-temperature industrial heat. Refrigeration energy inputs other than those for space cooling are included (scale given in Figure 2.4e).

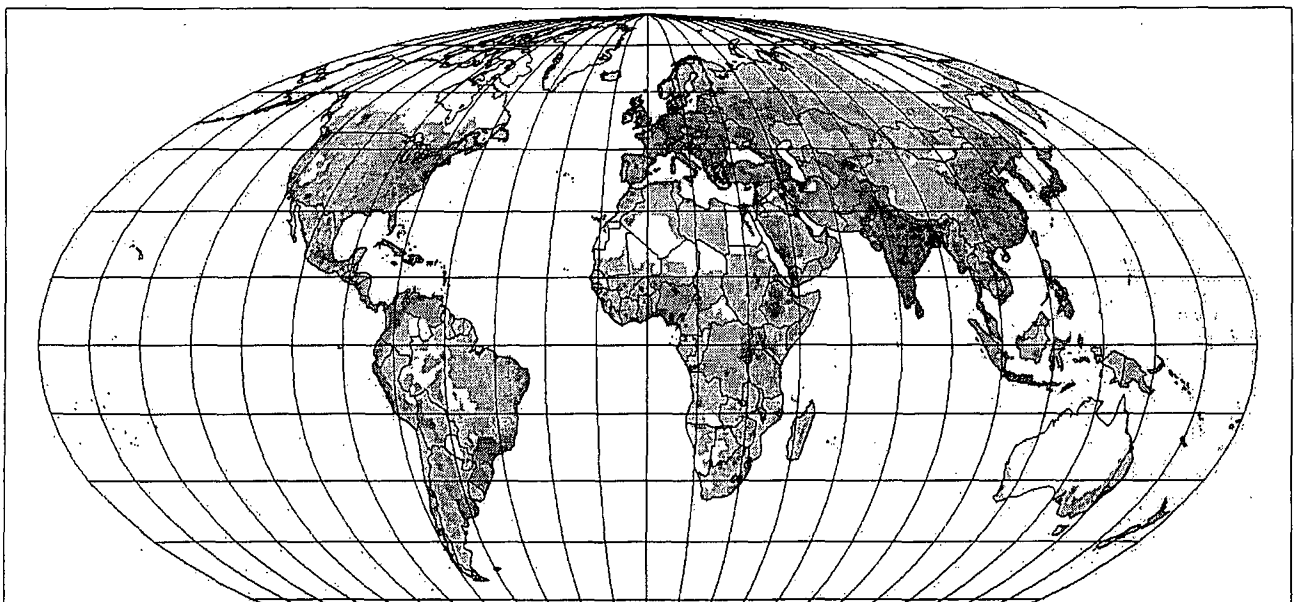


Figure 2.11. Total energy directly delivered to consumer in 2050 scenario (including environmental heat and the food, transportation and electricity etc. columns of Table 2.6) (scale given in Figure 2.4e).

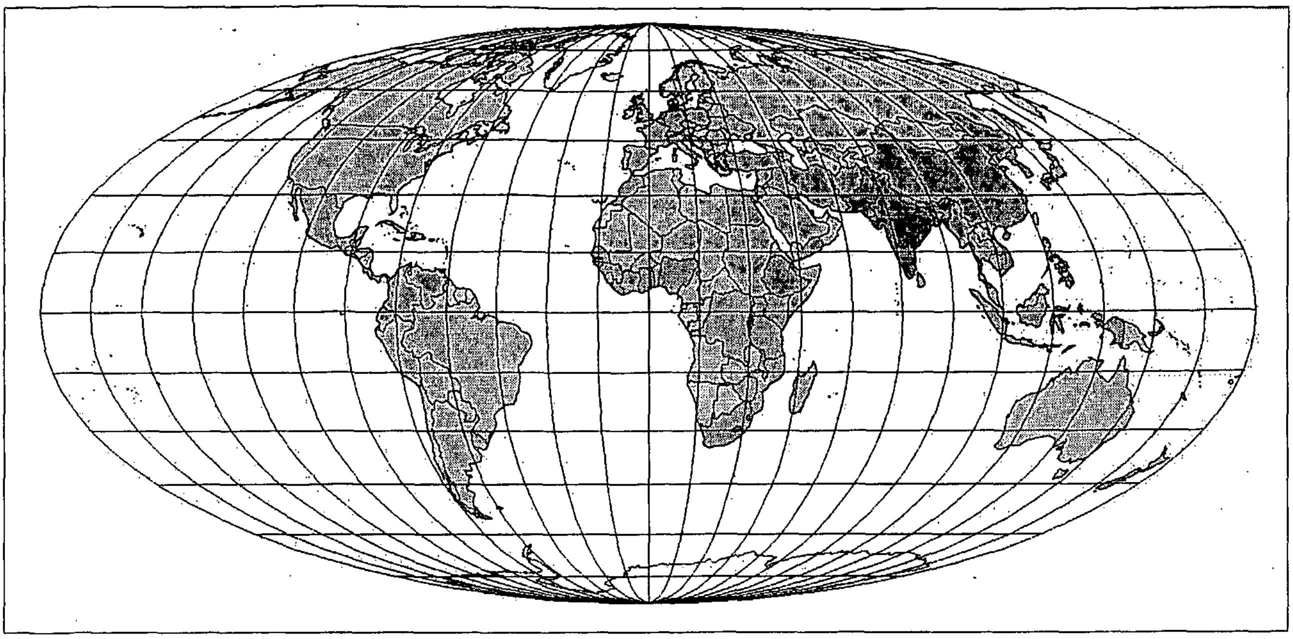


Figure 2.12. Gross energy content in food of vegetable origin, delivered to consumers in the 2050 scenarios, and averaged over each country (unit: W/m^2; scale given in Figure 2.4e).

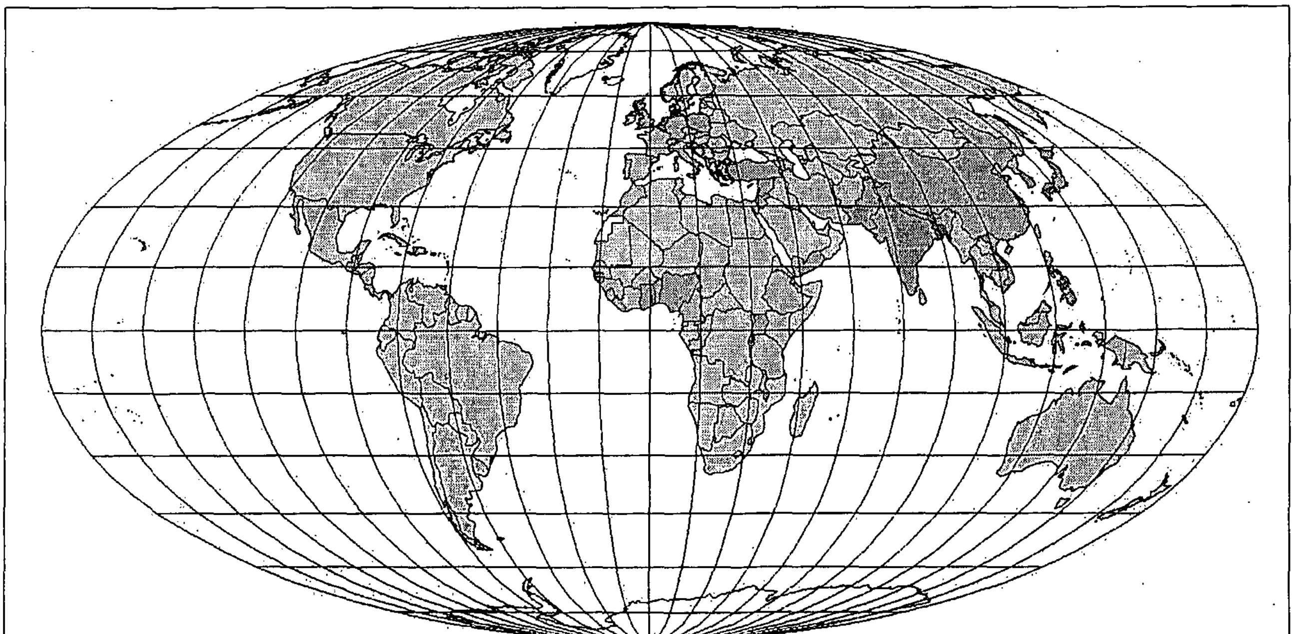


Figure 2.13. Gross energy content in food of animal origin, delivered to consumers in the 2050 scenarios, and averaged over each country (unit: W/m^2; scale given in Figure 2.4e).

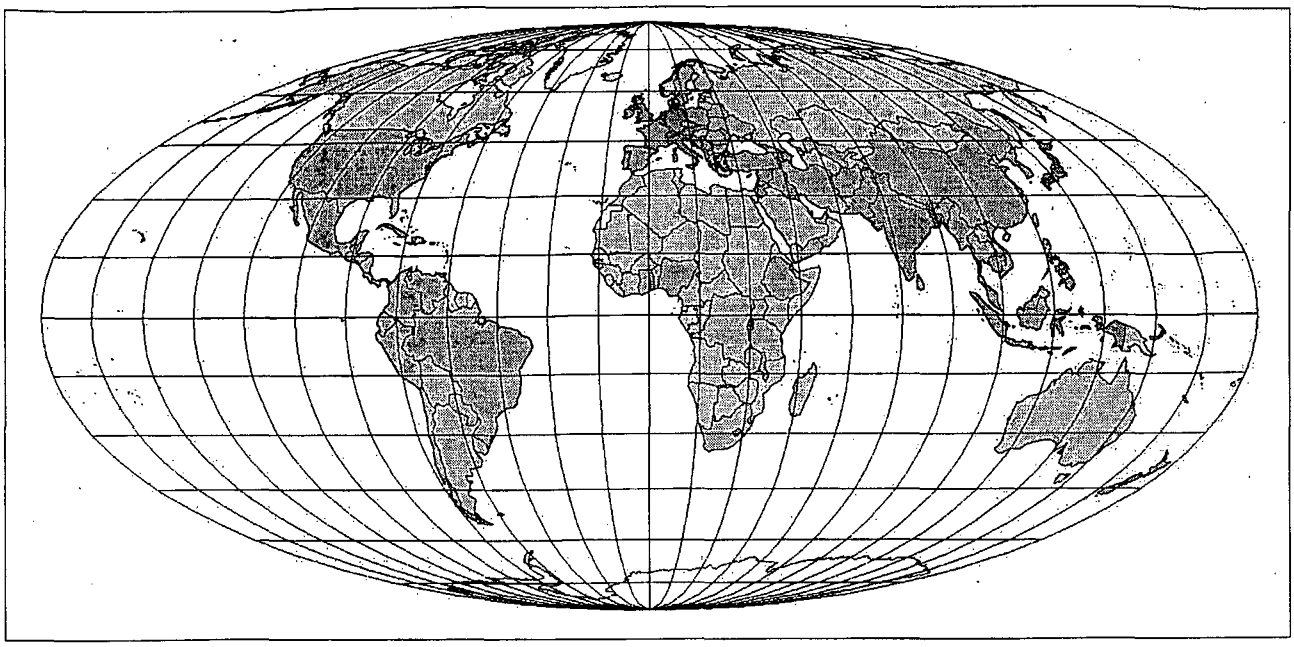


Figure 2.14. Gross energy demand for transportation energy at delivery to final consumers in the 2050 scenarios, and averaged over each country (unit: W/m^2; scale given in Figure 2.4e).

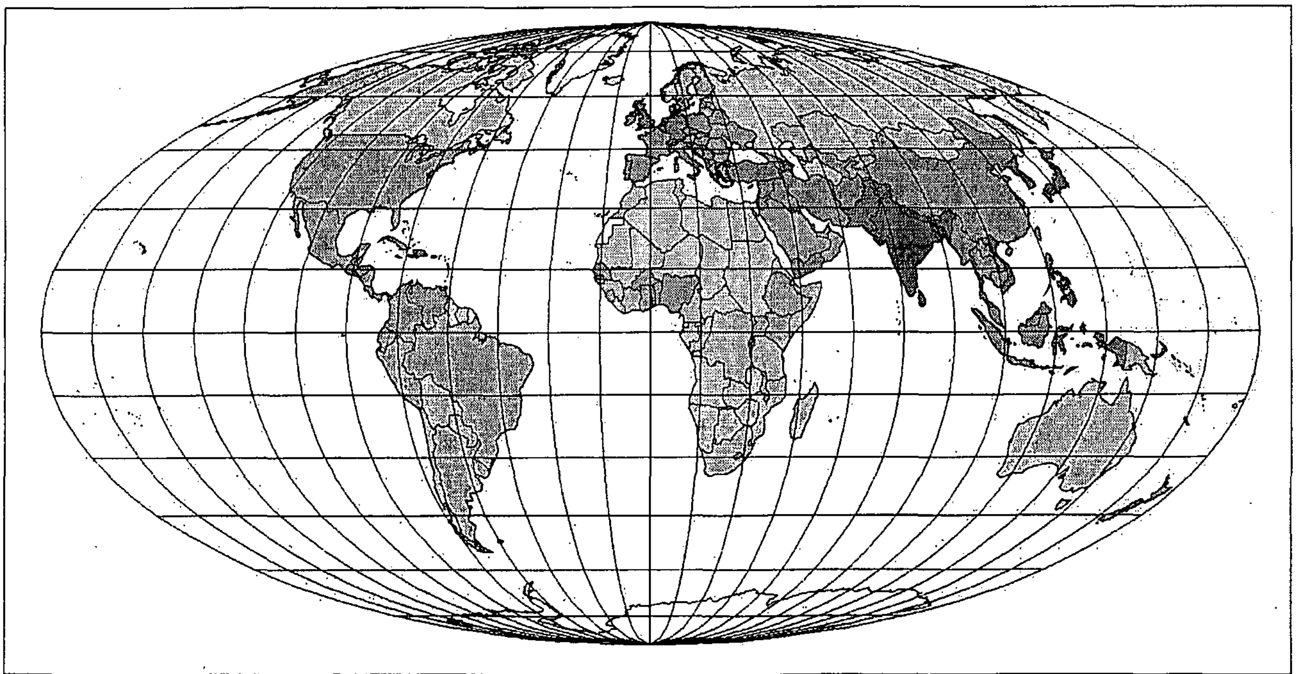


Figure 2.15. Gross energy demand for delivery to final consumers of electrical and other high-quality energy (dedicated electricity, stationary mechanical energy, medium and high temperature process heat, plus refrigeration energy inputs other than for space cooling), for the 2050 scenarios and averaged over each country (unit: W/m^2; scale given in Figure 2.4e).

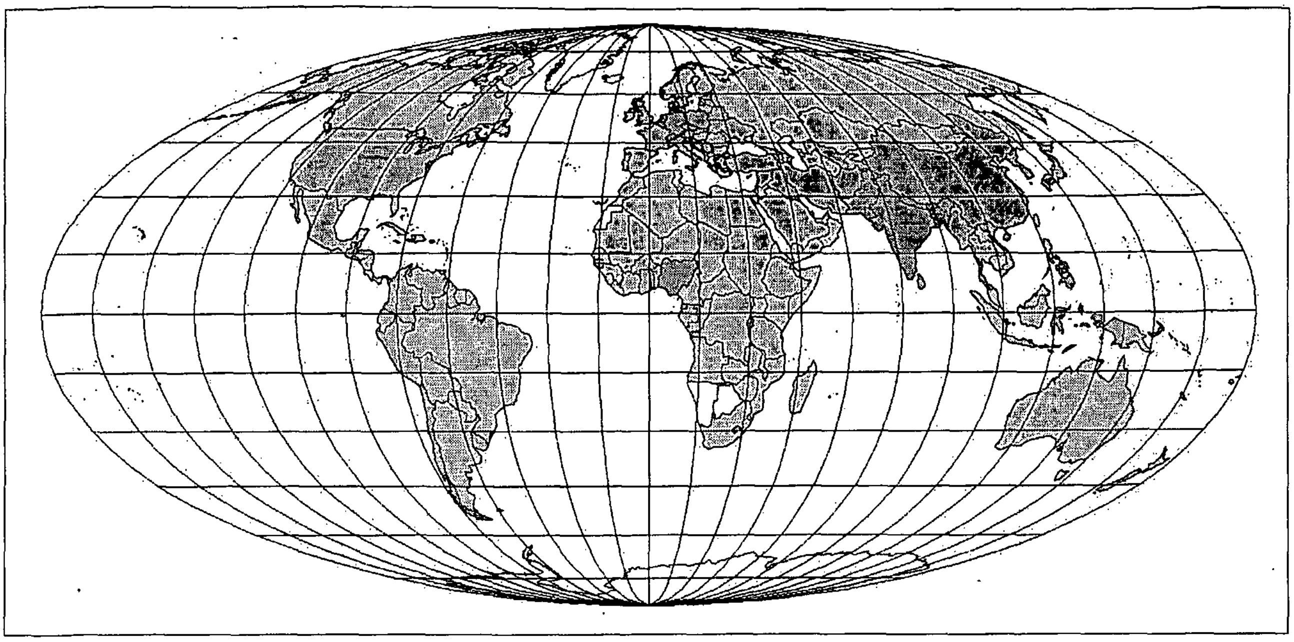


Figure 2.16. Gross energy demand for space heating, space cooling and other low temperature heat, given as the equivalent electricity input to heat pumps with COP=3.33, for the 2050 scenarios and averaged over each country (unit: W/m^2; scale given in Figure 2.4e).

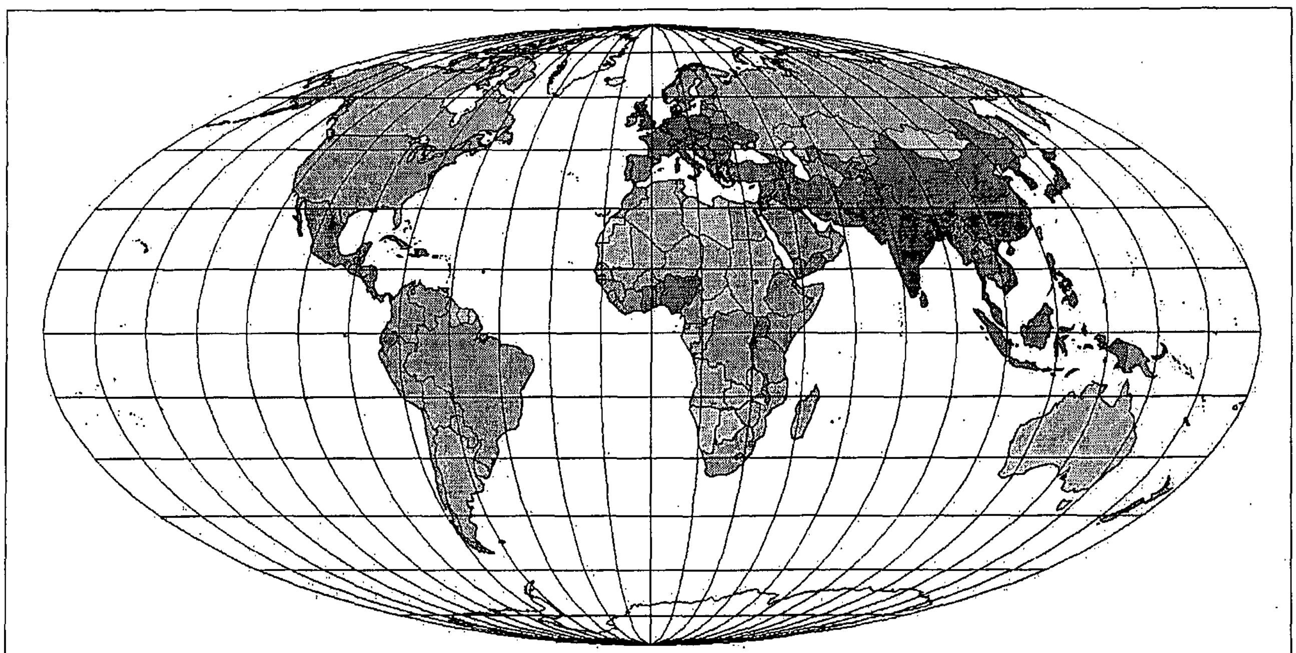


Figure 2.17. Total required energy delivery to final consumers (including environmental heat and food energy), for the 2050 scenarios and averaged over each country (unit: W/m^2; scale given in Figure 2.4e).

Chapter 3

THE CLEAN FOSSIL SCENARIO

3.1 THE AIMS

The interest in a future scenario based on fossil energy resources is to be able to maintain as much as possible of the current energy infrastructure, which is almost entirely based on the fossil option. The reason for having to depart from the present practice is partly air pollution, which is becoming unacceptable, particularly for motorcar traffic in cities, and increasingly greenhouse gas emissions, the adverse effect of which on climate is becoming more and more established. Air pollution from power plants has been diminished by a number of technical devices, but for the small engines of motorcars with breathing height emissions, no effective means has been found to reduce the health impacts sufficiently (the reduction achieved by catalytic converters placed in the exhaust system is not nearly enough to avoid the impacts). The greenhouse issue is seen as even more severe, placing demands of at least 60% reduction in carbon dioxide emissions for just stabilising the atmospheric content (IPCC, 1996).

There is also concern over the finite magnitude of fossil resources, which a few decades ago, when energy demand increased exponentially, were predicted to cause supply problems within the next fifty years. The problem is aggravated by the move away from the most abundant fossil resource, coal, due to its higher CO_2 emissions per unit of energy, and because it seemed to have more air pollution impacts than e.g. natural gas (although this depends very much on the technology used). However, the current scenarios for the mid 21st century assumes that energy efficiency measures are pursued, notably on the demand side, which will stretch the availability of fossil resources considerably. How much will be discussed in section 3.3 and 3.4 below. One may also remark, that particularly for natural gas, the current resource estimates may be on the low side. All together, it will be shown that with the scenario demand assumptions, the fossil resources can cover supply for at least a few hundred years, provided that techniques are introduced that allow also coal to be used outside the power sector.

A number of technical options are currently being explored, which will allow fossil fuels to be used without emission of CO_2 to the atmosphere. Ongoing research deals with primary conversion of fossil fuels before conversion or use, notably to hydrogen, the combustion or fuel cell use of which does not emit carbon dioxide but does form water, which should be recovered in liquid form (water vapour is also a greenhouse gas). Further, it is considered to recover carbon dioxide from the flue gases of fossil fuel combustion, and to sequester already emitted CO_2, e.g. by biological processes. The fossil scenario shall explore these technologies and make a choice of the mix of options to use. It is clear that this is a significant change in the way human societies will use fossil fuels, considering the shear mass of carbon dioxide to be handled, being orders of magnitude above the polluting SO_2 and NO_x currently being processed. This also means that the carbon dioxide recovered before or after use of the fossil fuels will not be easy to dispose of. Options for safely depositing CO_2 is therefore an integral part of the technology discussion performed in section 3.2. All of the technologies considered will add to the cost of using fossil fuels. However, the extra cost should be compared with the estimated externality cost of the negative impacts of the present emission of pollutants and CO_2 (see e.g. Kuemmel et al., 1997), and preliminary estimates suggest that the expenditure can be defended.

This clean fossil energy system is not so similar to the present as one may have hoped. Road-based vehicles will have to use zero-emission technologies, pointing to hydrogen and/or electric vehicles. Only for air and ship transportation may oil products retain a role. Also for the power sector, it will emerge that conventional power plants is not the best solution, due to the limitations on removing CO_2 from flue gases (decreased power plant efficiency, incomplete removal), and therefore fuel cell conversion technologies are seen as providing a better solution also for stationary purposes. Some of the hydrogen produced by conversion of natural gas and coal can be used directly for process heat in industry. This all points to hydrogen as playing a major role in the clean fossil scenario. It also plays a significant role in the nuclear and the renewable energy scenarios, but not in the dominating fashion found to optimise the fossil scenario. One could therefore with good reason use the term *"hydrogen scenario"* as an alternative name for the clean fossil scenario.

3.2 CLEAN FOSSIL TECHNOLOGIES

Removal of CO_2 after conventional combustion may be achieved by absorbing CO_2 from the flue gas stream (using reversible absorption into e.g. ethanol amines), by membrane techniques or by cryogenic processes leading to the formation of solid CO_2. These techniques have the disadvantage of requiring substantial energy inputs, and the most accessible techniques (absorption) further only leads to a partial capture of CO_2 (Meisen and Shuai, 1997). However, there is hope to achieve about 90% recovery, which would be quite acceptable for greenhouse gas mitigation, and the energy requirements may be reduced to around 10% (of the power generated) for natural gas fired units, and 17% for coal fired ones (Mimura et al., 1997). In the scenario, it is assumed than an average power plant conversion efficiency of 40% can be achieved for a modern combined power and heat producing plant with removal of CO_2 from the flue gas.

An alternative "after combustion" type of CO_2 removal is to convert atmospheric CO_2 to methanol by a catalytic process at elevated temperature and pressure. The catalysts may be based on Cu and ZnO, and laboratory demonstrations used a temperature of 150°C and a pressure of 5MPa (Saito et al., 1997). Additional reaction products are CO and water. Other options considered include carbon sequestering by enhanced biomass growth, where increasing forest areas can provide a long time interval between carbon assimilation and subsequent decay and release (Schlamadinger and Marland, 1997). Such options have not been incorporated into the present scenario.

The most promising option for avoiding CO_2 is to transform the fossil fuels to hydrogen and then use this fuel for subsequent conversions. Currently, hydrogen is produced from natural gas by steam reforming with water vapour. The process, which typically takes place at 850°C and 2.5 MPa (Sørensen, 1999), is given by

$$CH_4 + H_2O \rightarrow CO + 3H_2,$$

followed by the catalytic shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2.$$

The CO_2 is removed by absorption or membrane separation. The conversion efficiency is 70% (Wagner et al., 1998).

If the initial fossil fuel is coal, a gasification process is employed (partial oxidation),

$$2C + O_2 \rightarrow 2CO,$$

followed by the shift reaction as above (Jensen and Sørensen, 1984). Nitrogen from the air is used to blow oxygen through the gasifier, and impurities in the crude gas (called *producer gas*) are removed. With impurities removed, the hydrogen fuel is now of pipeline quality, ready to be transported to the points of use. The overall conversion efficiency is about 60%.

The quantities of CO_2 to be disposed following the processes above are huge, and storage in aquifers or abandoned wells may well be insufficient (capacity less than 100 Gt of coal according to Haugen and Eide, 1996). This leaves ocean disposal of CO_2 as the only serious option. Storage would here be by dissolving liquified CO_2 in sea water at depths of 1000-4000 metres through special pipelines from land or from ships, or by converting the CO_2 to dry ice form and simply dropping it from a ship into the ocean (Koide et al., 1997; Fujioka et al., 1997). The CO_2 is supposed to be subsequently dissolved into the sea water, and if sites are suitable selected, it may stay in cavities or at the ocean floor indefinitely, due to its higher density.

The cost includes that of liquefaction or dry ice formation, plus operational costs and pipelines if used. Fujioka et al. (1997) estimate these costs to be about 0.03 US$ per kWh of fuel (0.08 $/kWh of electricity if that is what is produced) for the liquefied pipeline and ocean tanker disposal scheme, and 0.05 US$ per kWh of fuel for the dry ice scheme.

The CO_2-rich waters will stimulate biological growth and may seriously alter marine habitats (Takeuchi et al., 1997; Herzog et al., 1996). Stability of the deposits, and the subsequent fate of any escaped CO_2 will have to be established, e.g. by experiments.

An additional survey of the literature on CO_2 removal and deposition is given in Appendix C.

The clean fossil scenario includes both hydrogen produced from natural gas and from coal, with the efficiencies stated above. For use in fuel cells, the hydrogen to electricity conversion efficiency is taken as 65% (Sørensen, 1999). Losses in hydrogen storage and transmission are taken as 10%, as compared with 5% for electricity transmission.

3.3 FOSSIL RESOURCE CONSIDERATIONS

Fossil resources are biomass that has undergone transformations over periods of millions of years. Their use as fuels is anyway limited to a fairly short interval in history and should be seen as a unique opportunity to smooth the road to a more sustainable energy system.

The discussion of fossil resources and their geographical distribution will be made on the basis of a simple version of the standard distinction between reserves and other resources. Three categories will be used:

- Proven reserves are deposits identified and considered economic to exploit with current price levels.
- Additional reserves are deposits that exist and are economic, with a probability over 50%.
- New and unconventional resources are all other types of deposits, typically inferred from geological modelling or identified but not presently being considered economic to exploit.

The sum of all known and inferred (with reasonable probability) resources without consideration of economy of extraction is the *resource base*. The level of investigation is uneven among re-

gions, and therefore additional amounts may be discovered, particularly in areas not well studied today. Also, extraction methods vary with time, and new techniques (e.g. enhanced oil recovery) may alter the amount of reserves assigned to a given physical resource.

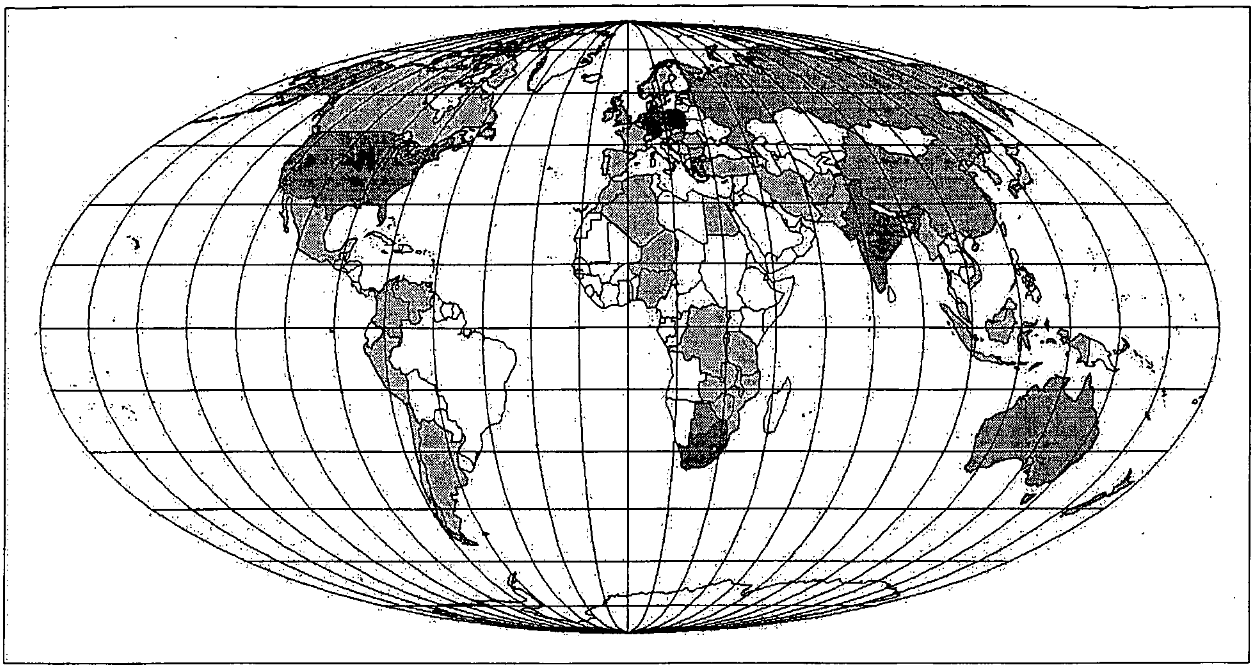


Figure 3.1. Proven reserves of bituminous coal (scale given in Fig. 3.1a; unit Wy/m^2, i.e. for each country, the average number of years for which an energy flow of 1 W per m^2 of land surface could be derived at 100% energy extraction efficiency) (based on World Energy Council, 1995).

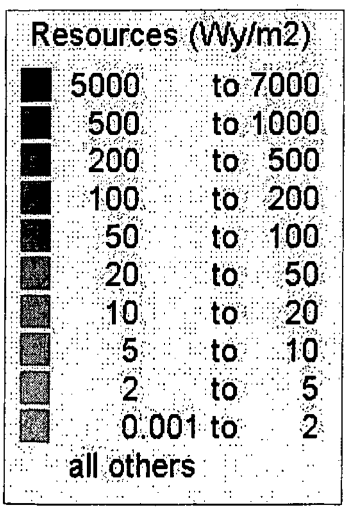


Figure 3.1a. Unit labels for use with resource estimates (Wy/m^2).

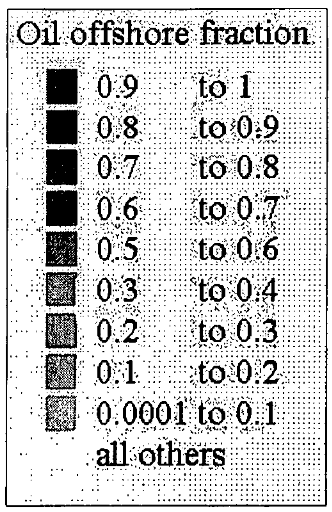


Figure 3.1b. Labels used for off-shore fraction in Fig. 3.7.

Figures 3.1 and 3.2 shows the country distribution of proven reserves of bituminous coal ("hard coal") and other coal (sub-bituminous coal or lignite), Figs. 3.3 and 3.4 the additional reserves for the same two categories. Finally, Fig. 3.5 gives the total amount of coal estimated in place (i.e. the resource base).

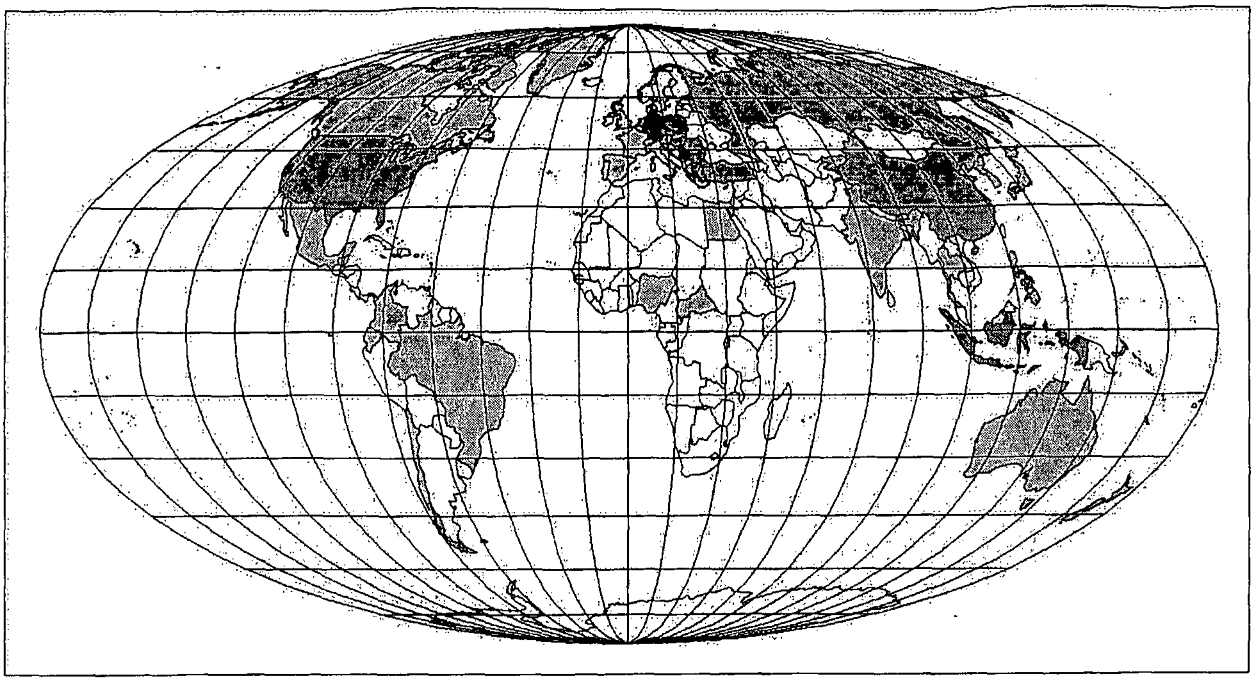


Figure 3.2. Proven reserves of sub-bituminous coal and lignite (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

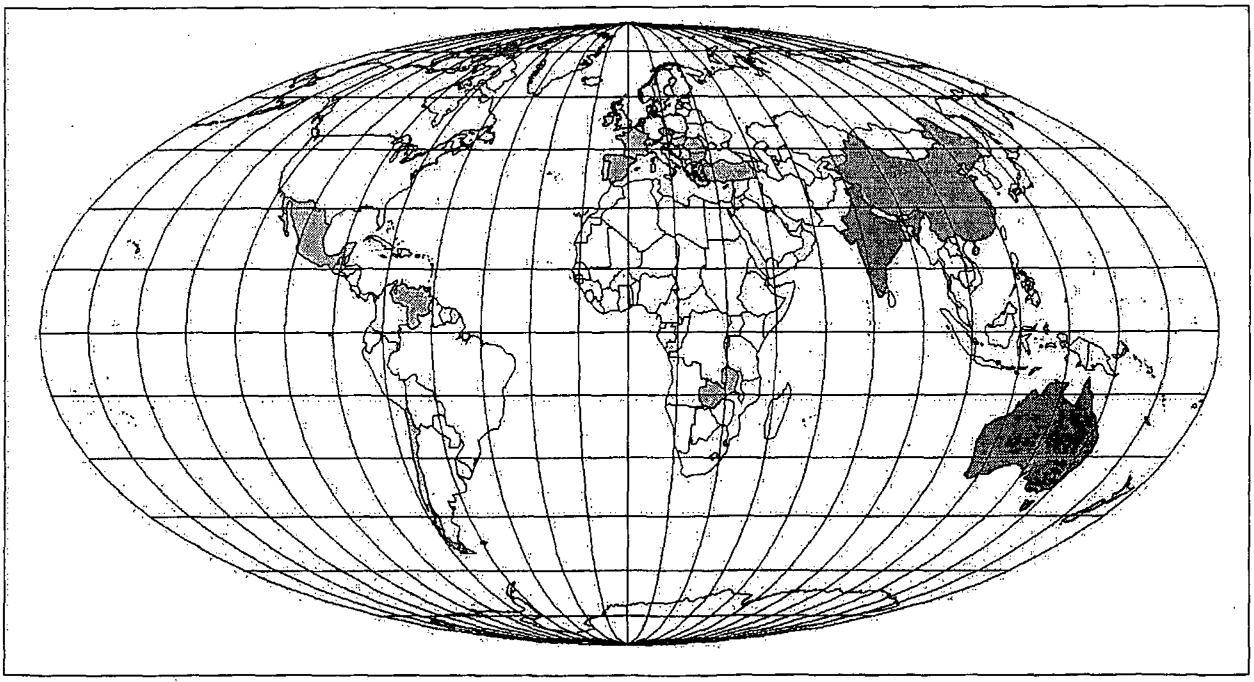


Figure 3.3. Additional reserves of bituminous coal (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

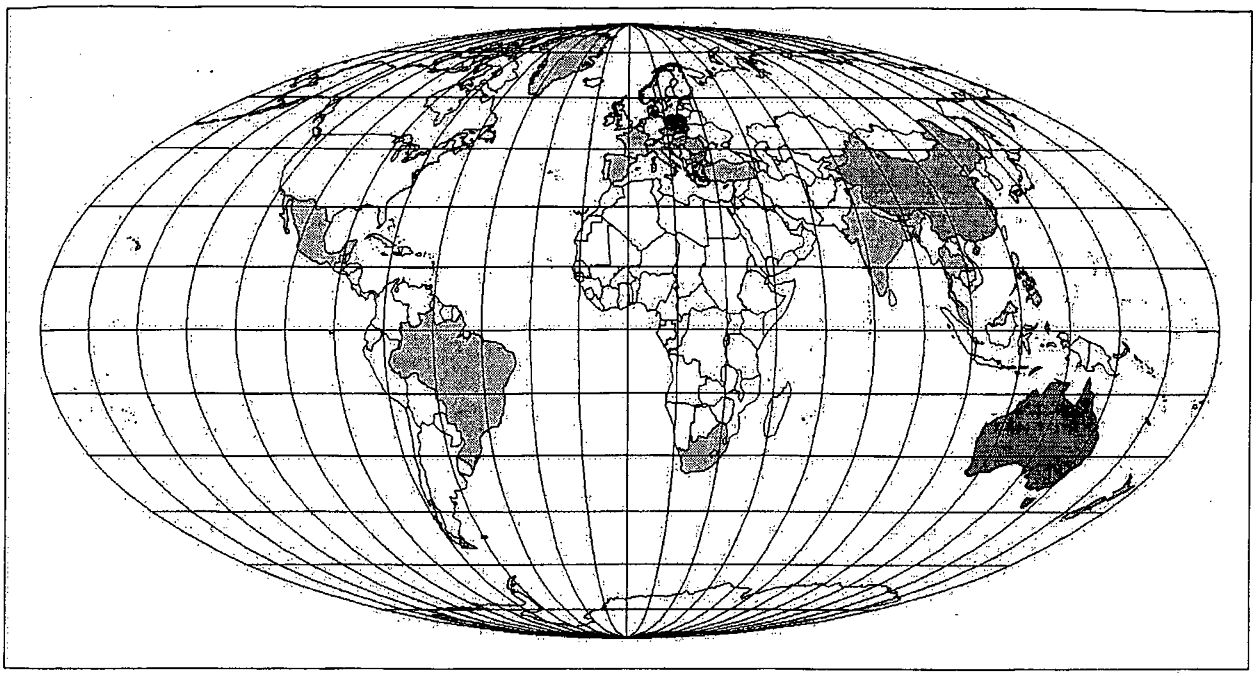


Figure 3.4. Additional reserves of sub-bituminous coal and lignite (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

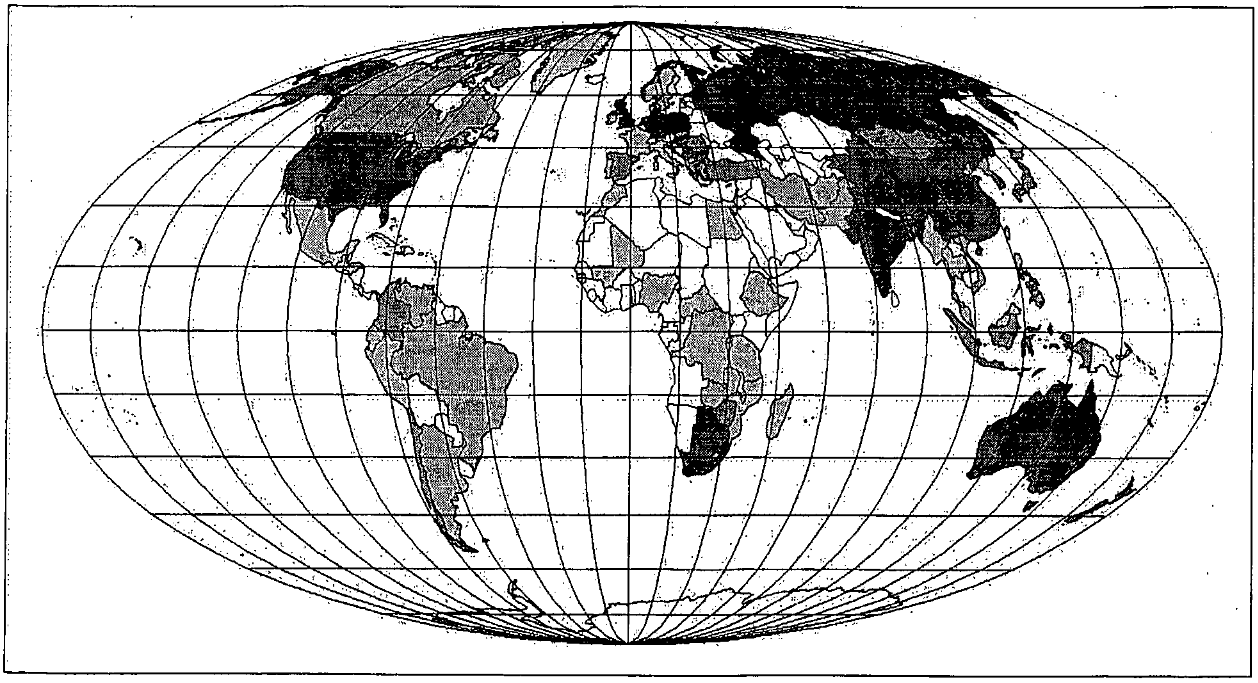


Figure 3.5. Total coal and lignite resources in place (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

Figure 3.6 gives the proven reserves of oil (including natural gas liquids), Fig. 3.7 the part of them located off-shore in the territorial waters of the countries indicated, and Fig. 3.8 estimates additional reserves. Figure 3.9 shows the total amounts in place (resource base). Figure 3.10 gives the proven resources of oil shale and natural bitumen, Fig. 3.11 the estimated additional reserves, and Fig. 3.12 the known amounts in place, for these possibly exploitable resources.

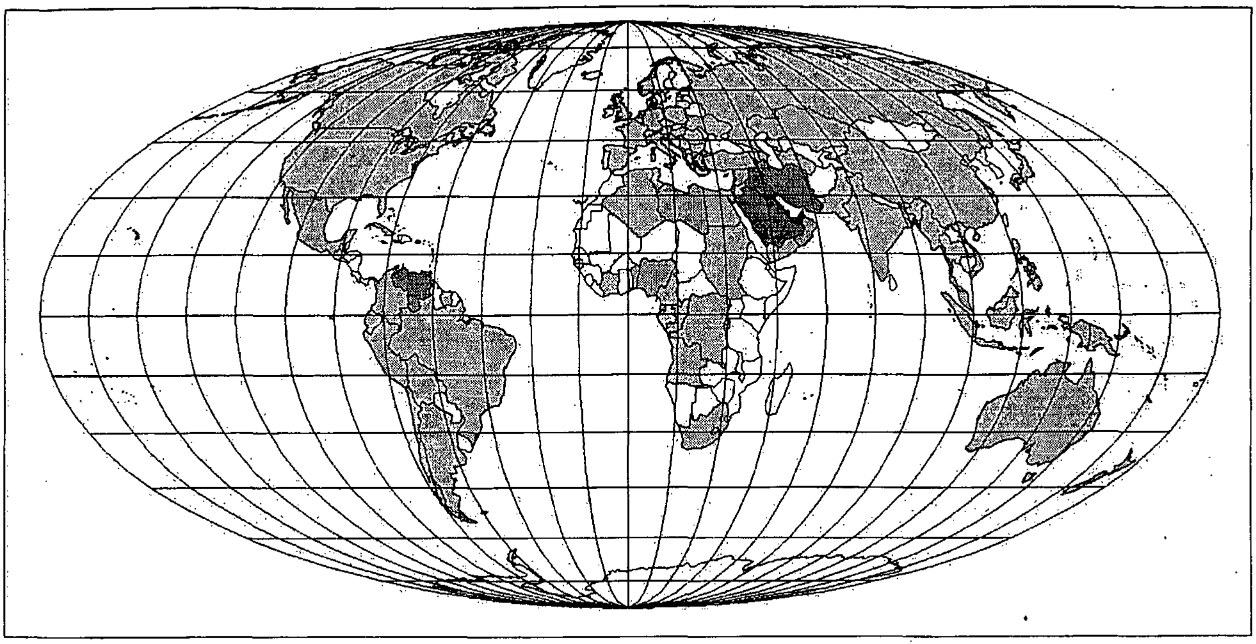


Figure 3.6. Proven reserves of oil and natural gas liquids (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1; the resources are distributed over the country land areas, although many of the reserves and resources actually occur off-shore, see Fig. 3.7) (based on World Energy Council, 1995).

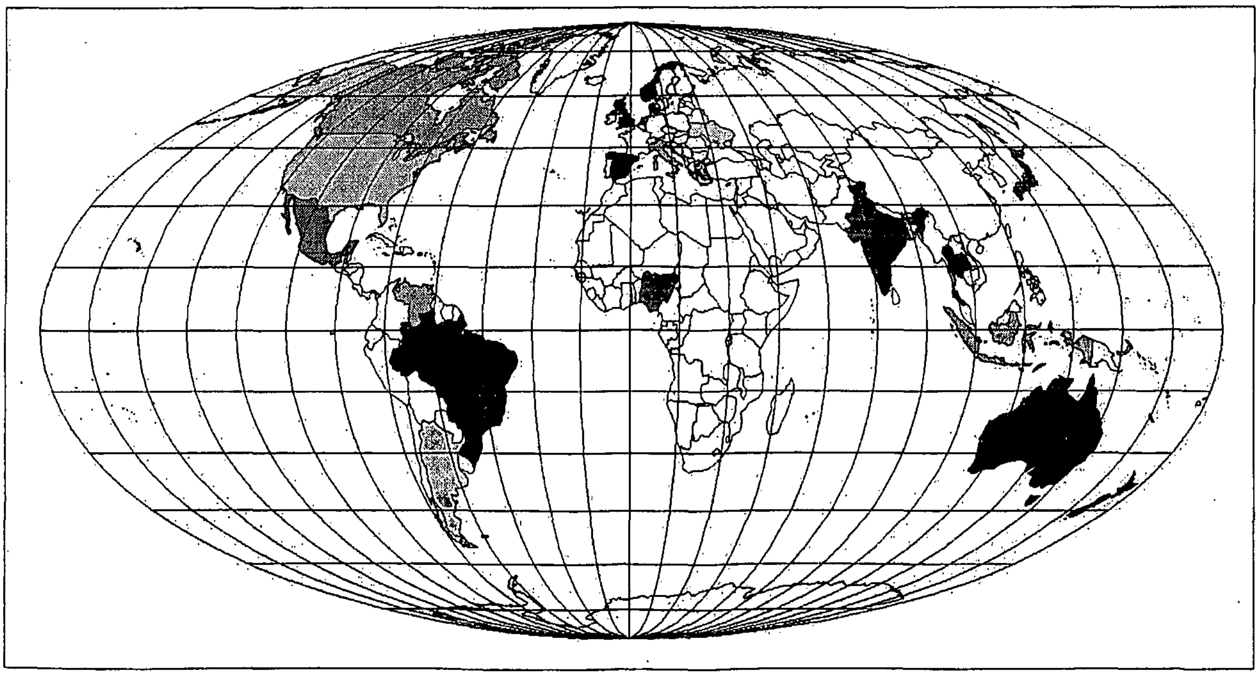


Figure 3.7. Off-shore fraction of the reserves given in Fig. 3.6 (scale given in Fig. 3.1b) (based on World Energy Council, 1995).

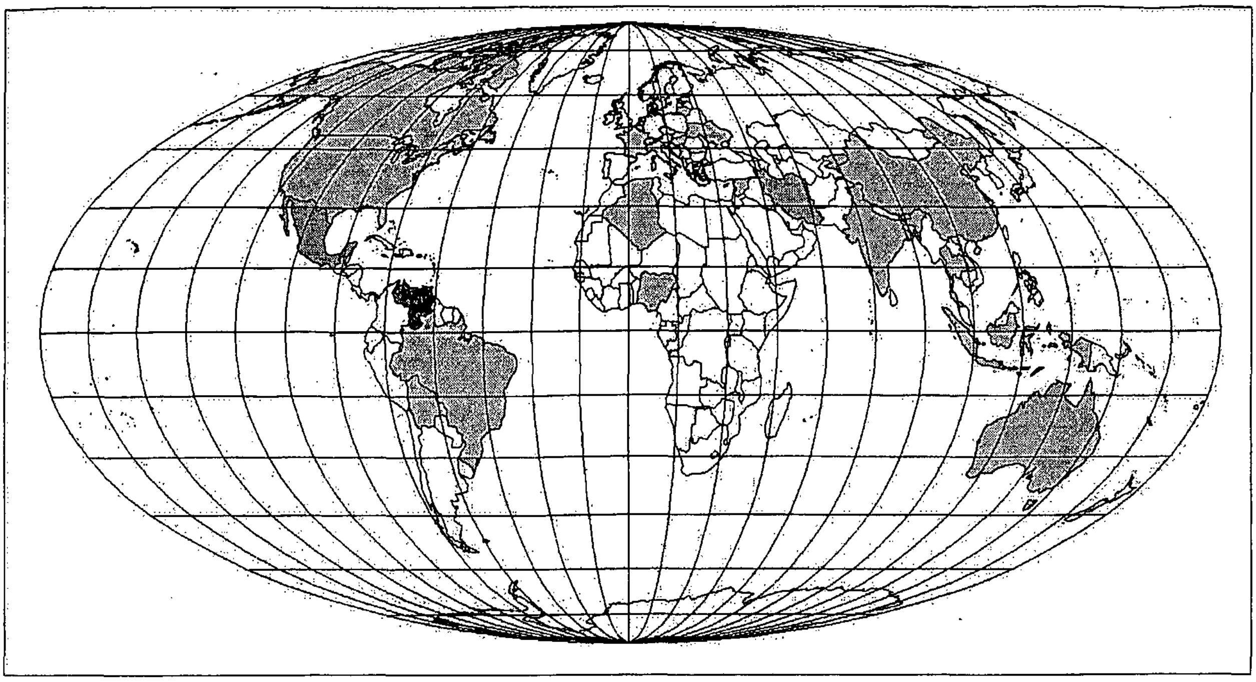


Figure 3.8. Additional reserves of oil and natural gas liquids (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

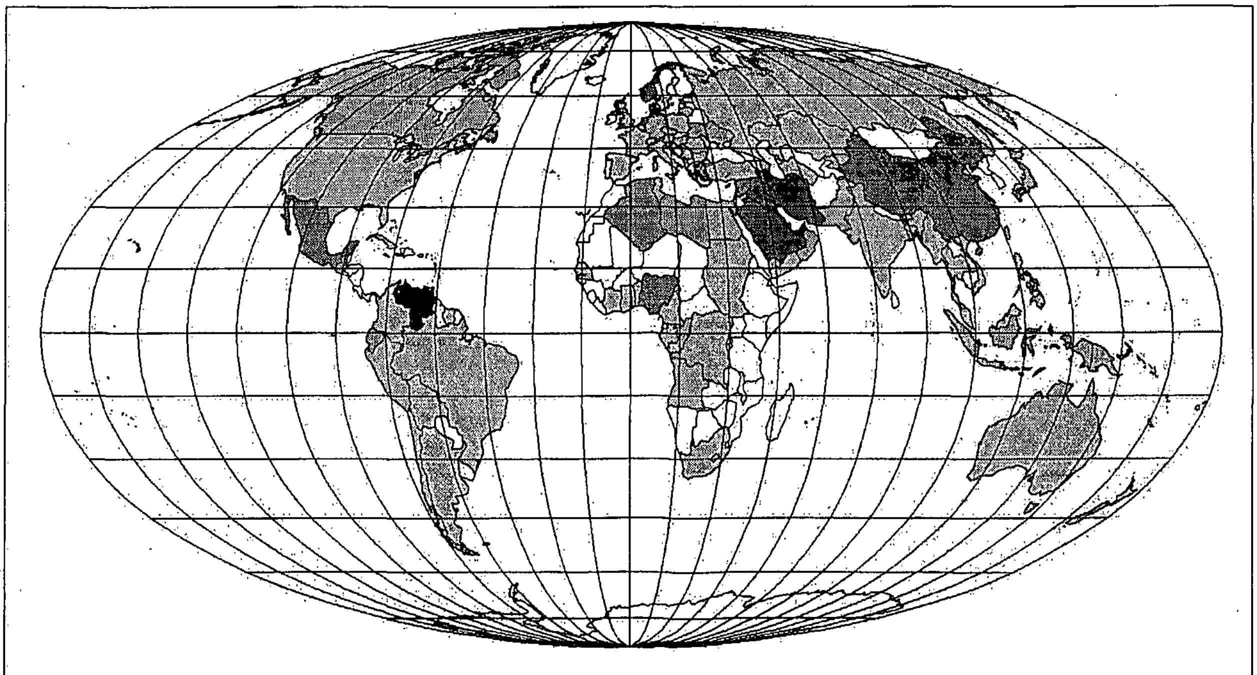


Figure 3.9. Total resources of oil and natural gas liquids in place (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

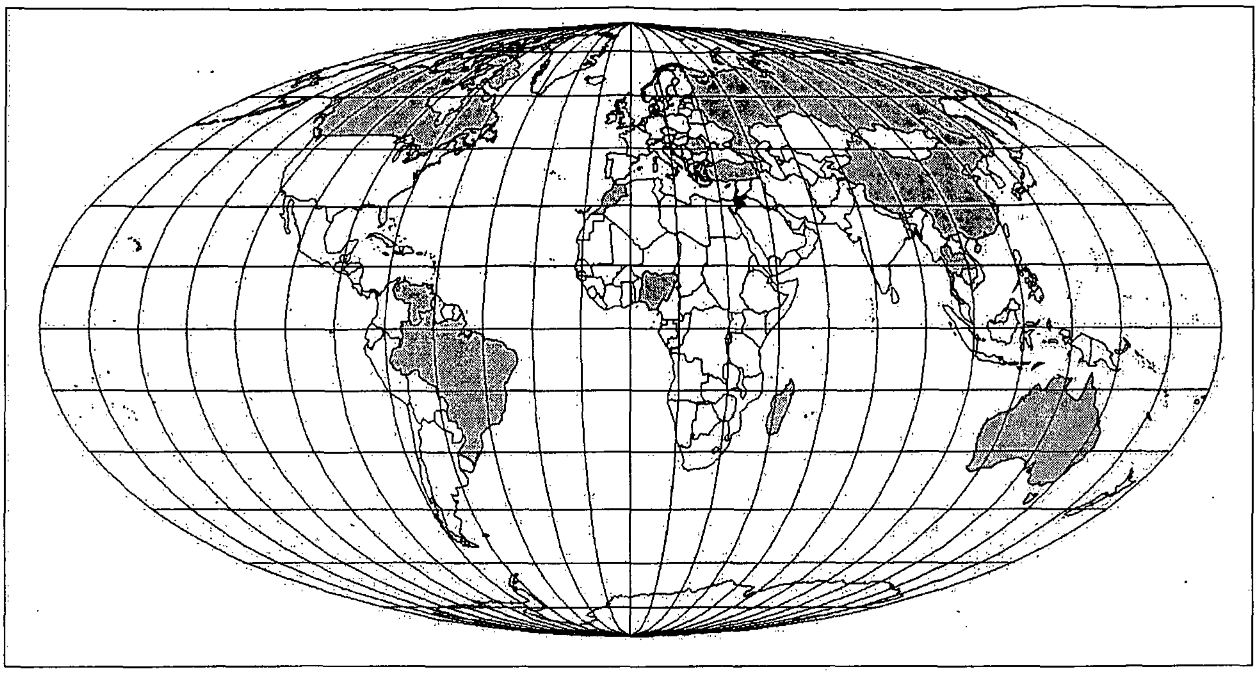


Figure 3.10. Proven reserves of oil shale and natural bitumen (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

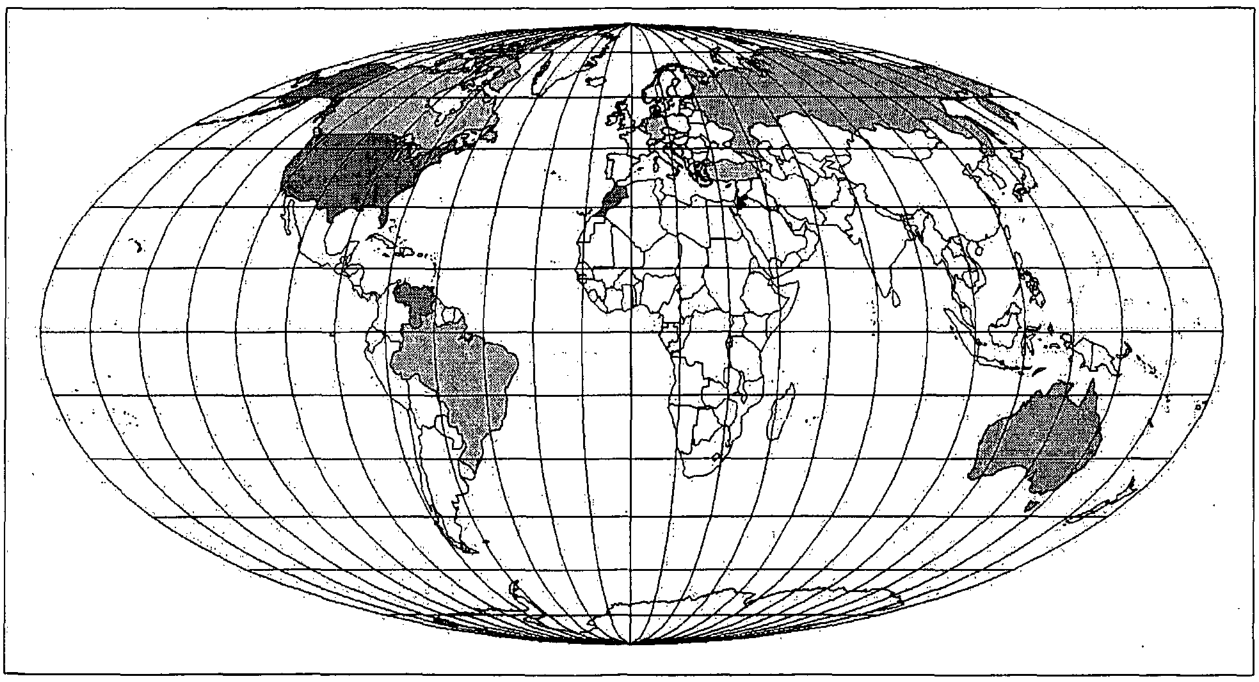


Figure 3.11. Additional reserves of oil shale and natural bitumen (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

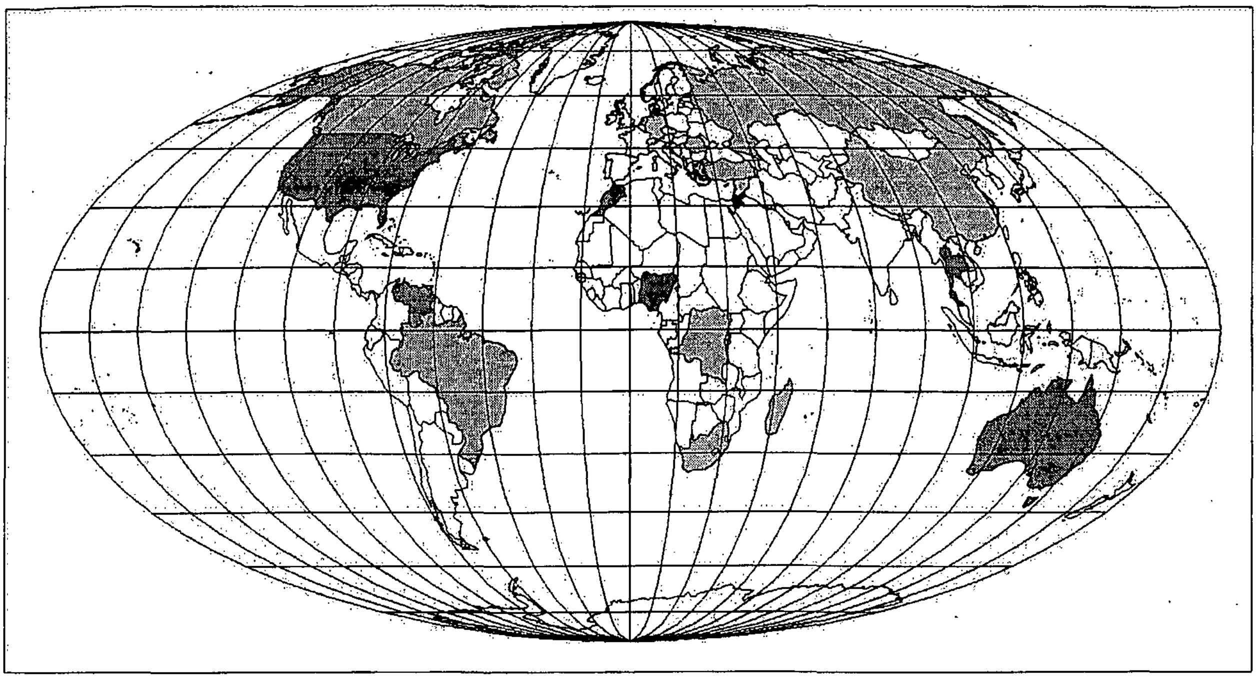


Figure 3.12. Total resources of oil shale and natural bitumen in place (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

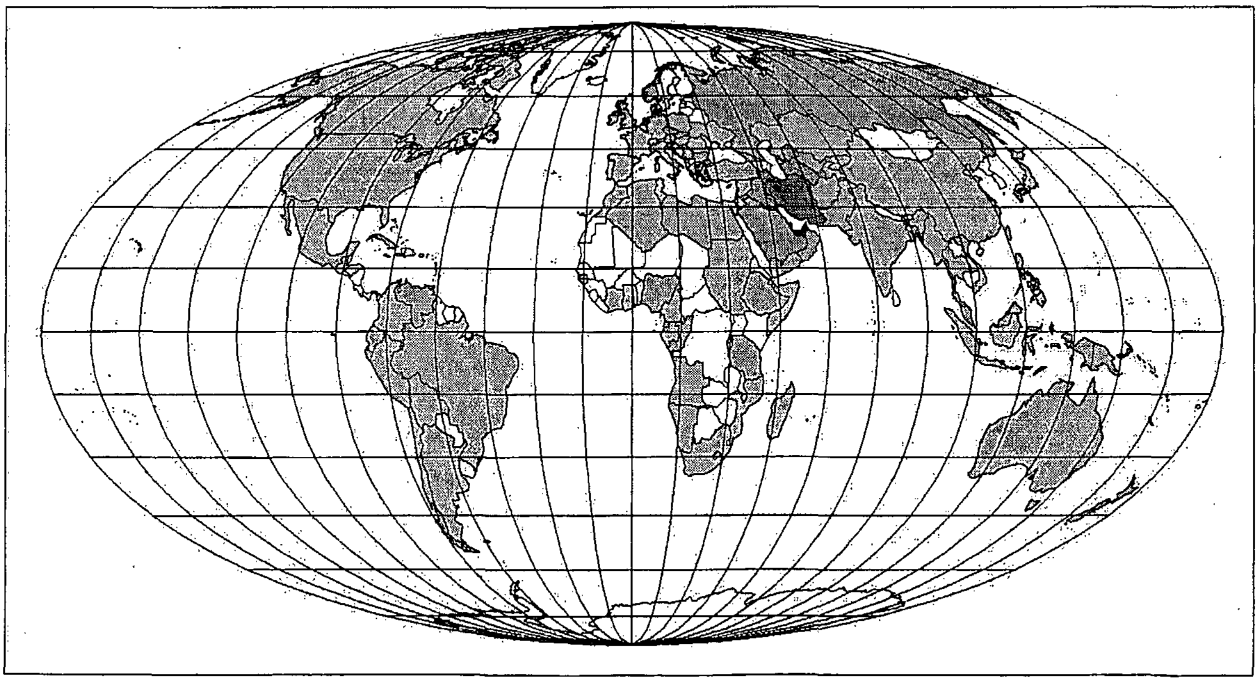


Figure 3.13. Proven reserves of natural gas (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

Figure 3.13 shows the proven reserves of natural gas, Fig. 3.14 the additional reserves and Fig. 3.15 the total amounts in place.

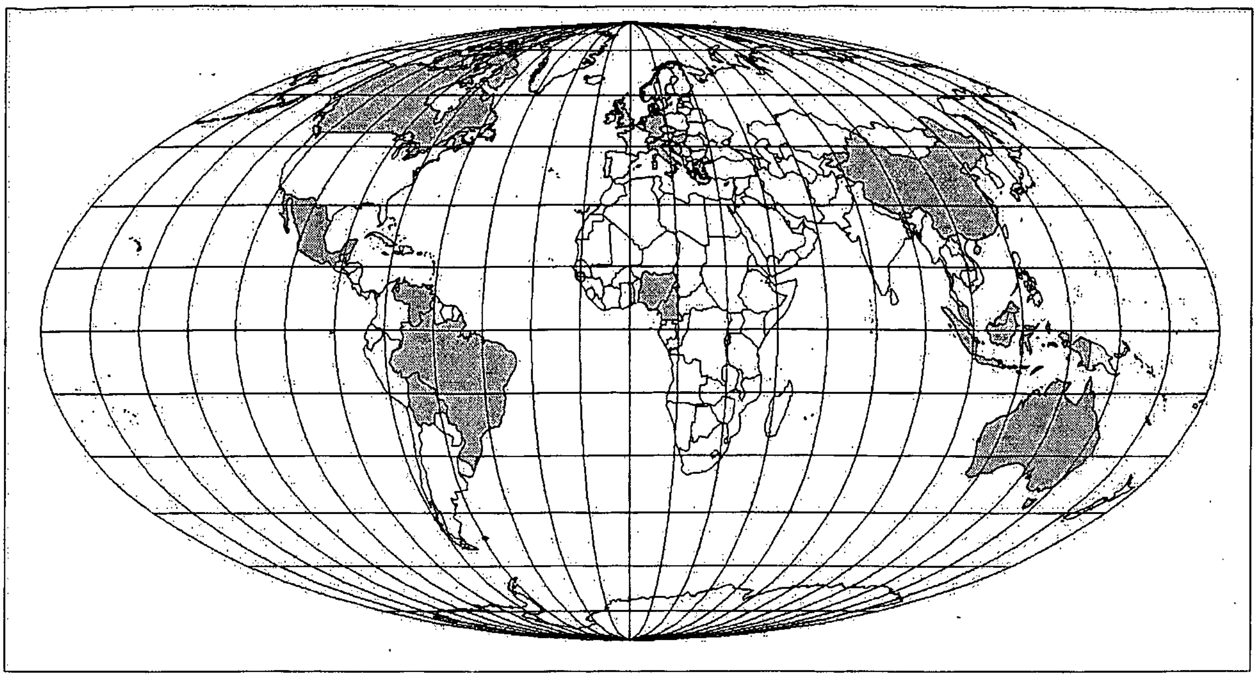


Figure 3.14. Additional reserves of natural gas (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

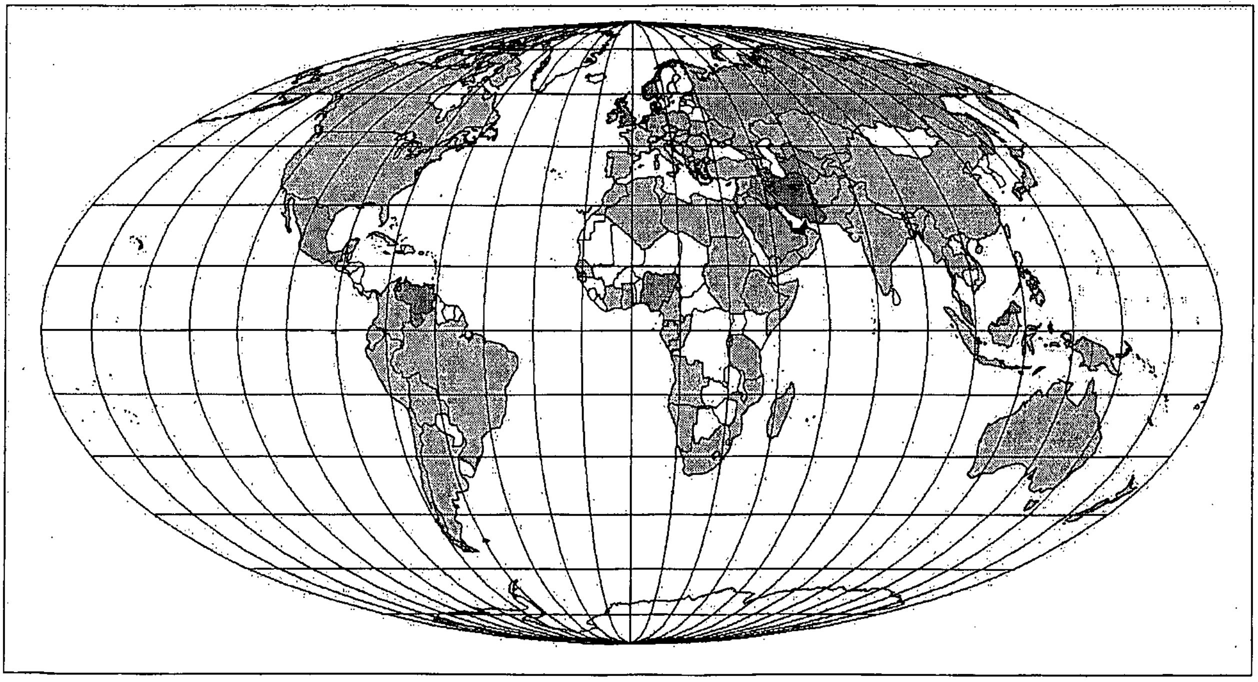


Figure 3.15. Total resources of natural gas estimated in place (scale given in Fig. 3.1a; unit Wy/m^2, cf. caption to Fig. 3.1) (based on World Energy Council, 1995).

It is clear that estimates of reserves and resources are uncertain, and more uncertain, the less exploration has been made. Assessments found in the literature therefore differ among themselves, and the reporting of national agencies to international compilations may be of varying quality, for reasons of incomplete knowledge, or for commercial reasons. Figures 3.1-3.15 are based on estimates collected by the World Energy Council (1995). They agree fairly well with other estimates for coal and oil, while they are substantially lower for natural gas than what as a global total has been found most likely in the assessment made for IPCC by Nakicenoviç et al. (1996). For example, the oil producing countries in the Middle East quote very small associated gas reserves, which may just indicate that such resources are not considered economic due to current limitations on transmission and liquefaction capacity that could transport them to regions of demand. From geological considerations, it is expected that there is more natural gas than oil (according to some estimates much more), and the assessment in the WEC of only half as much is almost certainly an underestimate.

The current (1990ies) rate of use of coal is 2886 GW, of oil 4059 GW and of natural gas 2188, This means that the proven reserves shown in Figs. 3.1, 3.6 and 3.13 at constant rate of use would last 167 years for coal, 46 years for oil and 70 years for natural gas. Relative to the total estimated resource in place the numbers would be 3554 years for coal, 210 years for oil plus another 184 years from oil shale and bitumen, and 96 years for natural gas. This again hints at the underestimate of total natural gas resources, but in any case, the resources in place are not necessarily exploitable at any price.

3.4 THE FOSSIL SCENARIO

In constructing the clean fossil scenario for satisfying the demand scenario described in Chapter 2, the basic consideration has been to make use of the technologies described in section 3.2 in such a way, that the resource utilisation becomes acceptable. Because oil resources are considered the most limiting constraint, and because oil is in widespread use outside the energy sector, as lubricants and feedstock for a number of industrial products including first of all plastics, it is decided not to use oil in the energy sector, except possibly for a few sectors where substitution with other fossil technologies may be difficult, notable as an aviation fuel. Non-energy uses of oil could alternatively be substituted with e.g. biomass-based raw materials, but the way the base scenarios are constructed this would rather belong in the renewable energy scenario.

In regard to the balance between natural gas and coal, it is for resource reasons considered appropriate to increase the relative use of coal. Both fossil resources can be transformed to hydrogen (as could oil), for providing a carbon-free energy carrier, but the efficiency of transforming coal to hydrogen is a little lower than that of transforming natural gas, and the cost is higher. However, the price of natural gas is already above that of coal, and would develop in the direction of an increased difference, as the resource constraint makes itself more felt, which according to the estimates quoted in section 3.3 will happen before the selected scenario year, 2050.

The scenario choice is then in the transportation sector to cover half the demand by electric vehicles (all urban vehicles, trains) and the other half by hydrogen (used in fuel cells, e.g. transformed to methanol for reasons of storage). The fuel cell vehicles are of course also electric vehicles, but with the power production taking place on board. Because de-carbonisation favours a large fraction of the fossil fuels being transformed to hydrogen, hydrogen is in the scenario also used in industry for medium and high temperature process heat, thereby avoiding a second conversion step to electricity and the associated conversion losses.

There is still a substantial demand for electricity (dedicated electricity, i.e. electric apparel that cannot be powered by other sources, plus stationary mechanical energy, that for environmental

reasons and efficiency optimisation is better served by electricity as input). The production of electricity is in the scenario partly performed at conventional power plants, but also by fuel cells that can use hydrogen. Again, this is because it is easier to transform the fossil fuels to hydrogen before conversion than to recover carbon dioxide from stack emissions. In the scenario, about two thirds of the power generation is from fuel cells. The higher efficiency is partly offset by losses in hydrogen production and storage, but the versatility is higher, because the fuel cells may become decentralised and integrated into individual buildings. This is made possible by a hydrogen distribution pipeline system, which in many countries could serve as a useful continuation of using the existing natural gas distribution network. The overall transmission of hydrogen and natural gas will both be needed.

For low temperature heat, the conversion of fuels in power plants and fuel cells both provide considerable amounts of associated heat production, which can be employed after distribution by district heating lines, and in the case of building-integrated fuel cells may serve to provide heat to the same building and its activities. However, because of the considerable direct use of hydrogen and the fairly high electric power conversion efficiencies achieved, there is in the scenario not quite enough "waste" heat to cover all low temperature requirements, and the remaining space and process heat (under 20% of the total, varying with season) is assumed to be provided by heat pumps. Also space cooling is provided by electricity-driven coolers, i.e. same technique as used in heat pumps and in the scenario lumped together with these, assuming the same coefficient of performance (ratio of heat output, added or removed, to electricity input), COP = 3.33. This is not the highest technically possible value, but because much of the space heating is in climates where the source of environmental heat to the heat pumps is of low temperature, it is considered reasonable to use a cautious estimate.

Although the scenario aims at only using fossil resources, the existing hydro electricity production is retained. This is a renewable energy resource, but it works well together with the ingredients of the fossil system, and only existing plants and plants currently under construction are assumed to be present in the fossil scenario. In Chapter 5, the distribution of power production from hydro will be discussed. Its total potential contribution is an average production of 440 GW.

The fossil scenario will be presented in terms of annual average energy flows between supply and demand. The handling of diurnal and seasonal variations is much the same as it is today. The only critical area is in the provision of space heating and cooling, where the co-produced heat from power plants and fuel cells on average is very close to the average demand. For space cooling, the high season just requires more electricity input, which is provided by a sufficient installed capacity of the power plants and fuel cells. For winter heating, the co-producing power and heat plants can already with technology currently used in many places avoid a locked ratio between electricity and heat production, and by regulation of the heat to power ratio within the available range cater to any heat demand situation, without need for adding storage to the system, except possibly for diurnal storage, which is already today economic in some cases.

Figure 3.17 shows country distributions of the amount of hydrogen, that would be needed to provide energy for the demand scenario medium and high temperature industrial process heat plus 50% of the transportation needs, making allowance for 10% losses in storage and piping of hydrogen to the end user. Figure 3.18 gives the electricity from fossil fuels required for stationary mechanical energy, electric appliances, cooling, refrigeration and the heat pumps covering 20% of space heating needs, plus the other half of the transportation energy needs. The power provided by hydro is given first priority, leading e.g. to no average fossil power requirement in hydro-abundant countries such as Canada, Sweden or Norway. In practice, the fast regulation of hydro plants allows them to be used in load-levelling efforts.

In Fig. 3.19, the amount of hydrogen that is needed as fuel for electricity producing fuel cells is shown, assuming a conversion efficiency of 65% (for electricity, the rest being available as low temperature heat). Figure 3.20 similarly gives the coal input to power plants, at an electric efficiency of 40%, again with the remaining 60% being available for district heating. One third of the electricity in the scenario is assumed to come from coal-fired power plants, two thirds from fuel cells with hydrogen as input. In Figs. 3.21 and 3.22, the natural gas and coal inputs to produce the required amounts of hydrogen is shown. The scenario assumes 40% to be based on natural gas, with a conversion efficiency of 70%, and 60% from coal with a conversion efficiency of 60%.

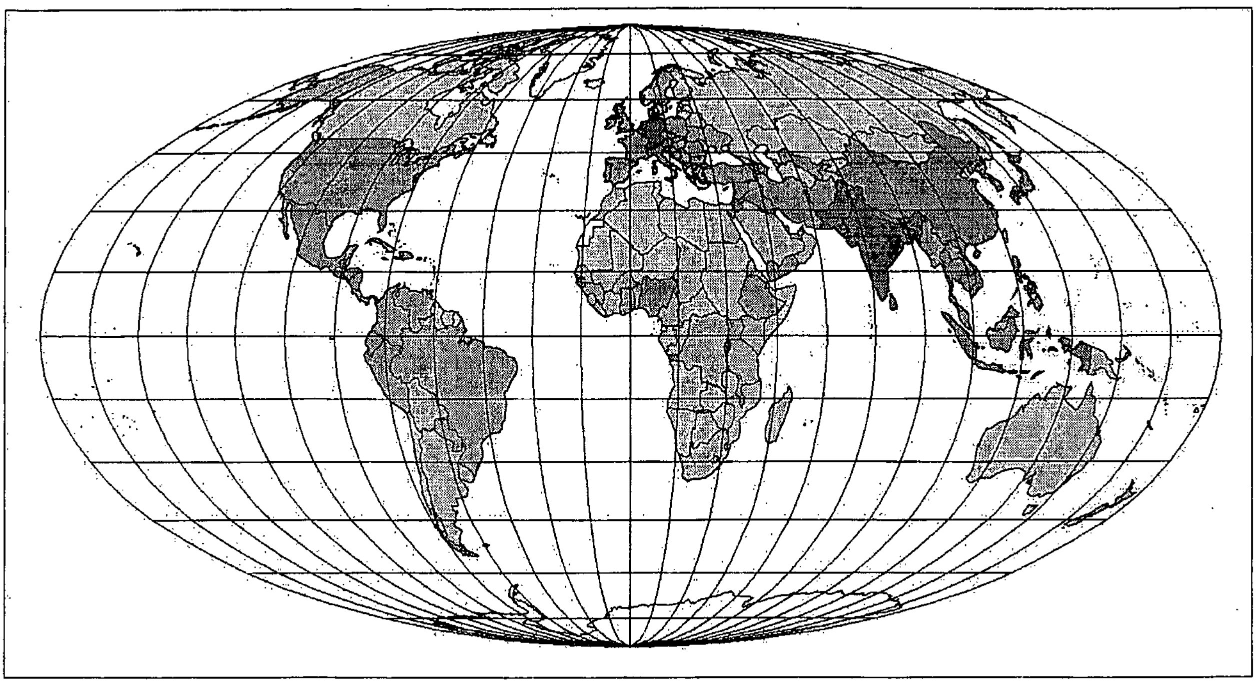


Figure 3.17. Hydrogen derived from fossil energy, to be used for covering half the needs in the transportation sector and all requirements for medium and high temperature process heat, after transmission and storage losses. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

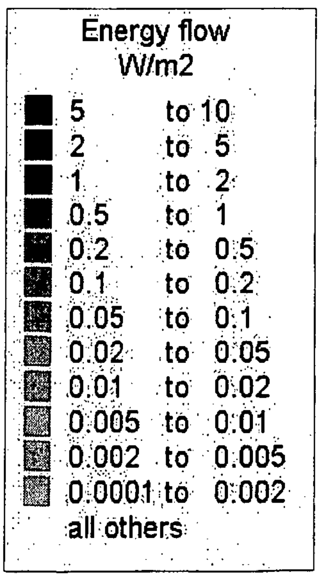


Fig. 3.16 (left). Scale of energy flow (logarithmic, unit W/m^2).

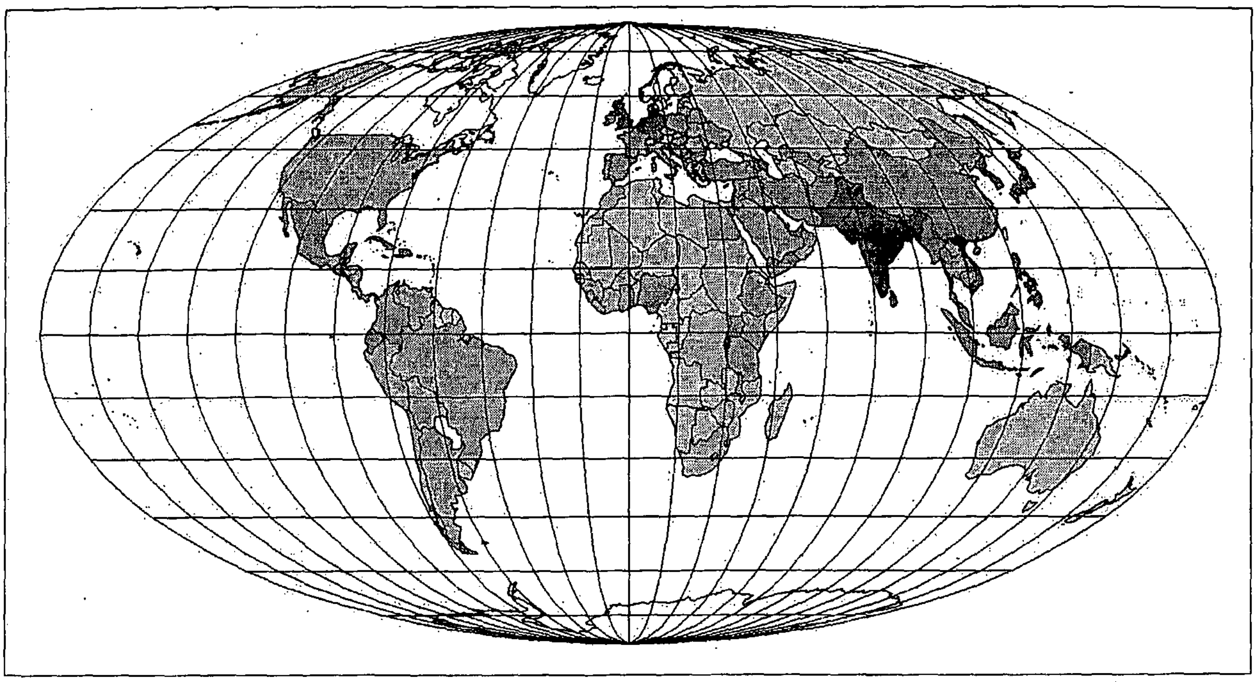


Figure 3.18. Electricity derived from fossil energy, to be used for covering half the needs in the transportation sector and all requirements for stationary mechanical energy, dedicated electricity and electricity for cooling, refrigeration and heat pumps, after transmission losses. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

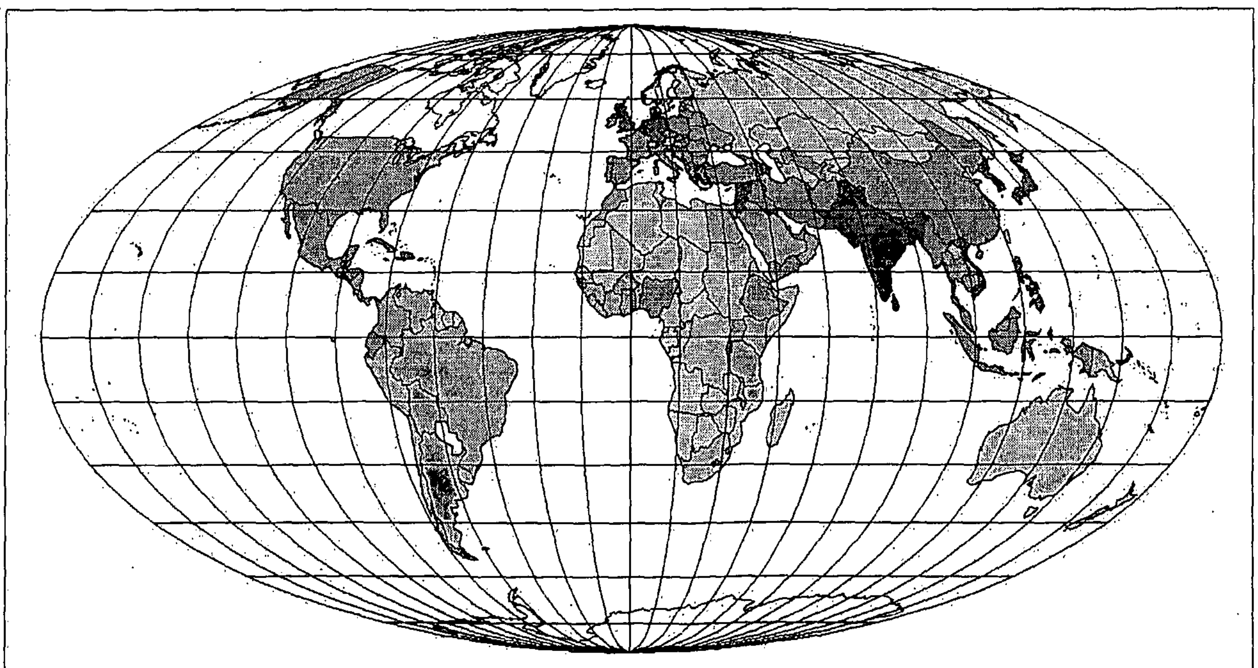


Figure 3.19. Hydrogen required as input to fuel cells. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

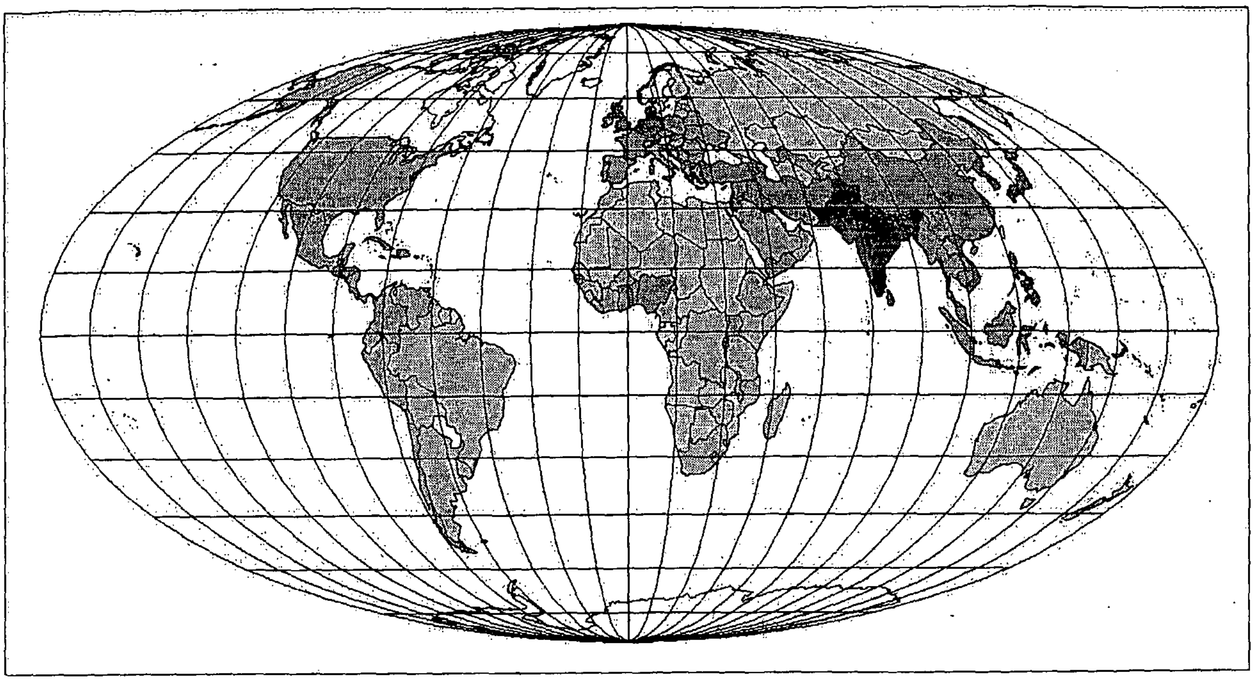


Figure 3.20. Coal required as fuel for power plants (co-producing heat and power). The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

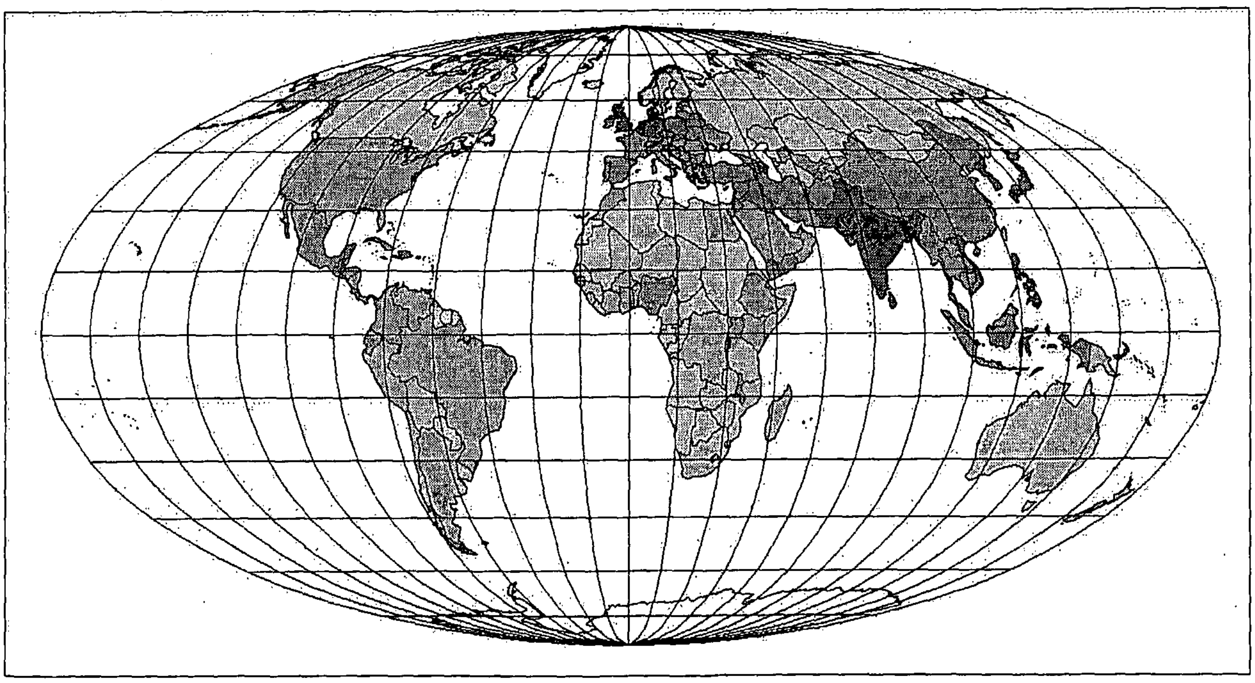


Figure 3.21. Natural gas required for hydrogen production. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

Figure 3.23 gives the energy for space heating (20%) and cooling (100%) covered by heat pumps and coolers, while Fig. 3.24 gives the rest of the low temperature requirements for space heating and process heat, to be covered by district heating based on power plant and fuel cell waste heat.

Figure 3.25 gives an overview of the scenario energy system, with annual energy flows indicated. The coverage of heat with assistance from co-produced heat from power plants and fuel cells is indicated.

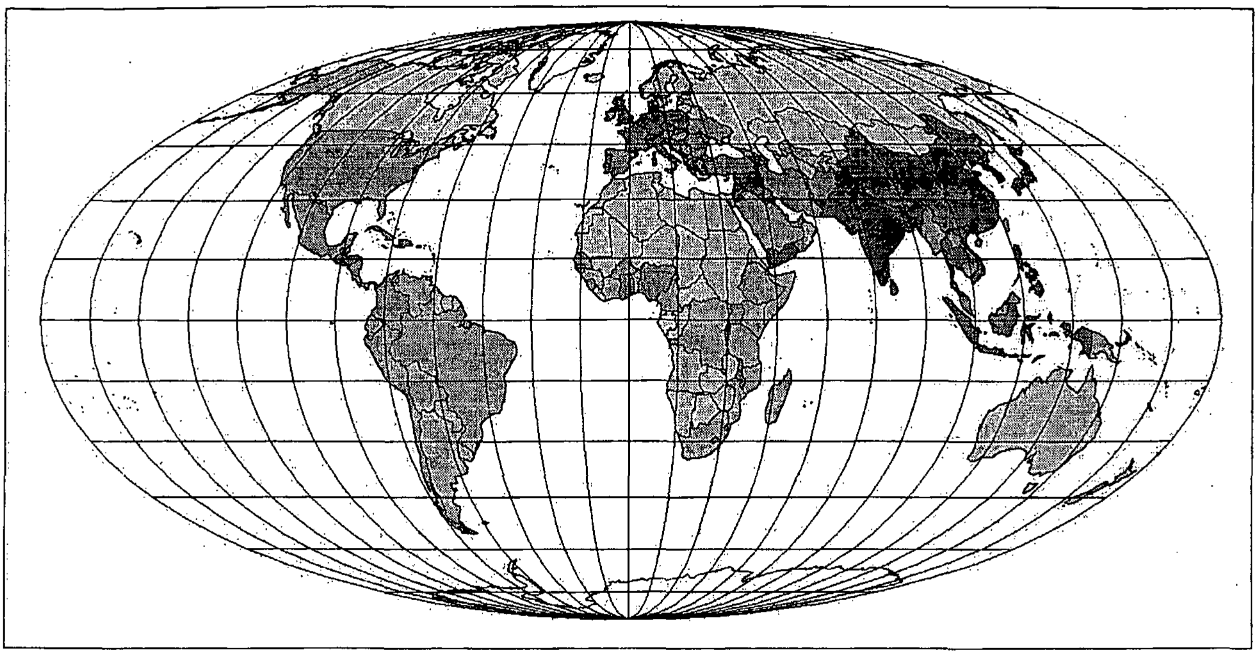


Figure 3.22. Coal required for hydrogen production. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

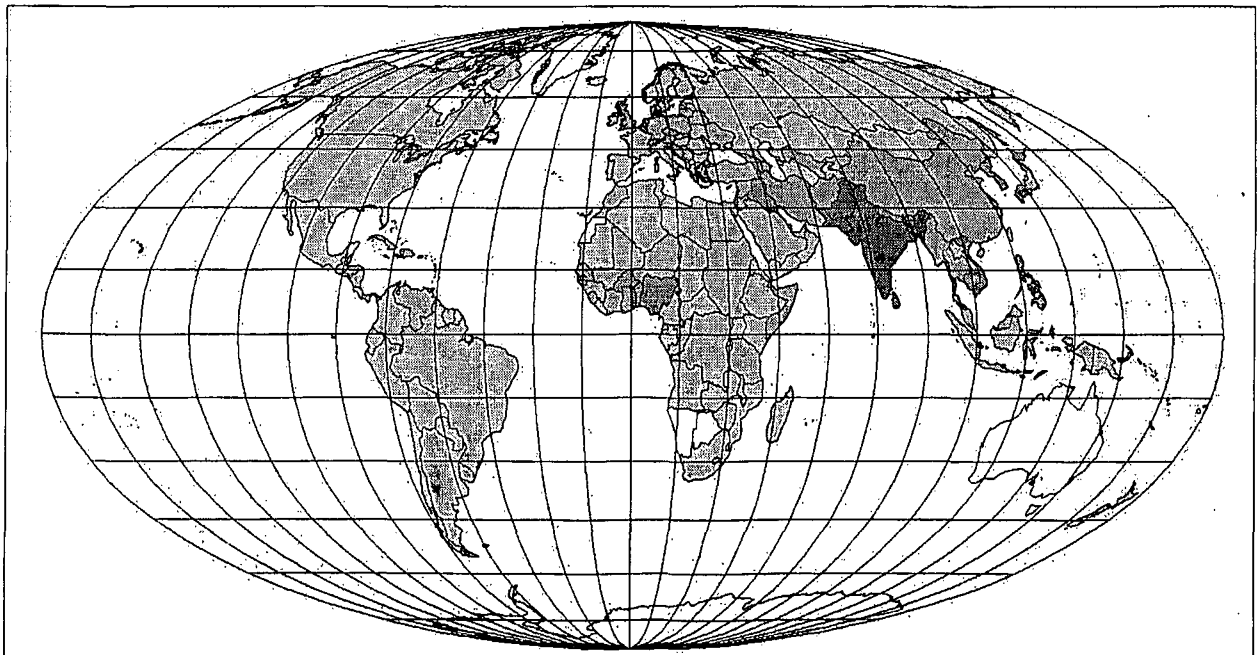


Figure 3.23. Space heating and cooling provided by heat pumps and electric coolers. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

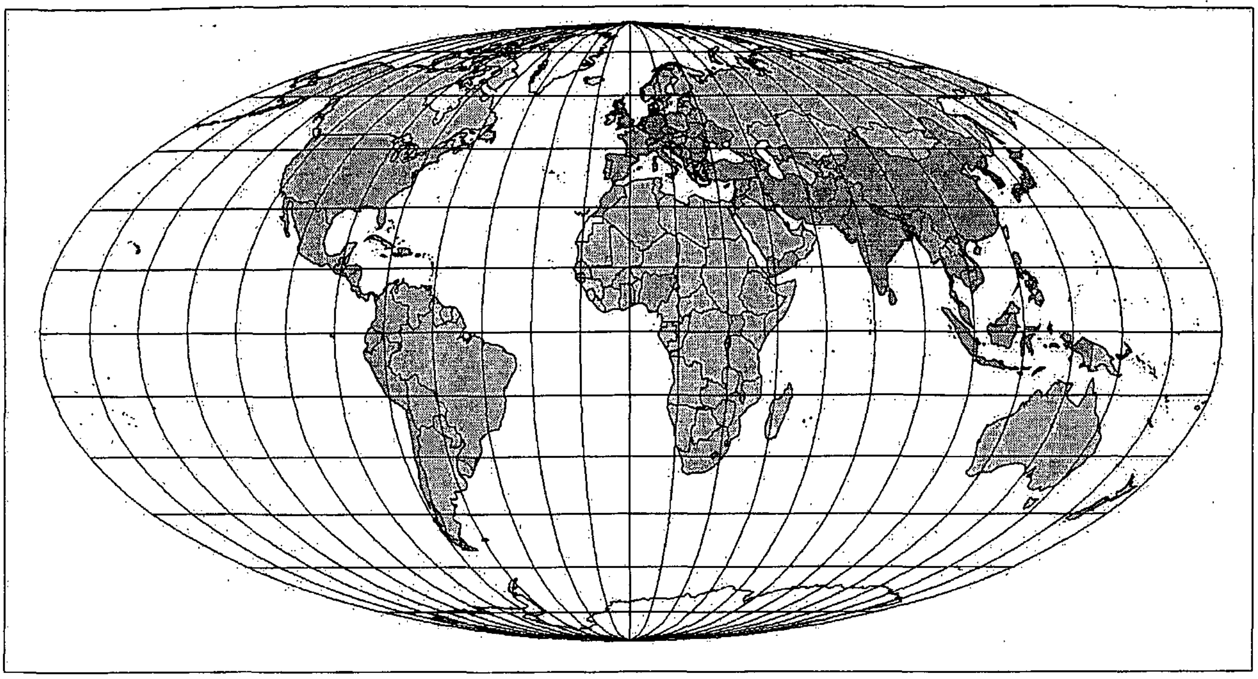


Figure 3.24. Space heating and low temperature heat provided by district heating with heat input from power plants, and from associated heat from fuel cell plants located near the heat load. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

The production of natural gas and coal now known, the year 2050 scenario assumes that the annual requirement is produced by each country in proportion to its total estimated resources of natural gas and coal, respectively. This creates a need for trade of these commodities, much the same way as today.

The fixed percentages of natural gas and coal inputs would in practice be modified for countries with resources primarily of one type. E.g. Norway and Saudi Arabia would increase their use of natural gas in order not to have to import coal. For countries able to cover their own electricity requirements with existing hydro, e.g. Canada and Norway, the scenario construction does not initially take into account export options, and the hydro input in Fig. 3.25 is therefore less than the potential production (by 177 GW). This additional capacity will in reality be used for export of electric power to neighbouring countries, and thus will slightly diminish the use of fossil fuels, on a global level.

Figures 3.26 and 3.27 gives the surplus and deficit of coal production in a national basis, Figs. 3.28 and 3.29 the surplus and deficit of natural gas production, and Figs. 3.30 and 3.31 the totals. It is seen that trade follows the patters of the present situation, as one could expect. Although the fossil reserves are more evenly distributed over the globe than thought some years ago (cf. Figs. 3.1, 3.6 and 3.13), the matching with demand is most negative for countries in South America, Africa and South-East Asia, due to the low level of identified resources and in South-East Asia the high population density, and the assumed high standard of living in the scenario year 2050.

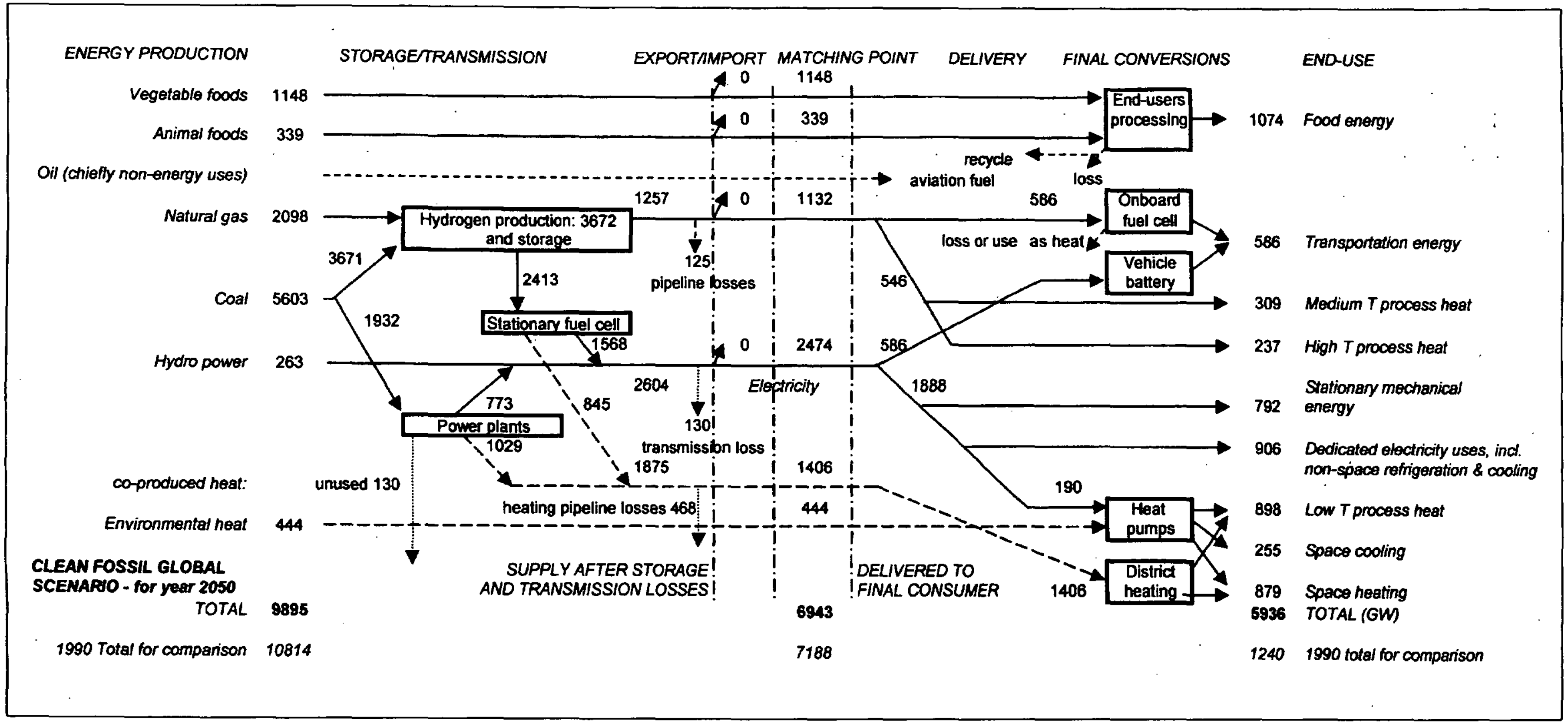


Figure 3.25. Overview of clean fossil scenario (flows in GW or GWy/y). For comparison, the 1990 totals are indicated at the bottom, with consumption total taken from the analysis in section 2. A large fraction of the stationary fuel cells might be placed in a strongly decentralised fashion, down to individual buildings. For the food production, here detached from energy production, see Chapter 5.

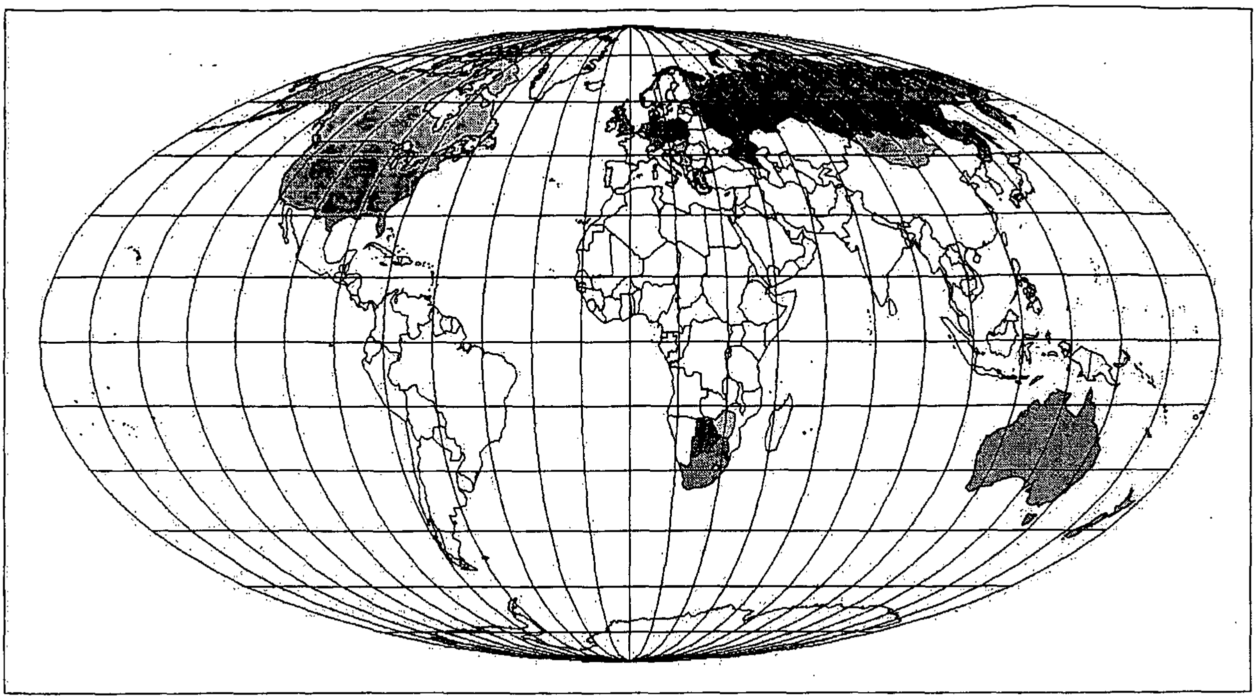


Figure 3.26. Coal surplus (production minus required supply for each country, if positive). The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

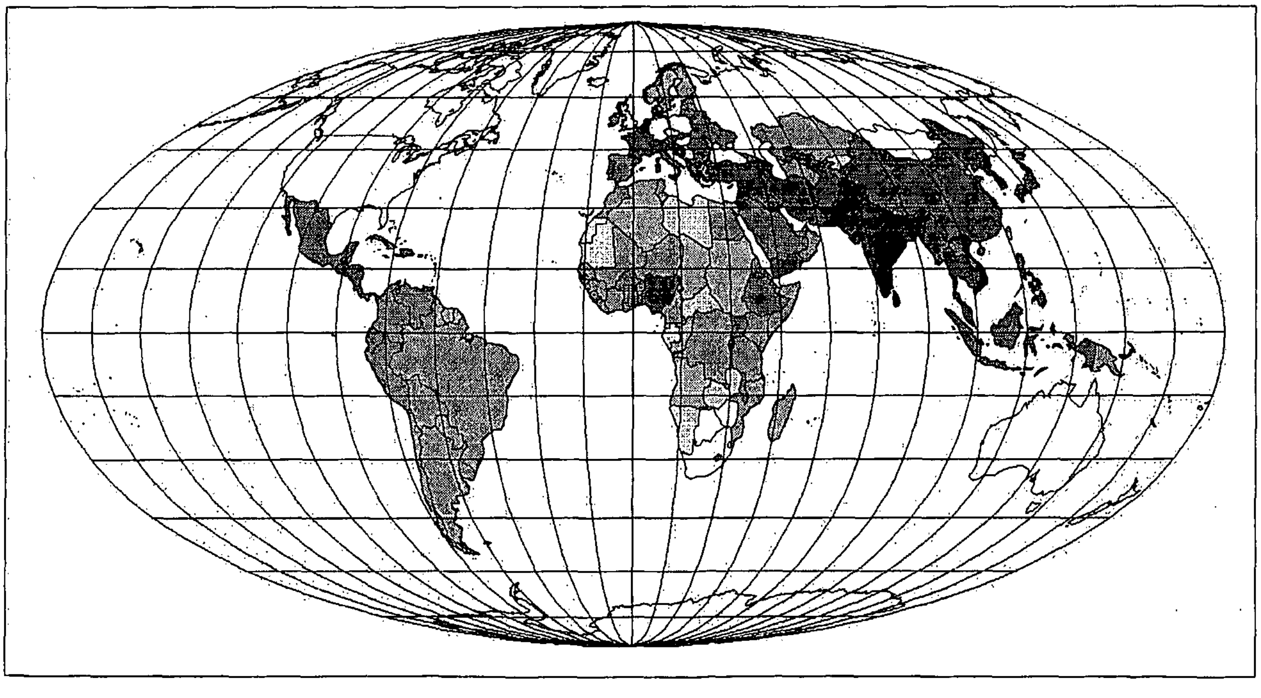


Figure 3.27. Coal deficit (required supply minus production for each country, if positive). The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.32.

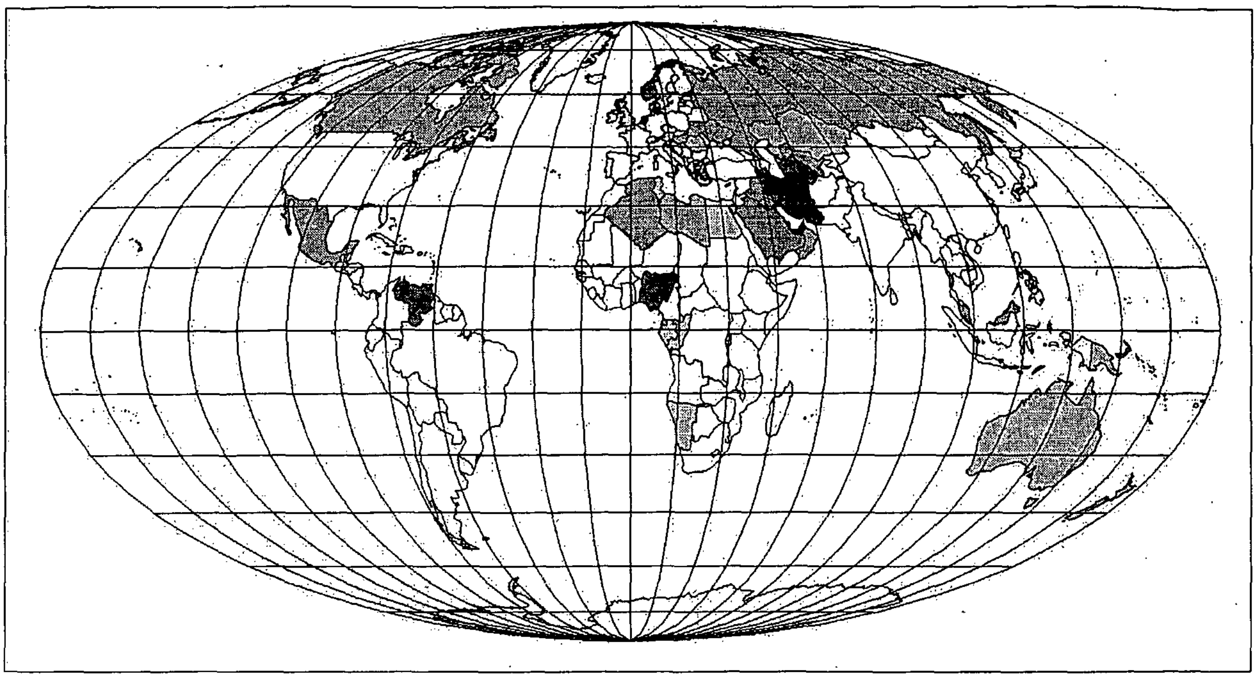


Figure 3.28. Natural gas surplus (production minus required supply for each country, if positive). The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

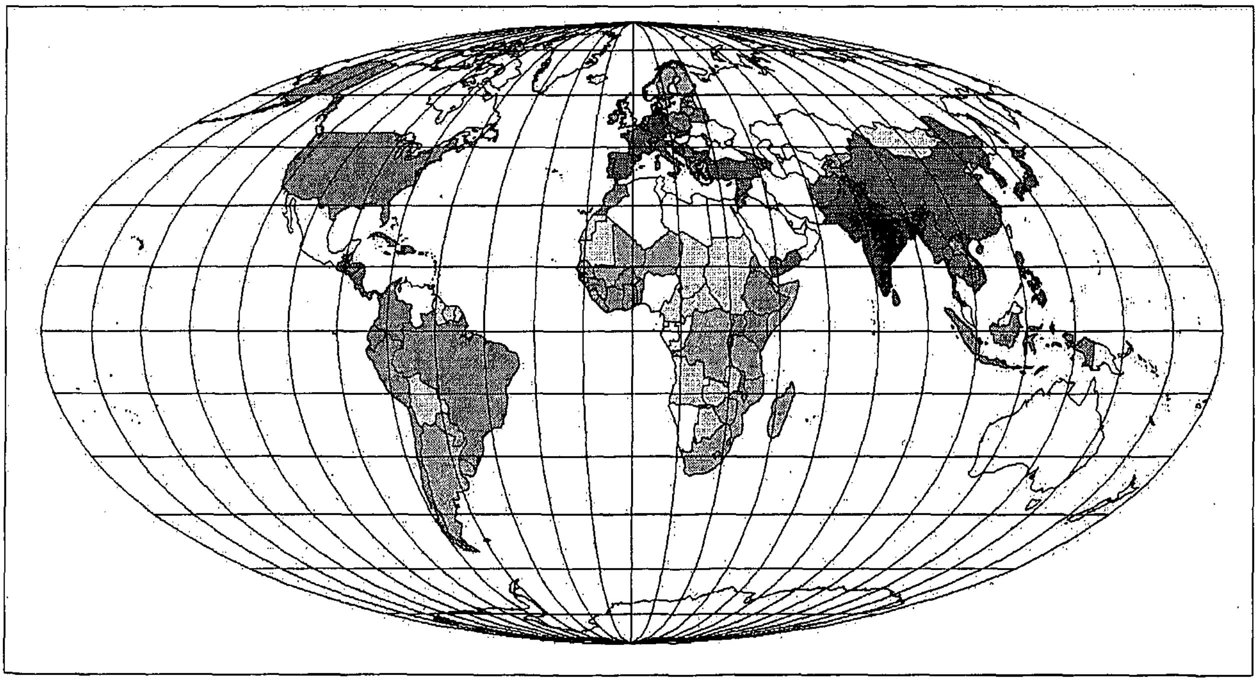


Figure 3.29. Natural gas deficit (required supply minus production for each country, if positive). The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.32.

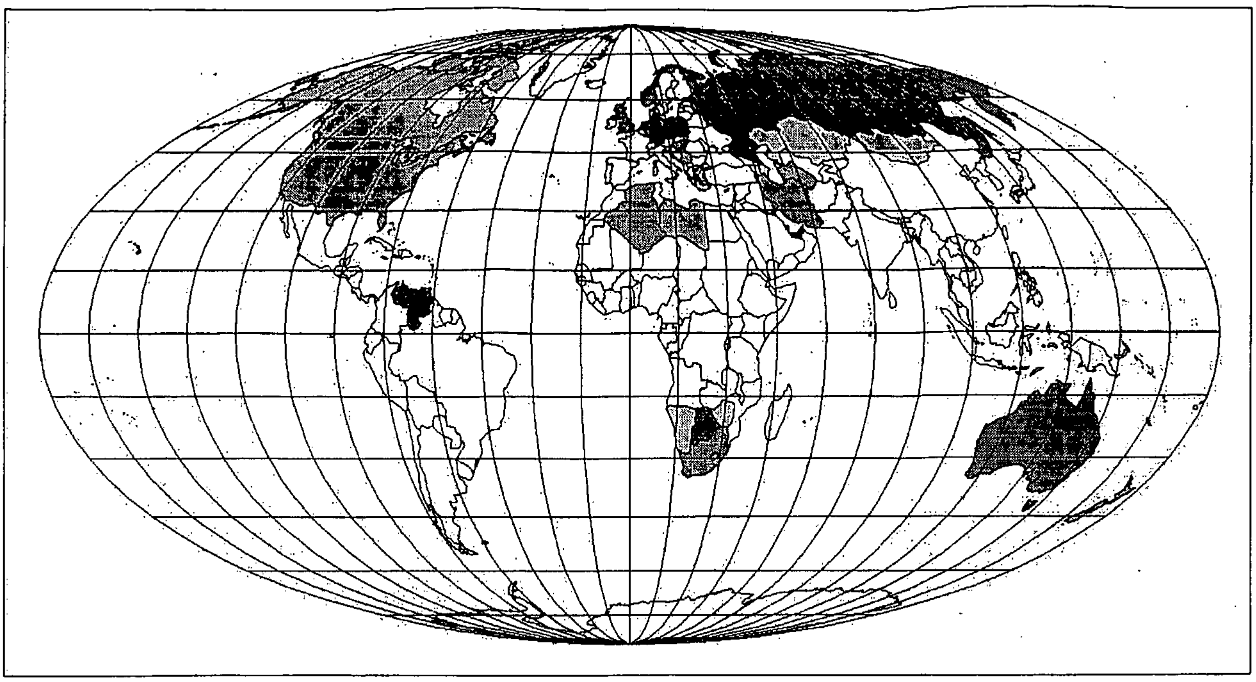


Figure 3.30. Total fossil fuel (coal and natural gas) surplus, i.e. production minus required supply for each country, if positive. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.16.

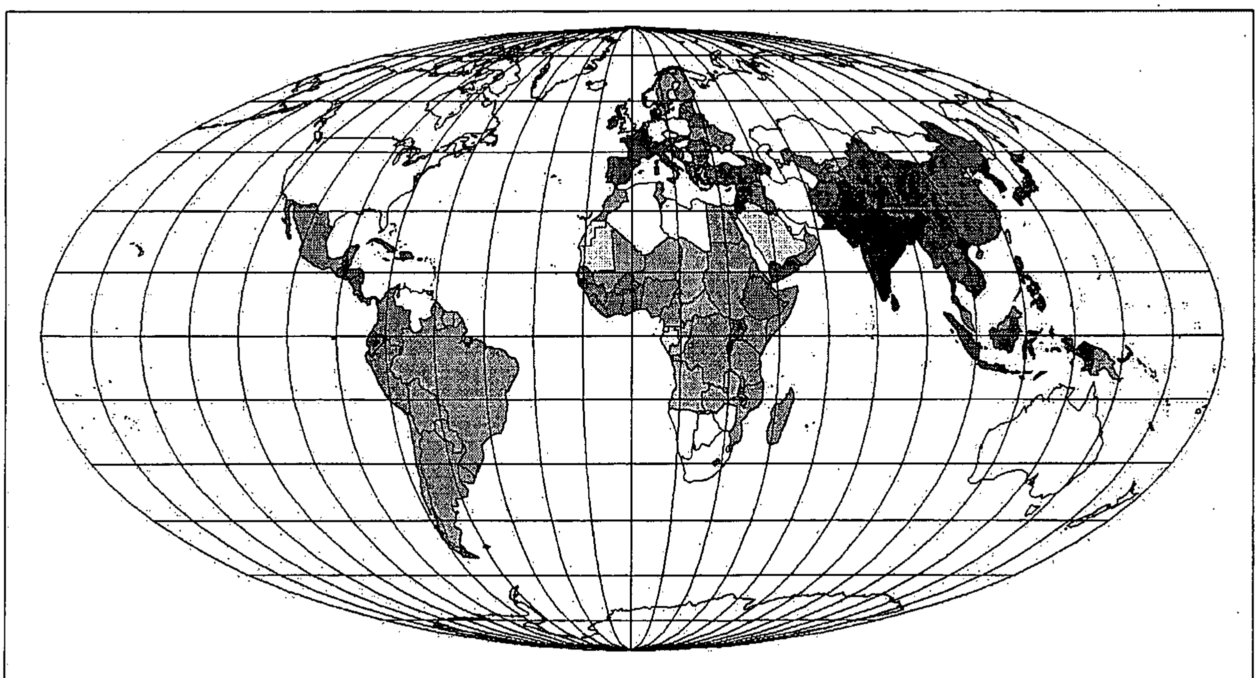


Figure 3.31. Total fossil fuel (coal and natural gas) deficit, i.e. required supply minus production for each country, if positive. The Figure shows average flows in W per m^2 of land area for each country, using the scale given in Fig. 3.32.

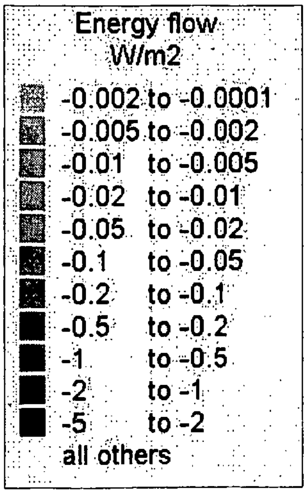


Figure 3.32. Scale of negative energy flows (W/m^2, e.g. deficit in supply minus demand rates; the scale is logarithmic and similar to that of positive energy flows, Fig. 3.16).

3.5 EVALUATION

Any fossil scenario has to be regarded as a parenthesis in the history of mankind (Sørensen, 1979 and 1999). The 2050 scenario described above allows the expected future demand to be covered by a rate of fossil fuel input no greater than the current one (see Fig. 3.25). Even then, the proven reserves of natural gas and coal will sustain the scenario primary energy use only for 73 and 86 years, respectively (the similarity of these numbers was aimed at in selecting the use of gas and coal in the scenario). Taken relative to the total resource base (whether exploitable or not), the scenario energy use can be sustained for 101 and 1830 years, for gas and coal, with the natural gas value possibly being underestimated, as discussed in section 3.3.

The carbon removal and deposition technologies described in section 3.2 have in most cases not been demonstrated in full scale. There may be technical problems and likely new environmental problems not foreseen, leading at least to higher prices if they can at all be fixed. Particular concern is in place regarding the ocean disposal of carbon dioxide, which could produce environmental problems as large as those one is trying to avoid, if the assumed stability turns out to not be secured. The cost estimates quoted in section 3.2 suggest that the ocean disposal will increase the cost of energy derived from fossil fuels by a factor 2-3. To this one must add the cost of the new technologies for producing hydrogen, whereas no extra cost is considered for the introduction of fuel cells, assuming that this new technology will come down in price to the level of conventional power plants, per unit of energy produced. All together, the cost of energy produced in the clean fossil scenario will be larger than the present by amounts having to be justified by the avoided greenhouse warming damage. This can be defended with the higher estimates found in the literature, but not with the lower ones (Kuemmel et al., 1997; IPCC b, 1996).

Apart from the question mark on the environmental implications of ocean CO_2 disposal, the fossil scenario seems to be technically feasible. However, the original justification for continuing use of fossil fuels was to be able to use existing infrastructure. This is not really the outcome of the scenario analysis: The transportation sector will be very different from the current (key technologies hydrogen, fuel cells, batteries and electric motors), a development which is needed in any case due to urban pollution considerations. District heating, which is presently common only in a few countries, will have to be expanded, and an increase must take place in the use of heat pumps for heating. The industry sector will not feel much change in going from e.g. natural gas to hydrogen, and electricity use will generally expand.

Chapter 4

THE SAFE NUCLEAR SCENARIO

4.1 THE CONCERNS

Electricity generated at nuclear power stations presently accounts for 2250 TWh/y or 18% of global electricity use (European Commission, 1997). The technology used is primarily light water reactors, a commercial spin-off from the submarine nuclear powered propulsion systems introduced in the 1950ies. The situation after World War II was characterised by two factors of some importance for the development of nuclear energy and the specific reactor choice:

i) The existence of a highly skilled group of nuclear physicists with a desire to be able to employ their knowledge for peaceful purposes, as opposed to the wartime bomb making. In other words to demonstrate that nuclear techniques could be used for beneficial purposes as well as for destruction. No group of researchers and developers held in similar esteem were available for the development of competing energy technologies such as those based on renewable energy sources.

ii) A general shortage of economic means, relative to the magnitude of tasks needing to be performed in rebuilding the assets destroyed during the war. This lead decision-makers to prefer the cheapest solution, without the regard to supply security and environmental impacts, that later became part of energy policy decisions. It meant that although alternative nuclear reactor designs were indeed suggested and developed (e.g. CANDU and high-temperature types), the economic advantage of copying an already existing military technology was very tempting, even if some critics found the design less than suited for civilian deployment.

The subsequent fate of nuclear power in the energy sector may be seen as a consequence of the special circumstances suggested by these observations: A major public dispute erupted in a number of countries with public participation traditions, basically centred on three issues:

1) The nuclear reactor technology selected poses risks of large accidents with major releases of radioactivity and unpredictable consequences.

2) Operation of nuclear power plants creates volumes of radioactive waste, to be kept separate from the biosphere during intervals of time that cannot be guaranteed as they are much longer than the lifetime of economic entities or even national states.

3) The nuclear fuel chain generates plutonium and other material useful for nuclear weapons production, and thus increases the risk of such material being diverted to belligerent states or to terrorist organisations for use in actions of nuclear blackmail or war.

The proponents of nuclear power made claims that any risk associated with the technology was zero or negligible, and that the engineering and operational safety was far superior to that of any other technology. Lengthy reports were procured, which seemed to prove these statements as being virtually mathematical tautologies.

This provoked a number of independent scientists to look closer at the claims, and they concluded that there were basic flaws in both the methodologies used and the actual calculations (see overview by Sørensen, 1979b). It is therefore not surprising, that when major accidents started to happen, the nuclear proponents lost credibility in a way that could perhaps have been avoided with a more honest approach to the information issue.

The important accidents were first the Three Mile Island Reactor partial meltdown, which did not breach the outer containment but totally ruined the plant, and the Chernobyl melt-down accident, which caused major releases of radioactivity to the atmosphere and global fallout.

Gradually, national energy policies were changed to exclude additional construction of nuclear power plants, either directly or indirectly by enforcing strong licensing conditions that could only be met with increased time-intervals between the decision to built and the final commissioning, and consequently with considerable increases in costs. Concurrent efforts to make the electricity industry more competitive caused power plant operators to forego the "difficult" nuclear option and thereby avoid to deal with its uncertainties.

A clear indication of this development is found in the current market projections of future world uranium requirements, as e.g. stated by the US Department of Energy (deMouy, 1998). The global 2015 requirements are estimated as only 85% of the current ones, as shown in Fig. 4.1, despite some growth in countries in South-East Asia and South America.

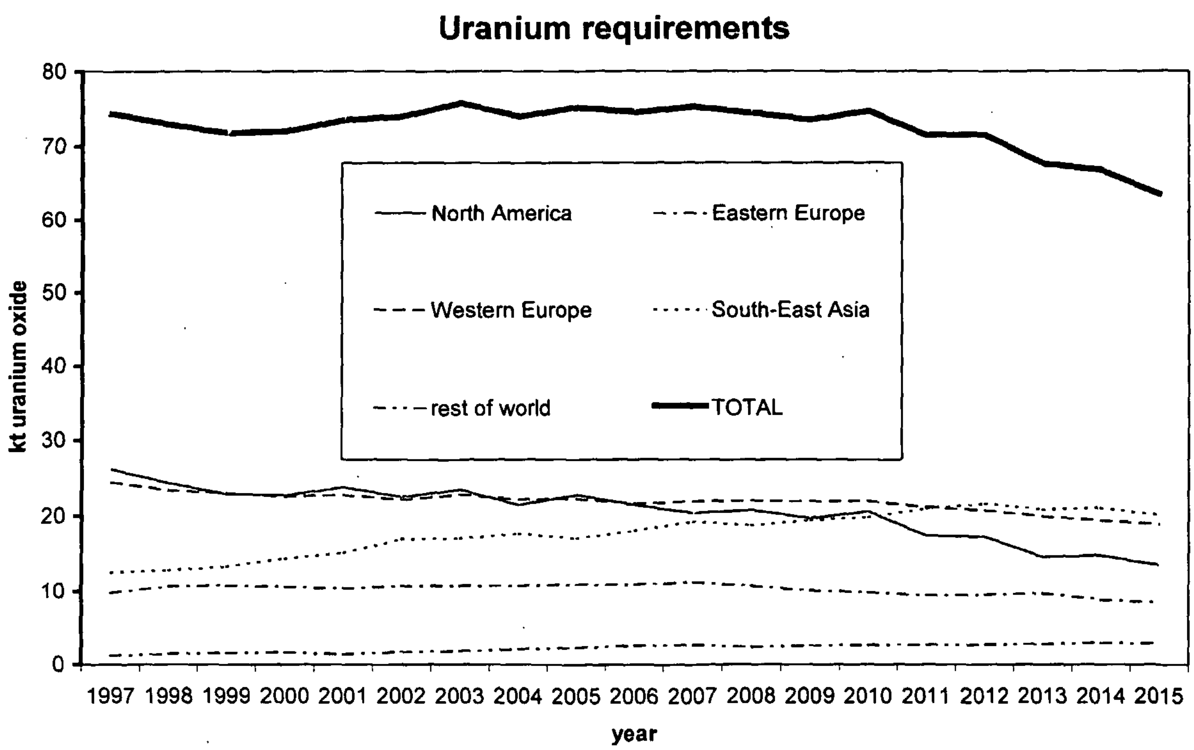


Figure 4.1. World uranium requirements according to US Department of Energy reference case projection (deMouy, 1998).

The purpose of the "safe nuclear scenario" is to investigate if nuclear technologies different from those employed today may solve the problem or strongly reduce the concerns stated above, while forming a solution that is viable in terms of the transition time needed, resource depletion, and has reasonable economy.

4.2 SAFE NUCLEAR TECHNOLOGIES

The technologies selected for the safe nuclear scenario should address the main objections to current nuclear power technologies: proliferation issues, large nuclear accidents and long-term storage of waste. A wealth of ideas and new technologies for avoiding or reducing these problems has been discussed for some years, but all are still fairly speculative. A few have been tested at laboratory scale, but their implementation will take further technical development and would presumably make nuclear power more expensive than today. These additional costs have to be justified by including social costs (including those external to current economic valuation) of the problems associated with current nuclear technologies.

To avoid proliferation, fissile material such as plutonium should never accumulate in large amounts, or should be difficult to separate from the stream of spent fuel. This can be addressed by using accelerators to produce fissile material at the same pace as it is used to produce energy. Accelerators are also among the options for "incineration" of current nuclear and military waste, in order to reduce waste storage time and again avoid storage of waste from which weapons material could be extracted.

There are two proposed technologies that use accelerators: One is called accelerator-breeding, as it aims at converting fertile material (e.g. Th-232) into fissile fuel to be used elsewhere in a (conventional) reactor (Lecocq and Furukawa, 1994). This does not in itself reduce accident probabilities, and to achieve this, the reactor should be of an inherently safe type. This concept means that the risk of core melt-down in case the heat from fission processes cannot be led away must be absent. Two examples of proposed inherently safe reactor designs are:

- either to reduce the size so much that core melt accidents almost certainly can be contained by the vessel used (this involves maximum unit sizes of 50-100 MW),
- or a different design, in which the core of a conventional pressurised water reactor (PWR) is enclosed within a vessel of boronated water, that will flood the core if pressure is lost: There is no barrier between the core and the pool of water, which in case pressure in the primary system is lost will shut the reactor down and continue to remove heat from the core by natural circulation. It is calculated that in an accident situation, replenishing of cooling fluid can be done at weekly intervals (in contrast to hours or less required for current light water reactor designs) (Hannerz, 1983; Klueh, 1986).

The other accelerator concept recently proposed (Rubbia, 1994; Rubbia and Rubio, 1996) integrates the accelerator and the reactor-like device into what is termed an *energy amplifier*. The central point in this design is, that the energy amplifier does not have to be critical (i.e. the nuclear processes do not have to sustain themselves), as there is a continuous supply of additional neutrons from spallation processes caused by the accelerated protons. This is supposed to greatly reduce the risk of criticality accidents. Exactly how much needs to be further studied. The main components of the fuel chain are illustrated in Fig. 4.2.

Technical details of energy amplifier

The proposed technology involves a proton accelerator (linear or cyclotron), for the purpose of producing fast neutrons. This is achieved by letting high-energy protons impinge on some heavy target (which could be lead, uranium or thorium). The process is called spallation and typically produces around 50 neutrons of energy 20 MeV per 1 GeV proton. The device proposed by C. Rubbia resembles a reactor or the blanket of a reactor. Fertile material such as thorium-232 ($^{232}_{90}Th$) needs bombardment with energetic neutrons to transform into nuclear isotopes capable of fissioning, i.e. splitting into two approximately equally heavy products under release of the energy difference (see e.g. Sørensen, 1979). Examples of fertile materials are ${}^{232}_{90}Th$ and ${}^{238}_{92}U$, whereas examples of isotopes that may undergo fission already by absorption of slow (little energetic) neutrons are ${}^{233}_{92}U$, ${}^{235}_{92}U$ and ${}^{239}_{94}Pu$. In current light water moderated reactors, the fissile isotope is ${}^{235}_{92}U$ and the additional neutrons released by fissioning are capable of sustaining a chain reaction (or in absence of careful control a run-away reaction, which is the criticality problem leading to accidents such the one in 1986 in the Chernobyl reactor, cf. Kurchatov Institute, 1997). In the dense core of fast breeder reactors, the number of ${}^{238}_{92}U$ isotopes hit by neutrons and transformed into ${}^{239}_{94}Pu$ is so large, that the potential energy derived from the fissile material may be 60 times that of the ${}^{235}_{92}U$ input.

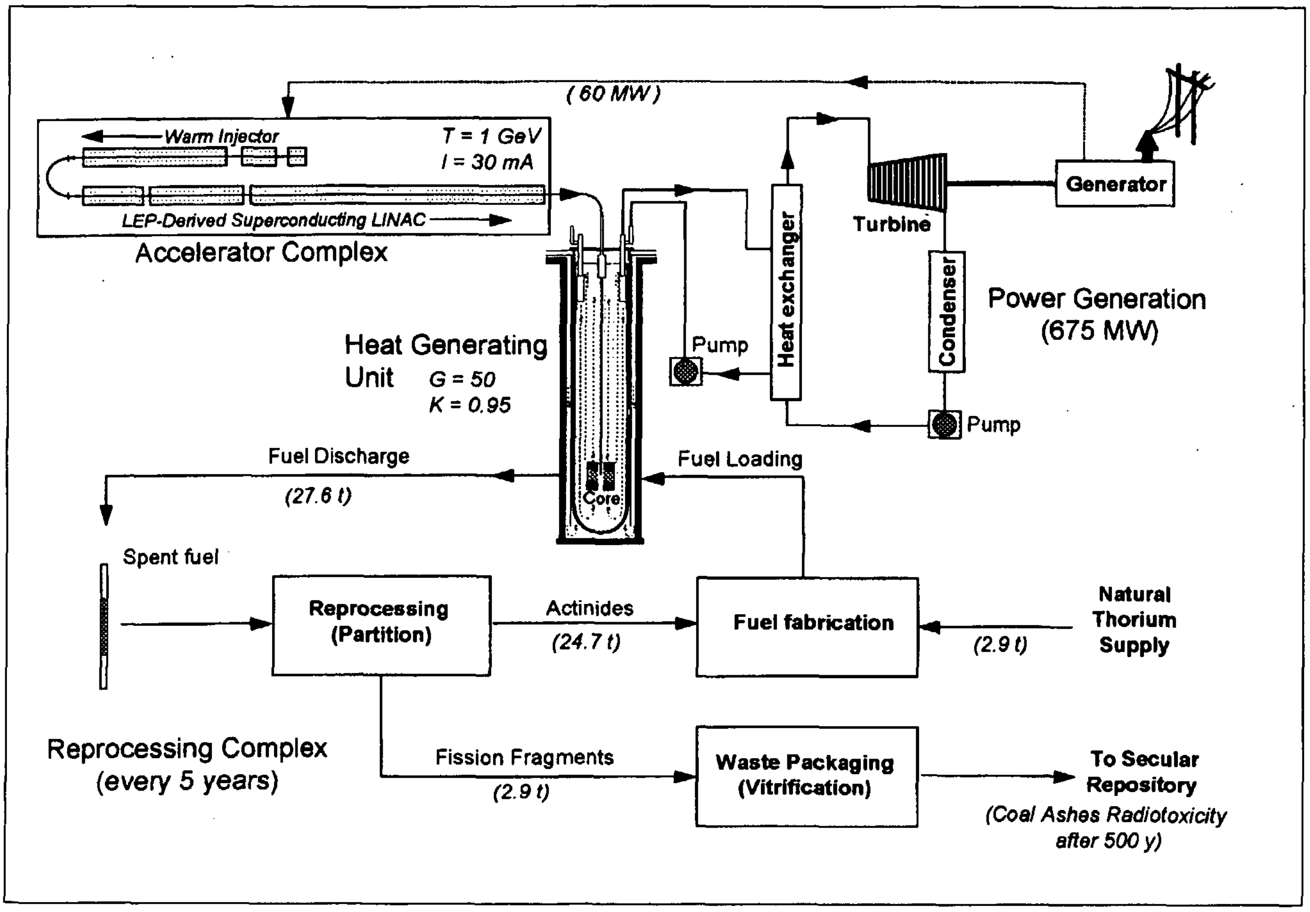


Figure 4.2. The energy amplifier fuel chain concept. The fraction of the generated electricity that has to be used for powering the accelerator is indicated. The reprocessing step is essential for the resource viability of the system (Rubbia and Rubio, 1996).

The accelerator breeding efficiency depends strongly on the neutron multiplication factor k, which is the proposed design should be about 0.95 (as opposed to very slightly above 1 in a conventional reactor). This is equivalent to an energy gain (breeding factor) of about 50, and it is believed that the value of k=0.95 is sufficient to avoid that k ever exceeds the value one, in situations of irregularity. If the accelerator is halted, the nuclear process will stop. The heat generating unit will be placed underground. The proposed design is shown in Fig. 4.3.

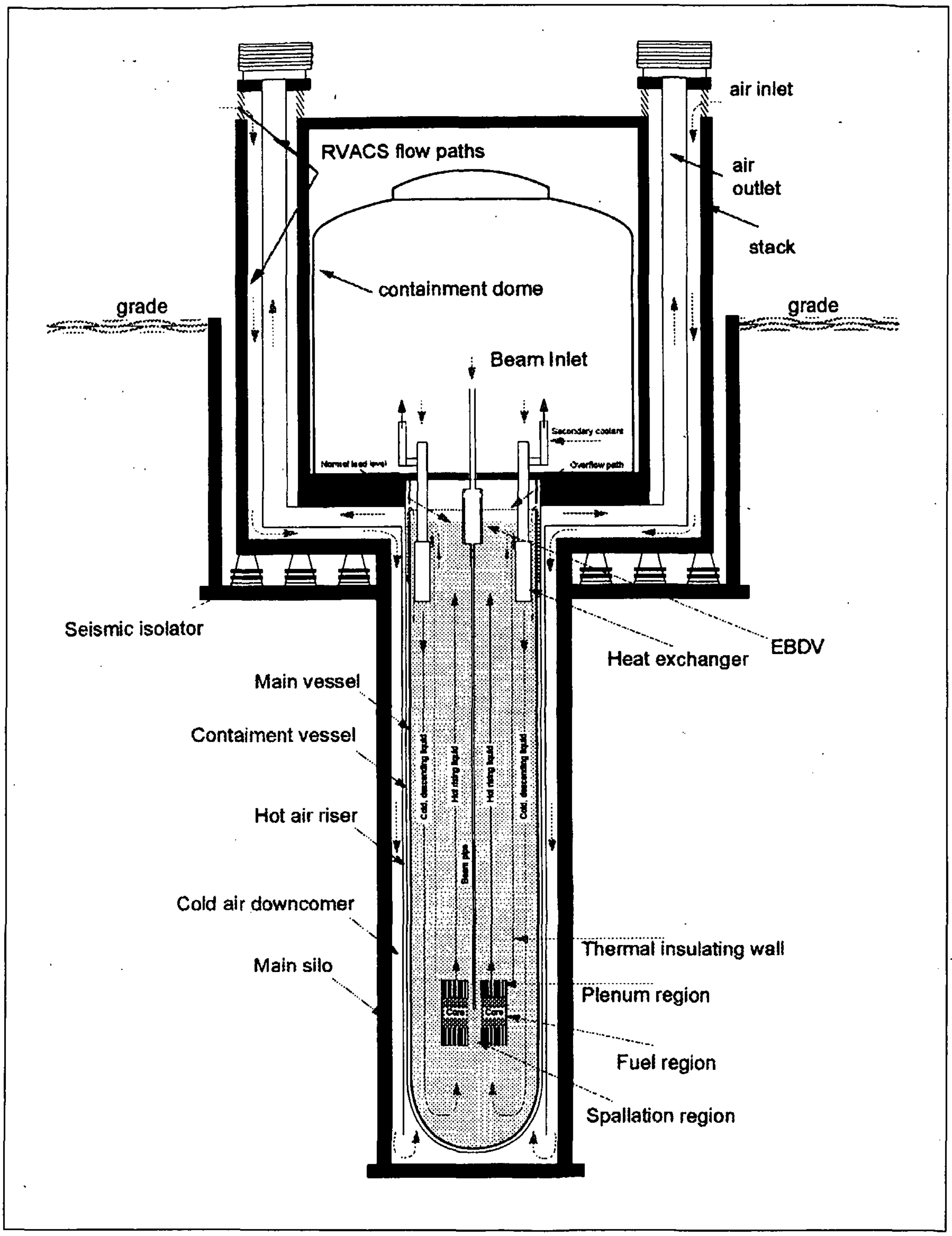


Figure 4.3. Layout of central heat generating unit, a 30m high silo to be placed underground. Note the emergency beam dump volume indicated as "EBDV" (Rubbia et al, 1995).

Subcriticality is the first essential feature of the concept; the second is the use of a thorium cycle, based on the accelerator-induced reactions ($T_{1/2}$ is the halflife, i.e. the time after which activity has been reduced to half),

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th\ (T_{1/2}=23m) \rightarrow {}^{233}_{91}Pa\ (T_{1/2}=27d) + e^- \rightarrow {}^{233}_{92}U\ (T_{1/2}=163000y) + e^-.$$

The fissionable end-product $^{233}_{92}U$ is not the only outcome, as some of the $^{233}_{90}Th$ will undergo an (n,2n) reaction to $^{231}_{90}Th$, that will further decay to $^{231}_{91}Pa$ and $^{232}_{92}U$, leading eventually to $^{208}_{81}Tl$, the strong gamma-activity of which makes reprocessing difficult, although not impossible. Because of the breeding property, reprocessing of fuel elements is expected to take place only with intervals of five years or more. The thorium cycle as described above has very significant advantages in terms of reducing the amounts of nuclear waste to be kept separated from the biosphere for long periods of time. Fig. 4.3b gives the calculated radiotoxicity of waste from the thorium energy amplifier (one-pass through or recycling reprocessed waste), and compares it with current reactor waste toxicity (Lung, 1997; Magill et al., 1995). The accelerator-breeder will accept current reactor and military waste as input, thus offering a way of disposing obsolete nuclear weapons and high-level waste from light water reactors.

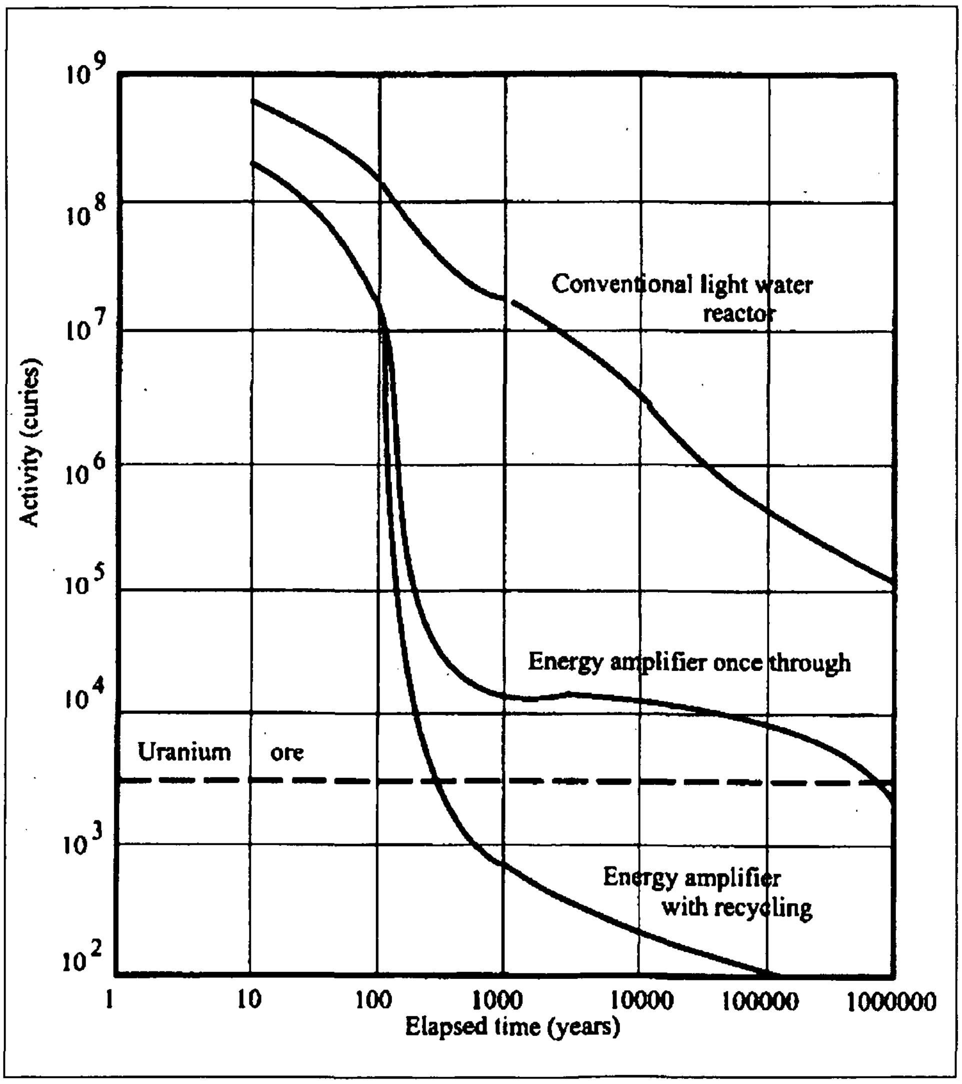


Figure 4.3b. Activity of radioactive waste from nuclear power plants after 40 years of continuous operation, indicating advantage of accelerator-breeder concepts. The calculations are preliminary and do not correspond to final designs (based on Rubbia et al., 1995; Lung, 1997).

The French physicist J. Maillard has expressed concern that the interface between the accelerator and the breeder could constitute a weakness in the Rubbia design, allowing escape of radioactivity together with molten lead, in case of sudden accelerator failure (Mirenowicz, 1977).

The combination of accelerator breeding and use of the thorium cycle with possible inclusion of uranium resources is needed in our global scenario for resource reasons, as further explained in section 4.3: the available U-235 reserves used in conventional reactor types would only last for a short time at the rate of usage assumed in a global nuclear scenario, and although additional resources may become available, the time horizon is not going to expand significantly towards a sustainable system. Therefore, breeding is necessary in any long-term nuclear scenario, and inclusion of thorium resources would extend the resources to last some 1000-2000 years in scenarios of efficient energy usage such as the present (Jensen and Sørensen, 1984; IPCC, 1996). Current thorium extraction is discussed by Hedrick (1998).

The ideas of accelerator breeding and thorium-based nuclear power have been around from the start of the effort to transfer nuclear techniques from the military to the civil sector, first for resource reasons (Lawrence as quoted by RIT, 1997), later for reasons of reducing the waste disposal problem (Steinberg et al., 1977; Grand, 1979; OECD, 1994) and getting rid of military nuclear waste and obsolete warheads (Toevs et al, 1994; National Academy of Sciences, 1994), and finally for avoiding proliferation and reducing accident risks (Rubbia et al., 1995). The ideas involving separation of the accelerator-breeding stage and the energy production stage (Furukawa, as quoted by Lung, 1997) were used in an early version of the present scenario (Sørensen, 1996). This is the preferred concept of the Los Alamos Group as well as the French and Japanese groups, and it would use a mixture of lithium, beryllium and thorium fluorides as input to the accelerator-breeder, allowing this molten-salt fuel to be transported to and used in graphite-moderated nuclear reactors, despite negative experiences with such a reactor operated for some years at Fort St-Vrain in Colorado (Bowman et al., 1994; Lung, 1997). Early schemes for waste transmutation proposed to use breeder reactors (Pigford, 1991), which do not fulfil the demand for inherent safety. The scenario presented in section 4.4 is based on the Rubbia idea, of which an early version was discussed by Kuemmel et al. (1997)[1], but it could include parallel operation of inherently safe reactors, from which spent fuel would be shipped to the reprocessing plant of the accelerator-amplifier installation. As stated above, this scenario is based on largely unproven technology, and would require huge R&D investments over significant periods of time, as have the current nuclear technologies.

4.3 RESOURCE CONSIDERATIONS

Current estimates of the available reserves and further resources of uranium and thorium, and their global distribution, are shown in Figs. 4.4-4.10. The uranium proven reserves indicated in Fig. 4.4 can be extracted at costs below 130 US $/ton, as can the probable additional reserves indicated in Fig. 4.5. Fig. 4.6 shows new and unconventional resources that may later become reserves. They are inferred on the basis of geological modelling or other indirect information (OECD and IAEA, 1993; World Energy Council, 1995). The thorium resource estimates are from the US Geological Survey (Hedrick, 1998), and similarly divided into reserves (Fig. 4.8), additional reserves (Fig. 4.9) and more speculative resources (Fig. 4.10). The thorium situation is less well explored than that of uranium: the reserves cannot be said to be "economical", as they are mined for other purposes (rare earth metals), and thorium is only a by-product currently with very limited areas of use. The "speculative" Th-resources may well have a similar status to some of the additional U-reserves.

[1] The nuclear scenario of Kuemmel et al. (1997) is shown in Fig. 23 of their book. Note that the amounts of thorium indicated in that Figure are 15 times higher than the annual flows needed to sustain the energy scenario.

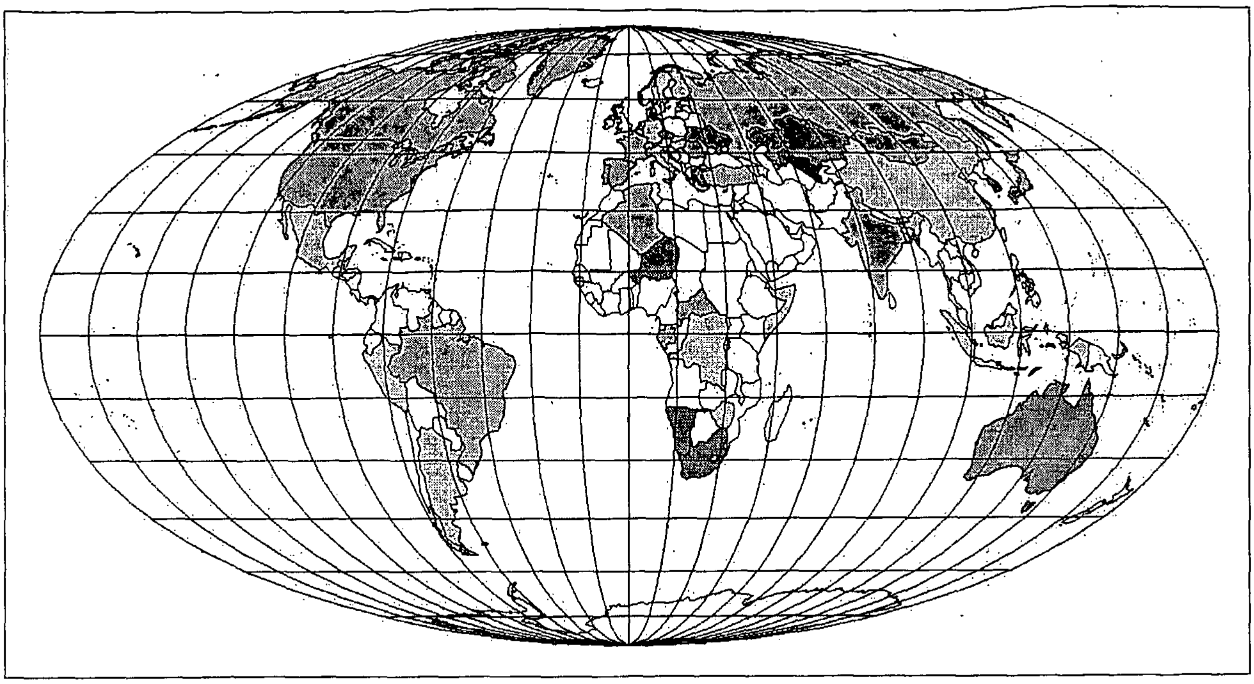


Figure 4.4. Proven uranium reserves given as kg uranium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7 (source: OECD and IAEA, 1993).

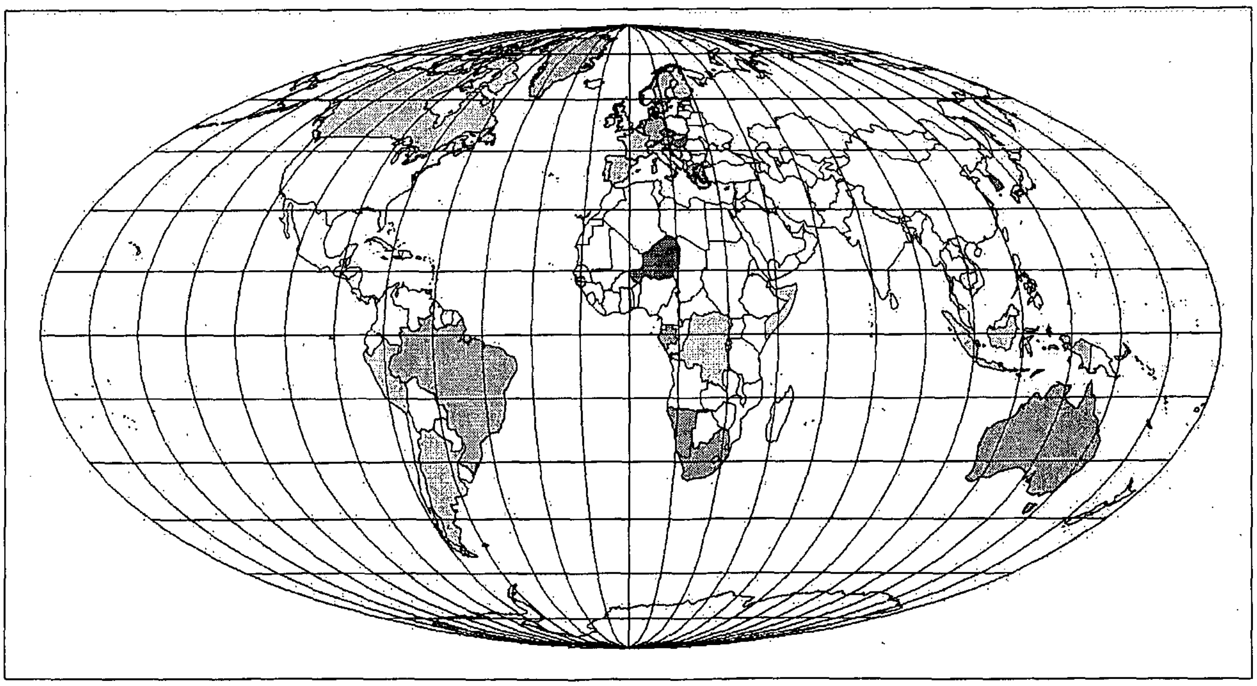
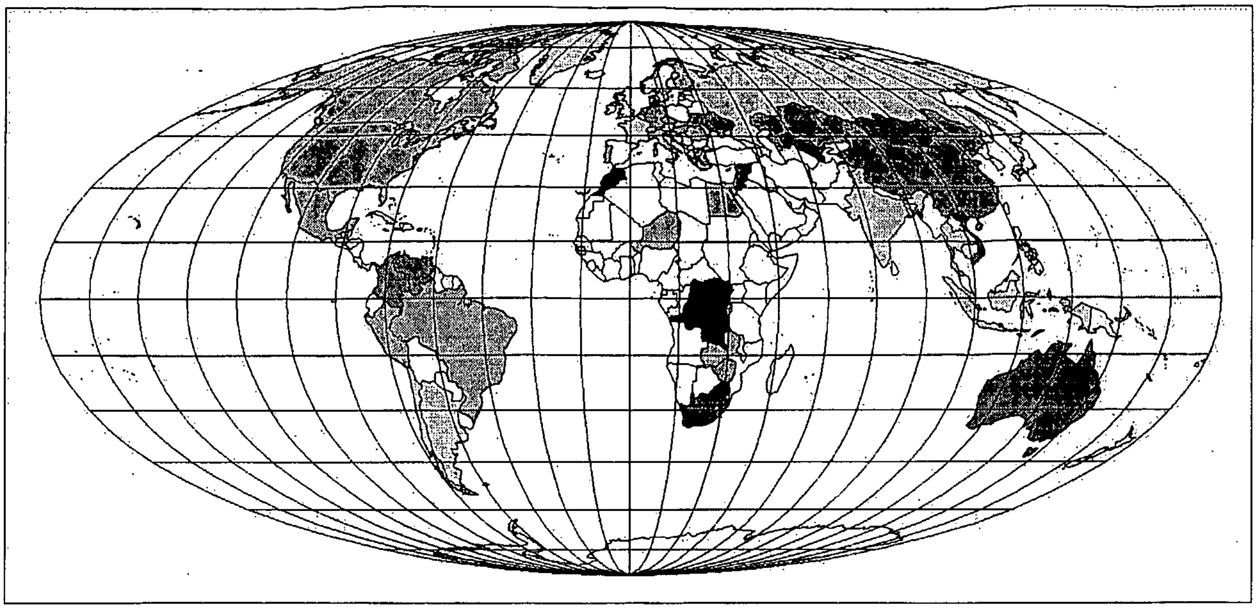


Figure 4.5. Estimated additional uranium reserves given as kg uranium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7 (source: World Energy Council, 1995).



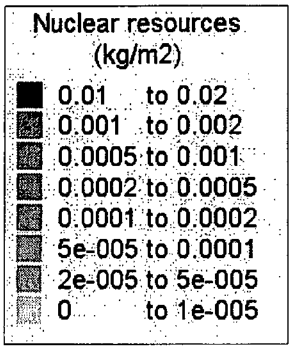


Figure 4.6 (above). New and unconventional uranium resources given as kg uranium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7 (source: World Energy Council, 1995).

Figure 4.7 (left). Scale used for nuclear resource distributions (kg per m^2).

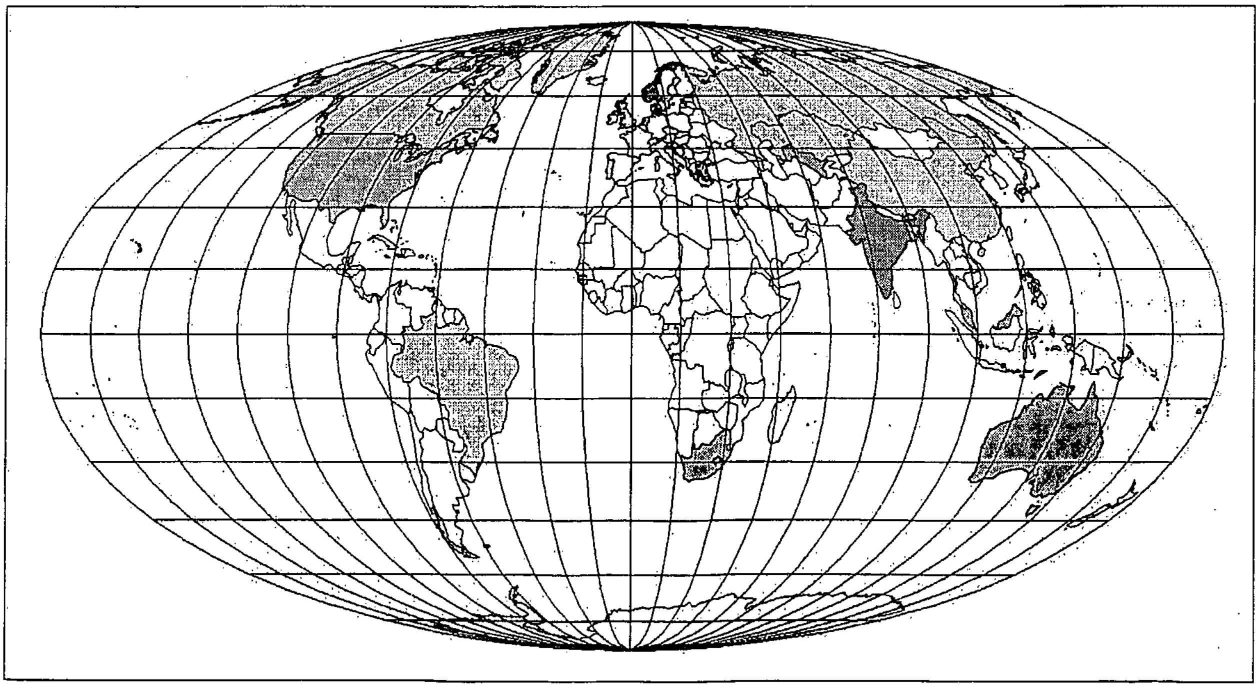


Figure 4.8. Proven thorium reserves given as kg thorium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7 (source: Hedrick, 1998).

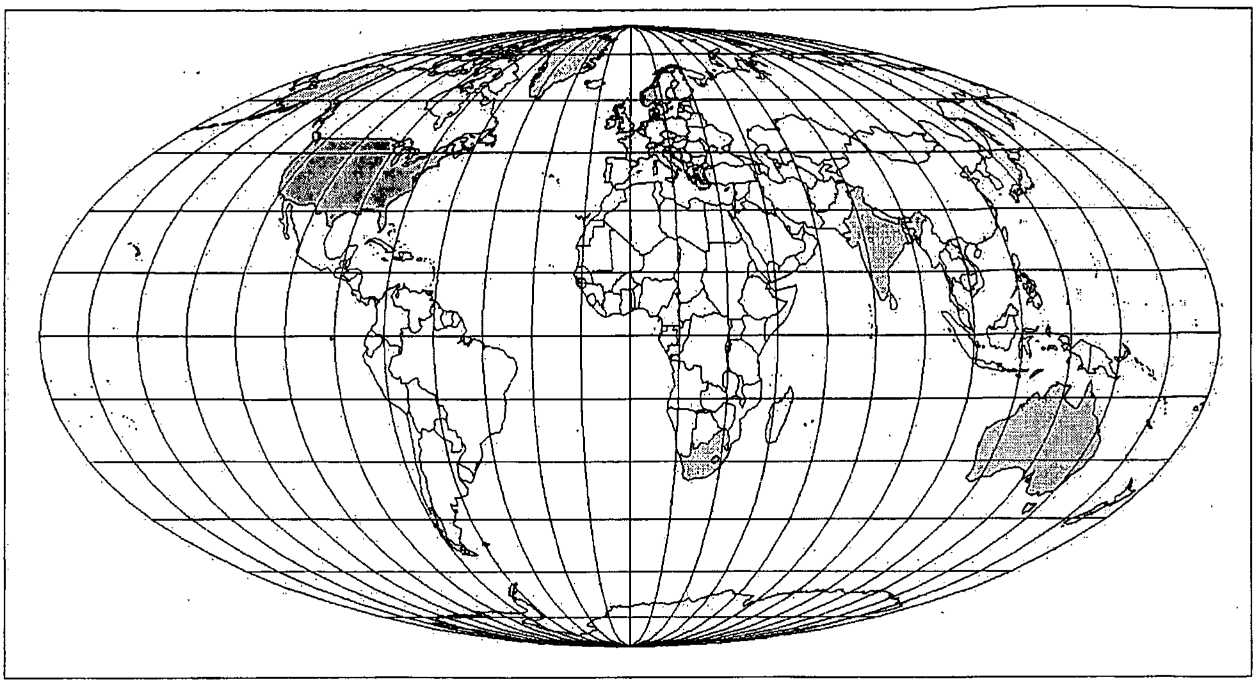


Figure 4.9. Additional thorium reserves given as kg thorium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7 (source: Hedrick, 1998).

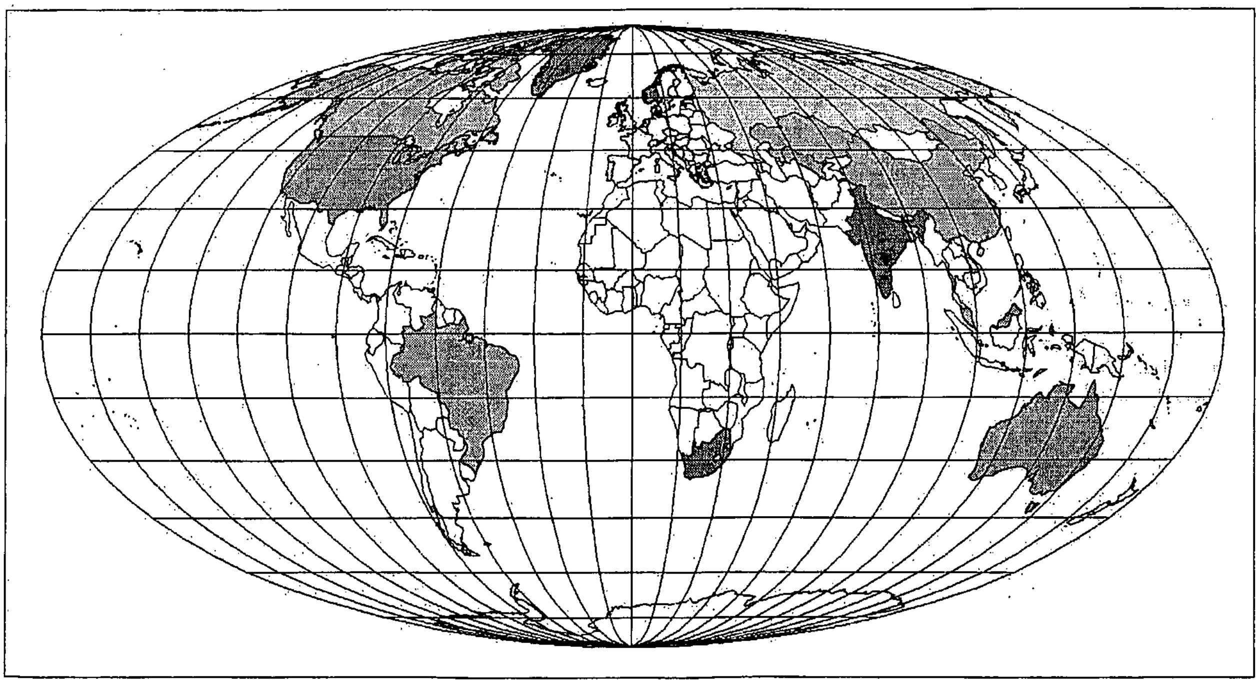


Figure 4.10. New and unconventional thorium reources given as kg thorium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7 (with use of Hedrick, 1998).

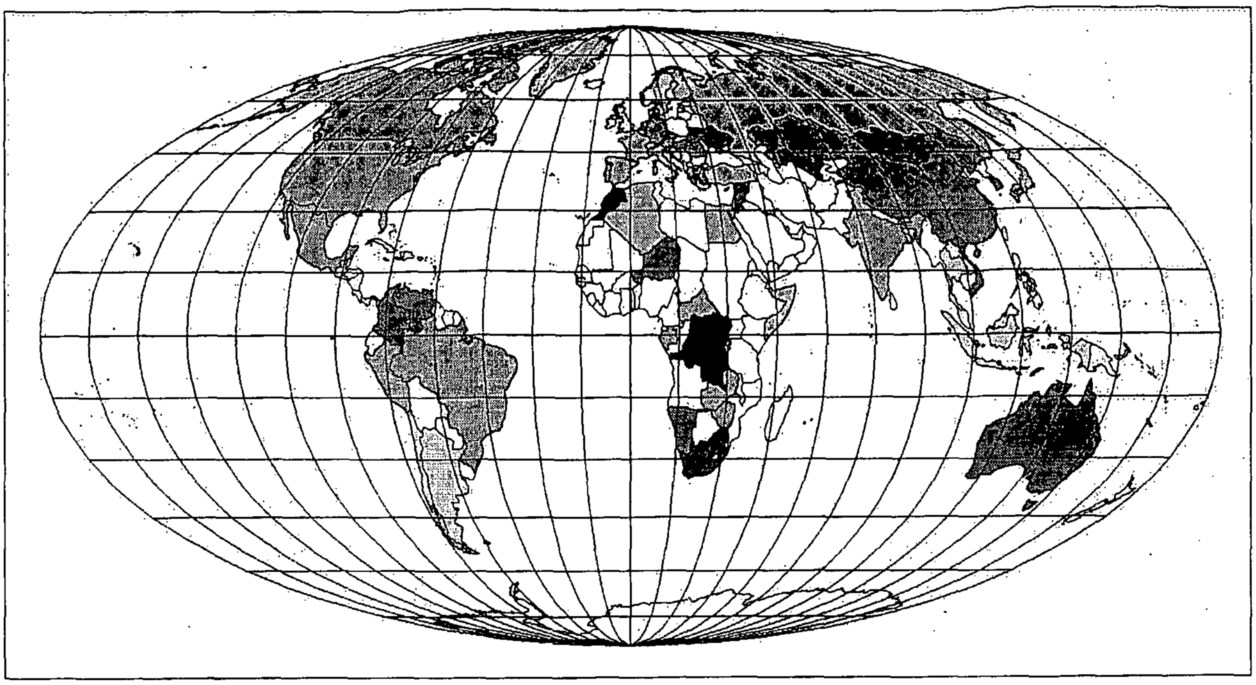


Figure 4.11. All estimated uranium resources (sum of Figs. 4.4-4.6), here given as kt uranium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7.

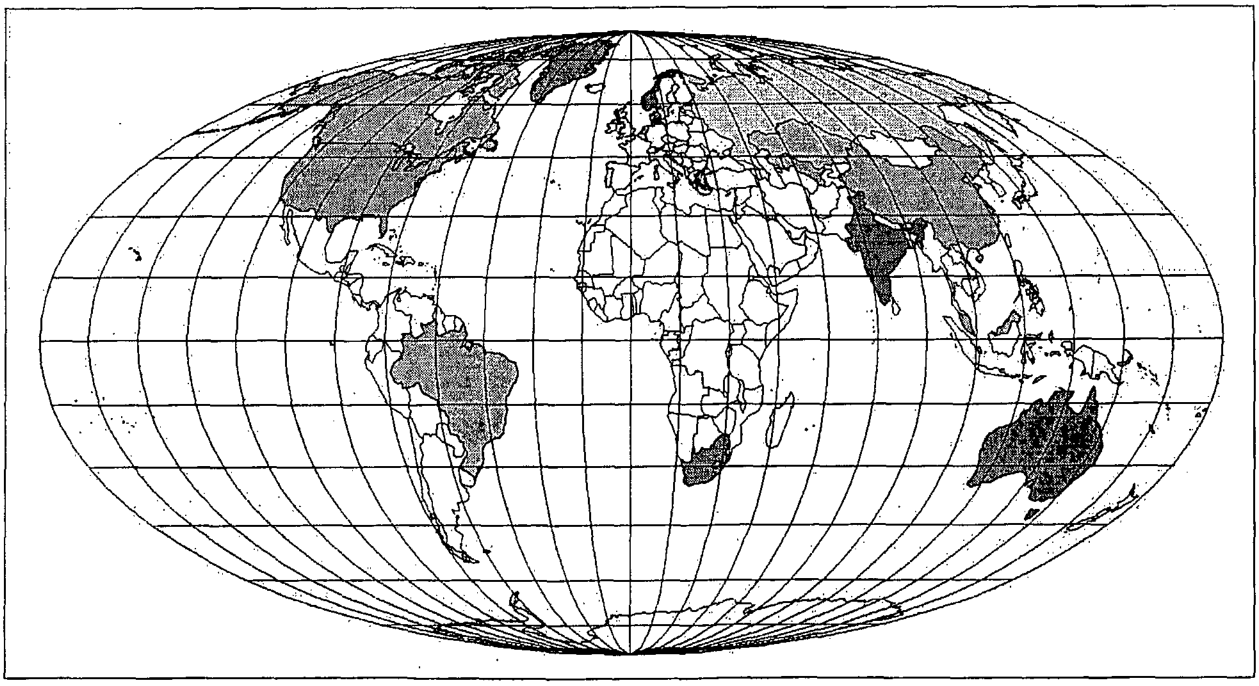


Figure 4.12. All estimated thorium resources (sum of Figs. 4.8-4.10), here given as kt thorium oxide per m^2, averaged over each country. Labels of units are explained in Fig. 4.7.

The magnitude of nuclear sources identified are similar to that of oil or natural gas, if the nuclear fuels are used in conventional non-breeder reactors (of the order of hundred years). Thus, if nuclear fission energy is to constitute a reasonably sustainable resource, some type of breeding is required. The breeding ratio for liquid metal fast breeders (which in the scenarios are excluded because the technology of liquid sodium cooling close to a very dense nuclear fuel core makes the occurrence of accidents with conventional explosions followed by fuel meltdown and possible criticality leading to nuclear explosions very high) may theoretically reach about 60, whereas for the accelerator-breeder concept outlined in section 4.2, a breeding factor of 10 is assumed to be technically feasible. This brings the thorium resources up to about 1000 years (the similar magnitude of uranium resources may not be of immediate interest, if thorium is selected as the principal fuel). It must be said, however, that once economic interest in thorium is established, the exploration of these resources will take a more serious shape, and it is possible that additional reserves are identified. The overall resource base is quite large.

The different levels of reserves and resources are summed up in Figs. 4.11 and 4.12, giving a probable magnitude of total exploitable resources. The one for thorium will be used as a basic for the scenario in section 4.4.

The highest grade of thorium resources is that found in veins of thorite ($ThSiO_4$), containing 20-60% of equivalent ThO_2. However, the most common mineral considered for exploitation is monazite (MPO_4, where M is Ce, La, Y or Th, often in combination), containing about 10% pure ThO_2 equivalent. A number of other minerals have been identified, which contains Th as a lower percentage (Chung, 1997).

4.4 SCENARIO CONSTRUCTION

The safe nuclear scenario employs the common energy demand scenario described in Chapter 2 and the following conversion technologies: The main source of energy is the Rubbia energy amplifier described in section 4.2, assumed to use primarily thorium as fuel (although some uranium-233 may be used during the first start-up, i.e. for the initial reactor cores). The scenario construction task is then simply to determine the thorium fuel annual input necessary for covering the demand. The conversion routes included are partly production of hydrogen for use in the transportation sector and possibly for industrial process heat, partly electricity for direct use or for powering heat pumps and cooling devices to provide low-temperature heating and cooling, with additional inputs of environmental heat. Whereas this is the preferred way of producing heat in the renewable scenarios (because no sources of waste heat exist), for scenarios such as the fossil and nuclear, associated heat production from power plants should have first priority, and the local heat production by heat pumps should only be used, when distances between power plants and load points makes it inconvenient or too expensive to use district heating lines to carry the heat to the end-user. In the nuclear case, "waste heat" is abundantly present, so only the transmission conditions limit their use.

The demand for food energy is covered by agriculture and taken as described in Chapter 5. Another renewable energy source that is incorporated in the nuclear scenario is hydro power, where existing plants and plants under construction are retained. This is due to their long productive life and ability to operate in harmony with the nuclear power plants, both being components of a centralised system with similar requirements for transmission. The fast regulation of hydro plants also adds to the technical viability of nuclear power plants. The scenario presented in the present work assumes that the nuclear plants can be regulated to a sufficient extent to allow following the load with minor backup from hydro are stored energy. However, should it turn out to be technically or economically inconvenient to perform this regulation, the solution is to increase the hydrogen production and use hydrogen as a storage medium, for subsequent use either directly for process heat or by regenerating electricity, presumably using fuel cell technology. This in indicated in Fig. 4.27, where lines of storage cycle supply are shown, but at the moment with zero flow.

The demand for transportation energy is assumed to be covered by equal amounts delivered to electric vehicles and fuel-based vehicles. For the former, a 50% storage cycle loss associated with the battery cycle operation is assumed, and for the fuel-based vehicles, operation by fuel-cell conversion of a fuel likely to be hydrogen or a more storable derivative (e.g. methanol) is considered to exhibit a 50% conversion efficiency. In both cases, the minimal losses that occur in the final electric motor conversion to traction power is considered included in the 50% overall loss. The nuclear electricity going through a hydrogen conversion process is assumed subject to a 20% conversion loss, which would be typical of fuel-cell type electrolysers. For conventional electrolysis processes in use today, the loss is more like 35% (Kuemmel et al., 1997). Figure 4.14 shows the amounts of hydrogen, which in this scenario will be produced from nuclear power.

The remaining energy delivered as electricity comprises all energy for electric apparel, stationary mechanical energy and input to coolers, refrigerators and heat pumps used for providing 50% of the low-temperature heat (space heating, hot water and other process heat under 100°C). The other half of the total low-temperature heat demand is covered by district heating based on nuclear waste heat. The available associated nuclear heat is much larger (as shown in Fig. 4.27), but the amount included is considered the maximum amount that can be provided to load areas with reasonable transmission distances.

The required electricity delivery for all these purposes (except that used to generate hydrogen) is shown in Fig. 4.15. This will be delivered by hydro or nuclear power, in that order of priority. Fig. 4.16 shows the total electric energy input required from nuclear energy, i.e. that for hydrogen production plus the part of the ones shown in Fig. 4.15, that can not be supplied by hydro, and all augmented by losses in transmission. In other words, Fig. 4.16 gives the power that must leave the nuclear power plants, after in-plant uses for the accelerator-based energy amplifiers. Fig. 4.17 gives the amounts of nuclear waste heat to be delivered through district heating lines (the heat leaving the power plants being some 25% higher due to transmission losses), and Fig. 4.18 shows the amounts of environmental heat drawn by the heat pumps used in locations unsuited for district heating (this may come from air, soil or waterways, and the assumed heat pump coefficient of performance, i.e. ratio between heat output and electricity input, is 3.33).

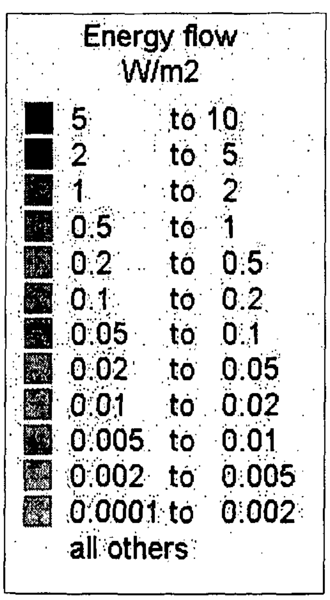


Figure 4.13. Scale of energy flow (logarithmic, unit: W/m^2).

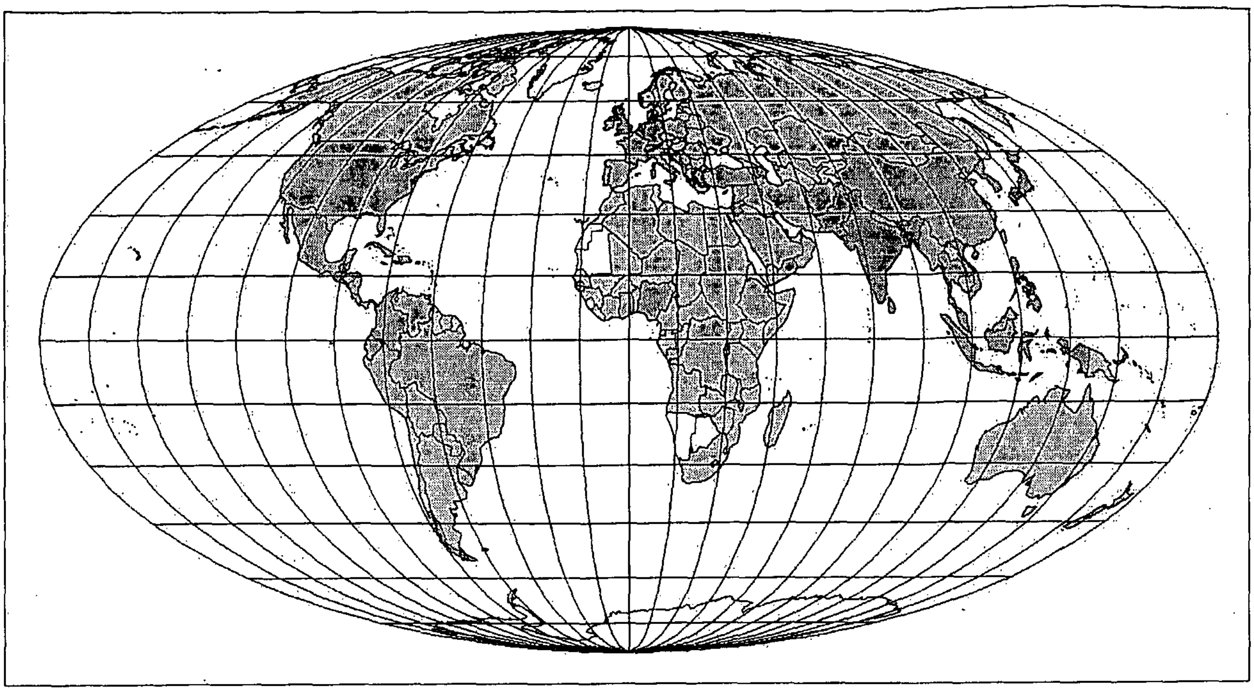


Figure 4.14. Hydrogen derived from nuclear energy (sufficient to cover 50% of needs in transportation sector). The Figure shows average flows in each country and the scale is given in Figure 4.13.

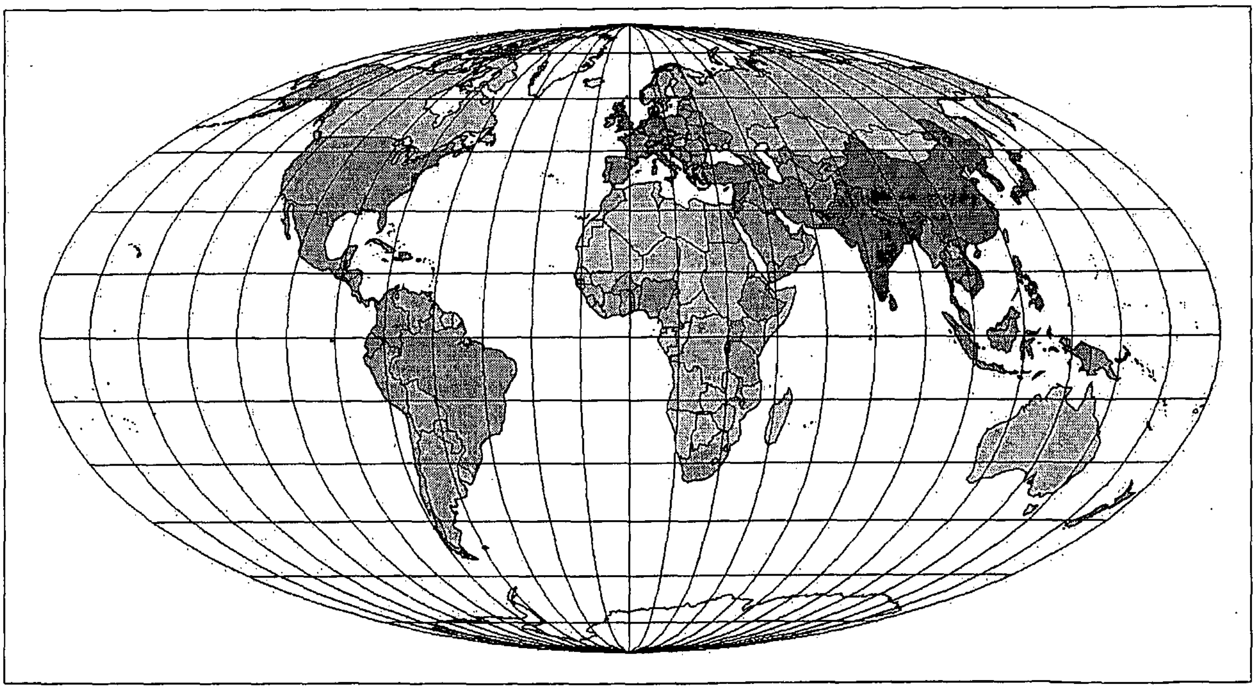


Figure 4.15. Electricity supply derived from nuclear or hydro energy (as delivered to the final consumer, covering dedicated electricity use including electric input to heat pumps and for refrigeration, stationary mechanical energy, medium and high-temperature process heat). The Figure shows average flows in each country and the scale is given in Figure 4.13.

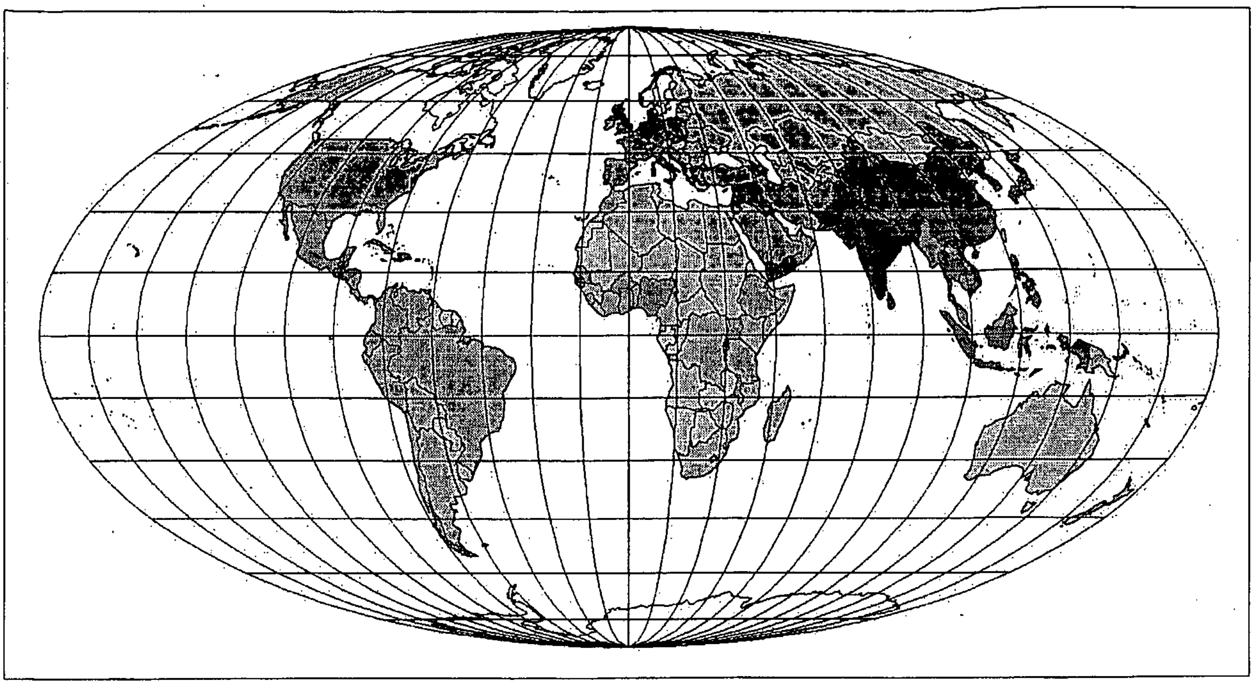


Figure 4.16. Electric energy derived from nuclear energy (delivered as electricity or used to produce hydrogen, and including transmission losses). The Figure shows average flows in each country and the scale is given in Figure 4.13. Note that countries with large hydro power production need no or little nuclear energy, as existing hydro is given first priority.

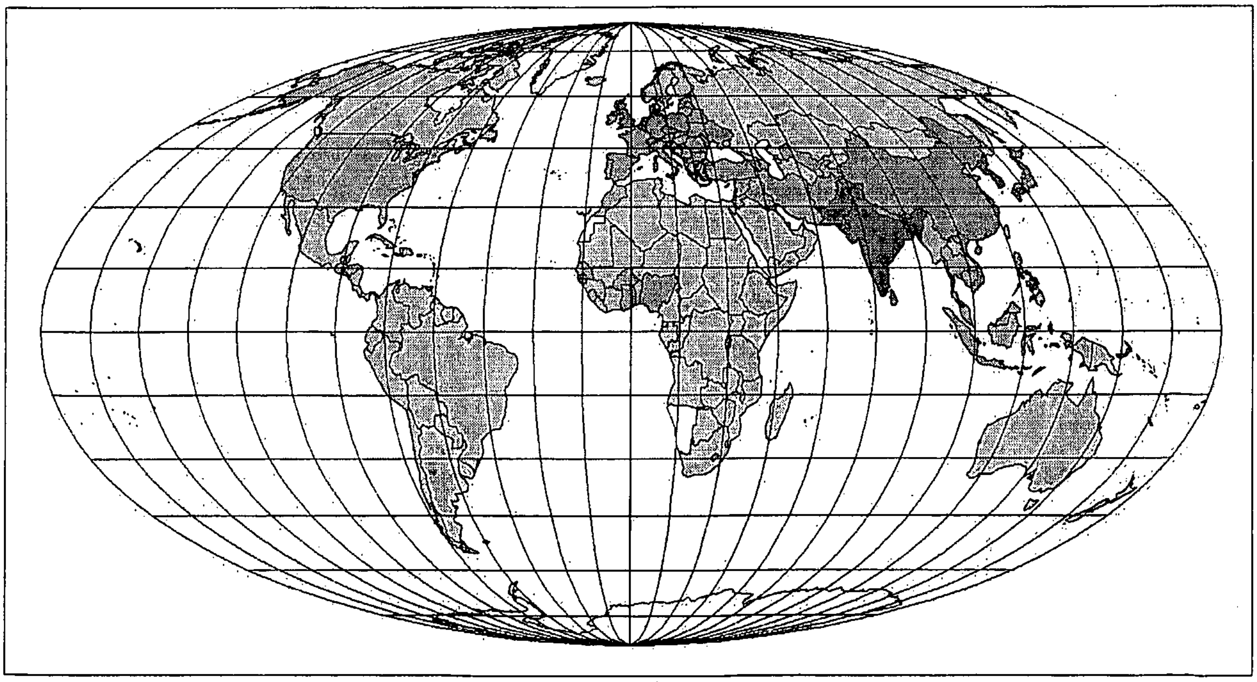


Figure 4.17. District heating derived from nuclear "waste heat" (50% of total low-temperature heat requirements considered suitable for piped delivery). The Figure shows average flows in each country and the scale is given in Figure 4.13.

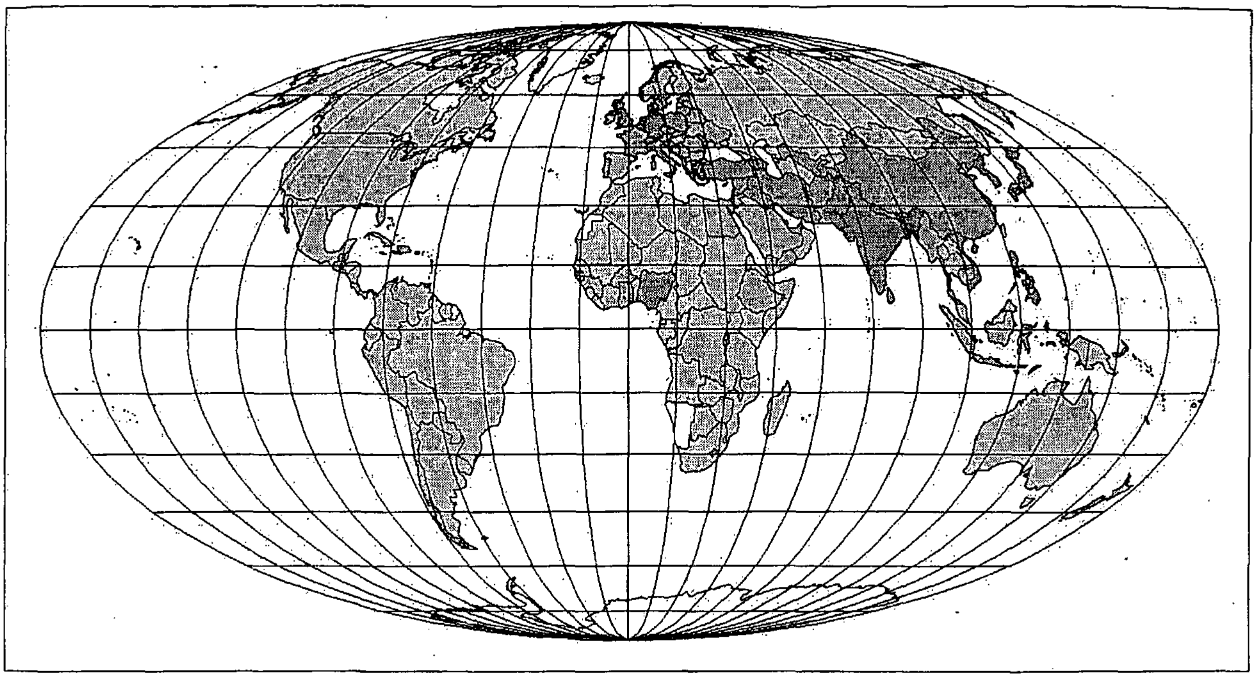


Figure 4.18. Environmental heat for heat pumps (that cover 50% of low-temperature demands). The Figure shows average flows in each country and the scale is given in Figure 4.13.

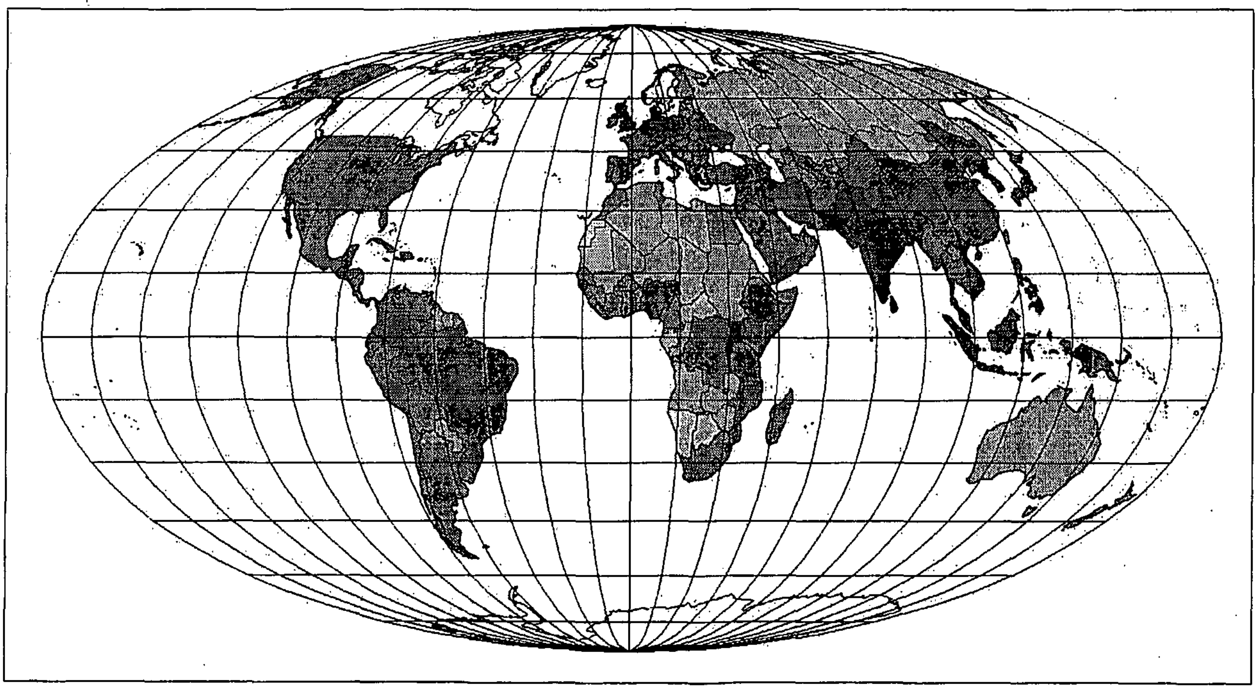


Figure 4.19. Thorium requirements for production of nuclear power assumed in the safe nuclear scenario, given as kt thorium oxide per year and per m^2, averaged over each country and over time. Labels are explained in Fig. 4.20.

Having now determined to total amount of nuclear electricity required, the thorium fuel input to the energy amplifiers can be determined from the design data of Rubbia and Rubio (1996). The thermal output from the prototype design reactor is 1500 MW, with a fuel asmount of 27.6 t in the reactor (Fig. 4.2). The fuel will sit in the reactor heat generating unit for 5 years, after which the "spent" fuel will be reprocessed to allow for manufacture of a new fuel load with only 2.9 t fresh thorium oxide supply. This means that 2.6/5 t/y of thorium fuel is required for delivery of 5*1500 MWy of thermal power over 5 years, or 675 MWy of electric power, of which the 75MWy is used for powering the accelerator and other in-plant loads. The bottom line is that 1 kg of thorium fuel produces very close to 1 MWy of electric power, and 1 kt thorium 1 TWh_e.

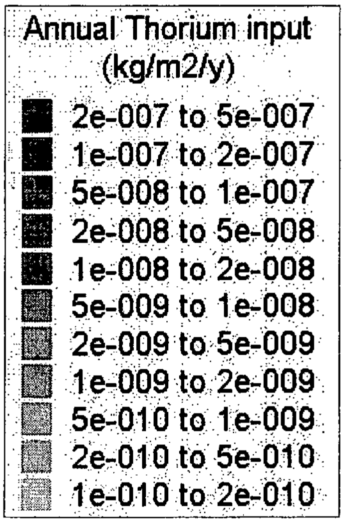


Figure 4.20. Units of nuclear fuel requirements: kt per m^2 per year.

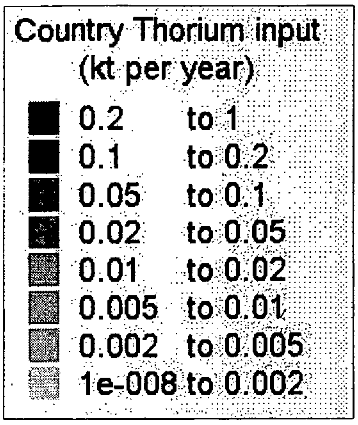


Figure 4.21. Units of nuclear fuel requirements: kt per year for each country.

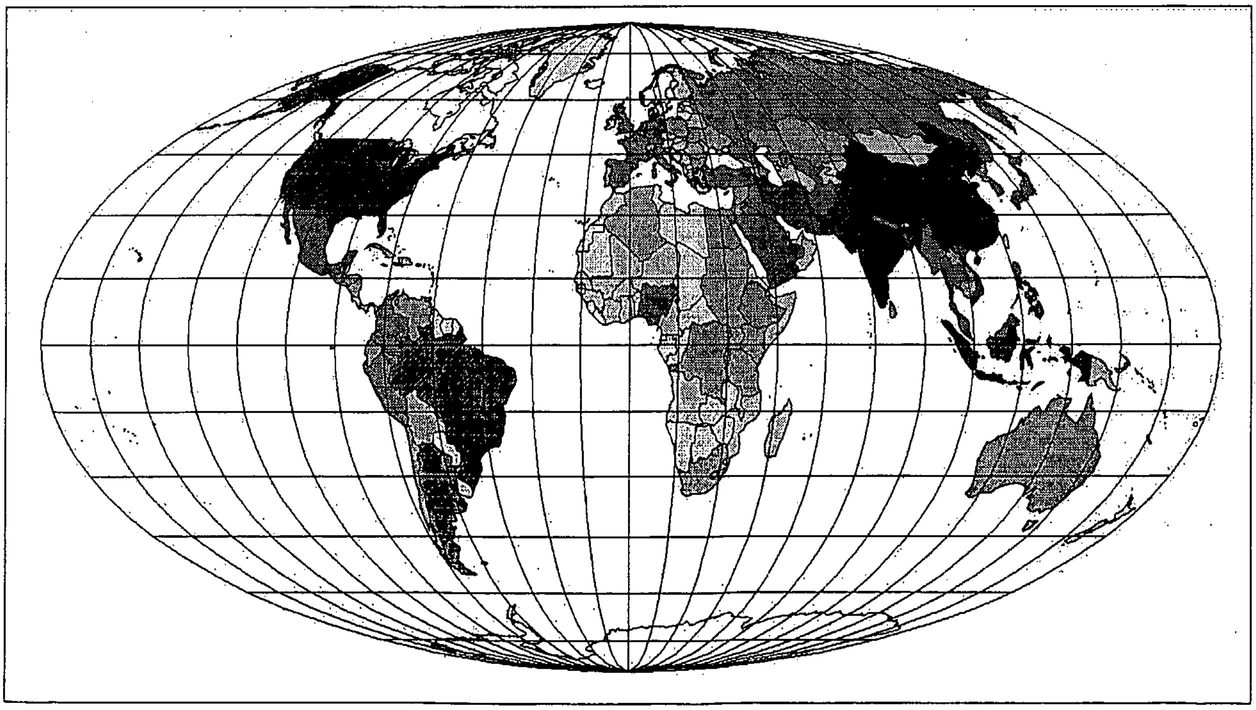


Figure 4.22. Thorium requirements for production of nuclear power as assumed in the safe nuclear scenario, given as kt thorium oxide per year for each country. Labels are explained in Fig. 4.21.

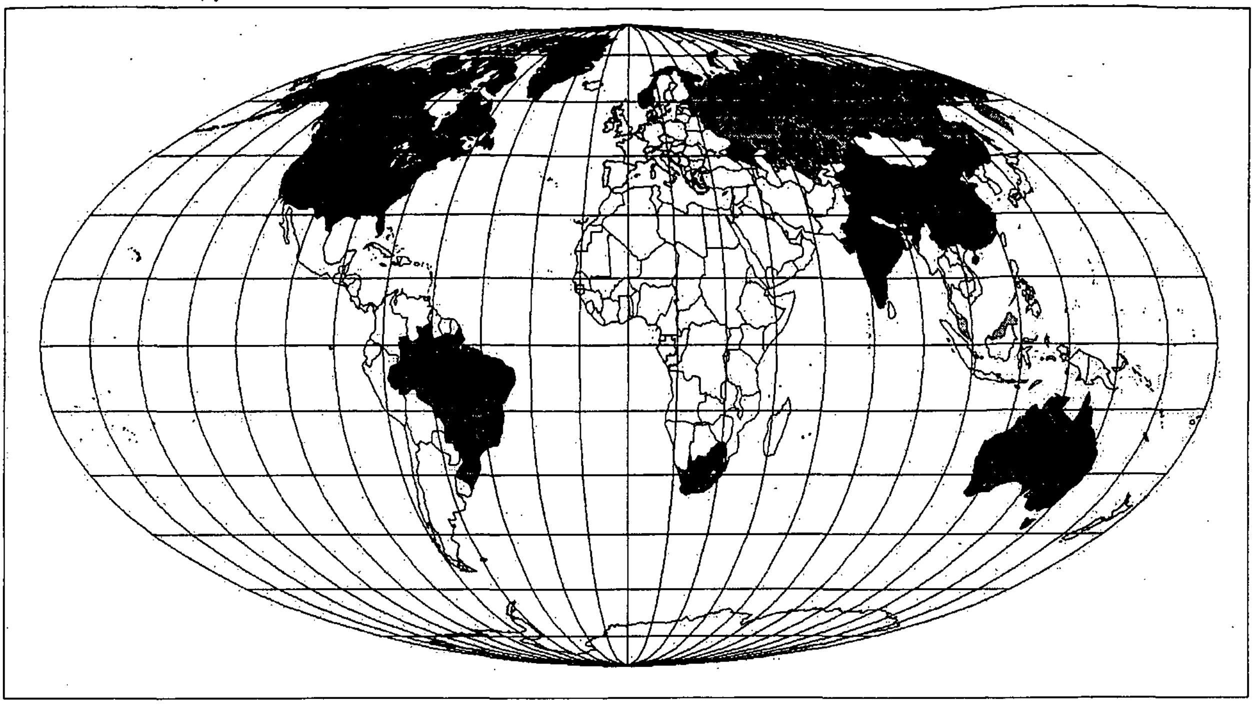


Figure 4.23. Thorium production assumed in the safe nuclear scenario, given as kt thorium oxide per year for each country. Labels are explained in Fig. 4.21.

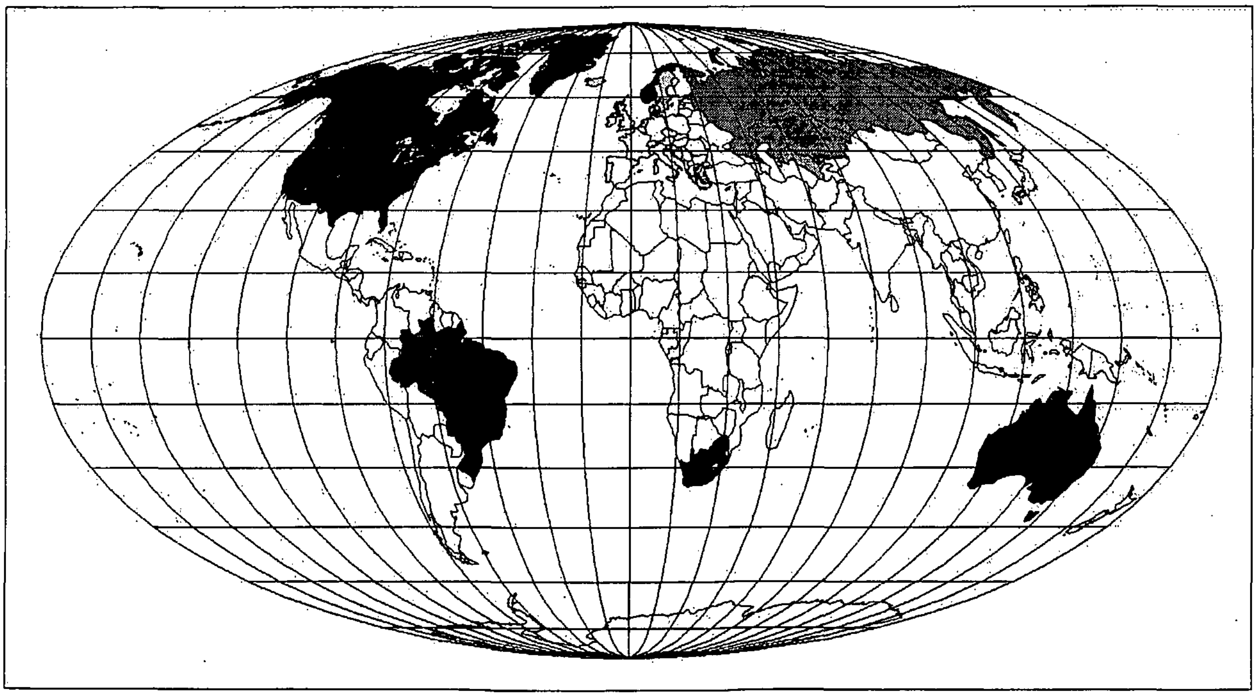


Figure 4.24. Thorium surplus (production minus required supply for each country, if positive) for the safe nuclear scenario, given as kt thorium oxide per year for each country. Labels are explained in Fig. 4.21.

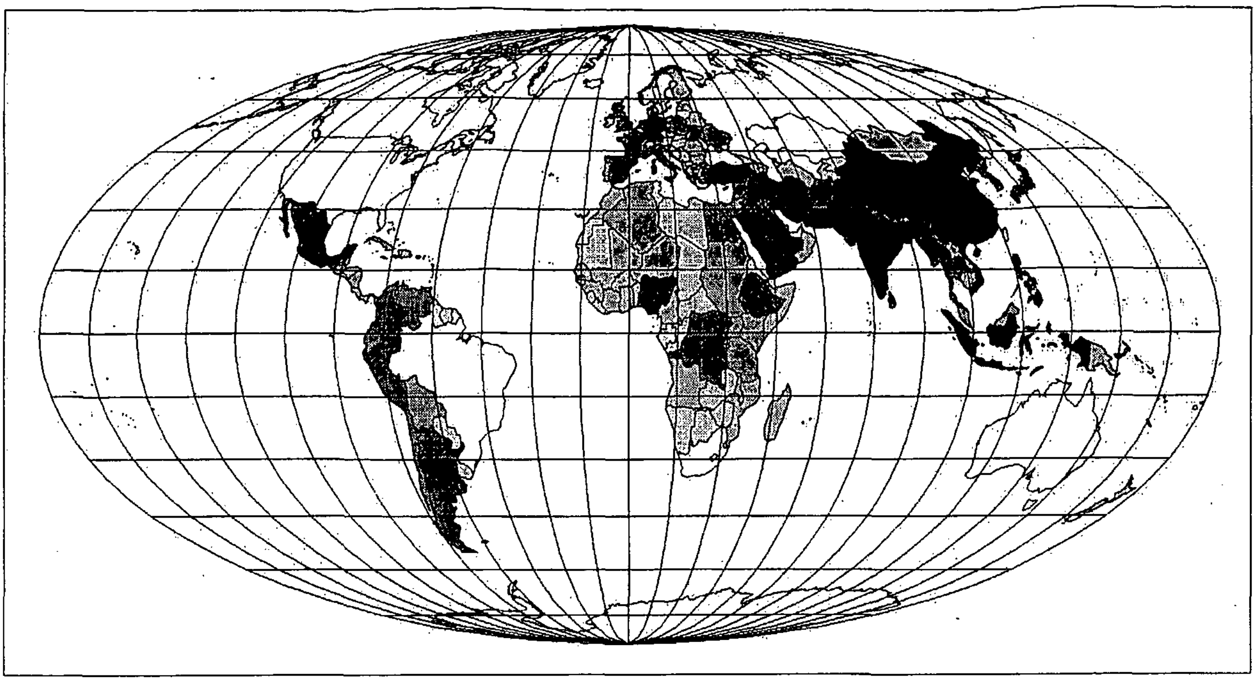


Figure 4.25. Thorium deficit (required supply minus production for each country, if positive) for the safe nuclear scenario, given as kt thorium oxide per year for each country. Labels are explained in Fig. 4.26.

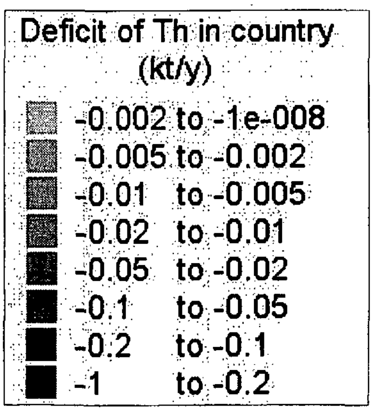


Figure 4.26. Units of nuclear fuel deficits in supply: kt per year for each country.

Fig. 4.19 gives the scenario requirements of thorium input per year and per m^2, averaged over each country, and Fig. 4.22 the total amounts per year for each country. It is seen that countries with abundant hydro power (such as Canada) does not need any nuclear energy in the scenario, even if they do today. The reason is the substantial increase in energy efficiency assumed, a fairly stable population in Canada, and maintaining all hydro plants currently operating or under construction. The hydro contribution is the same as in the centralised renewable energy scenario, shown in Fig. 5.26.

The thorium requirement per country may be compared with the production in each country, shown in Fig. 4.23. It is constructed assuming that the world production of thorium matches the world requirements, and that each country produces in proportion to its total thorium resources, as estimated in Fig. 4.12.

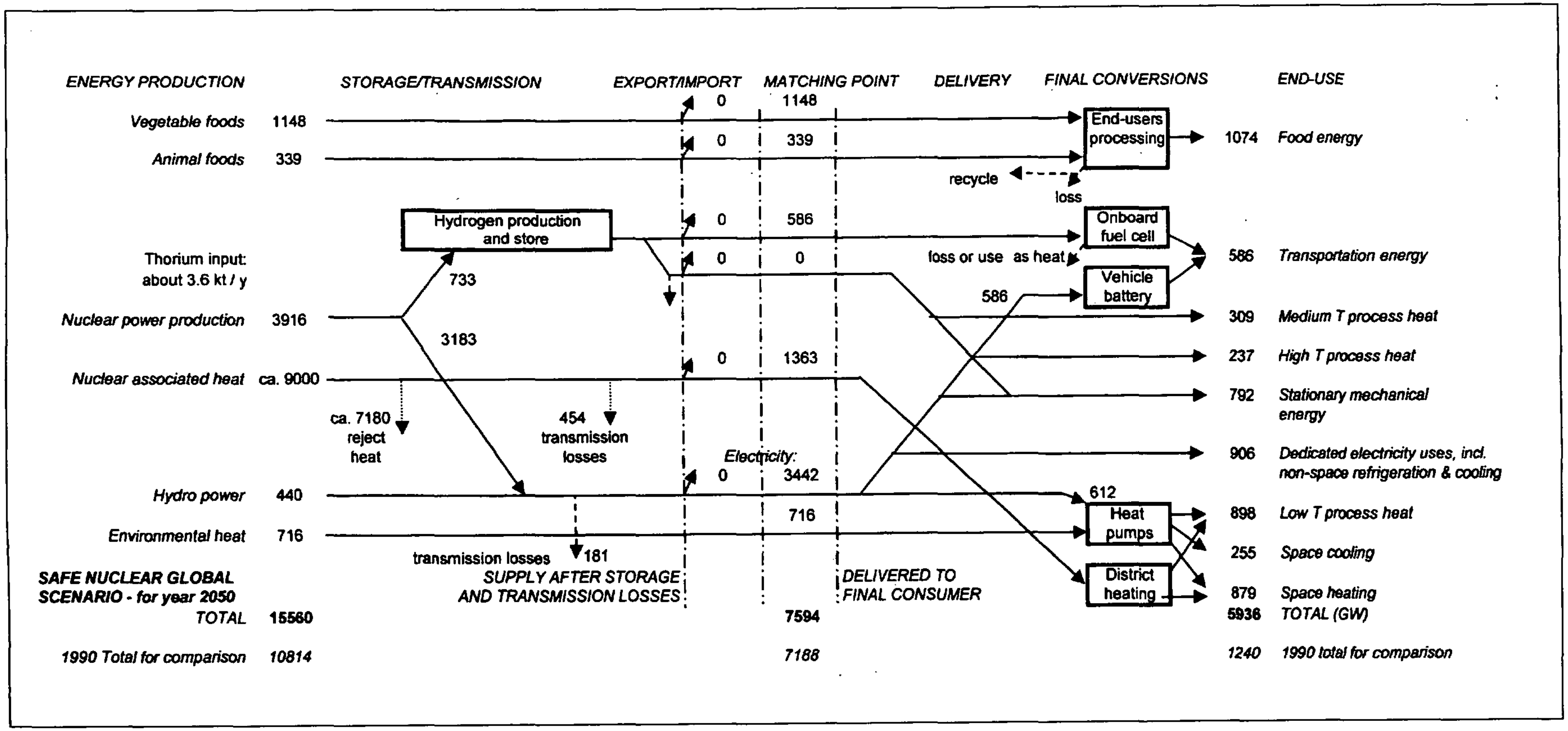


Figure 4.27. Overview of safe nuclear scenario (flows in GW or GWy/y, the thorium input is indicated at the left). 1990 consumption is indicated at bottom, based on the analysis in Chapter 2.

One can now determine the required trade of nuclear fuels by comparing the production and use of thorium fuels. This is done in Figs. 4.24 and 4.25, showing the surpluses and deficits in thorium balances for each country. It is seen that the world is fairly sharply divided into energy producer countries and energy importing countries, the latter being in South America (except Brazil), Africa, Europe (minus Sweden, Norway and Russia) and Asia (minus the former Soviet Union countries).

A summary of the scenario is shown in Fig. 4.26. The more than four times increase in energy services at the end-use level is here achieved by primary energy inputs 50% above the current ones. This is more than in the renewable energy scenarios discussed in Chapter 5, particularly due to the associated thermal energy from the energy amplifiers, that cannot all be made useful.

4.5 EVALUATION

The nuclear scenario presented in section 4.4 has zero emissions of greenhouse gases. It does largely avoid the accumulation of material with risk of diversion for military purposes, the only sensitive material being the spent fuel. It is suggested to join the power production and reprocessing units at the same location (Fig. 4.2), where the reprocessing is fairly delicate due to presence of strongly radioactive Tl-208 (cf. section 4.2). This makes it necessary to perform the reprocessing by robots in a heavily gamma-shielded environment, a technology just starting to be technically feasible end currently excessively expensive (Lung, 1997; Chung, 1997). On the other hand, this fact makes theft of the spent fuel unlikely.

As regards nuclear accidents, the sub-criticality suggests dramatic reduction in the risk (Buono et al., 1996), but it is clear, that more work is required to fully assure this proposition.

With respect to radioactive waste, Fig. 4.4 suggests large advantages over current nuclear reactor technology, in reducing the period in which wastes must be kept separate from the biosphere from some 10000 years to 500 years. However, this is still a very long time to require integrity of depository sites, in fact of the same order of magnitude as predicted for nuclear fusion wastes. In the first period of time, the energy amplifier waste produces a surge of radioactivity from the U-233 production, which requires special precautions in storage and disposal. It must therefore be concluded, that the overall advantage in regard to waste toxicity is modest or negative, as compared to present reactor waste containing plutonium-uranium mixtures.

Rubbia and Rubio (1996) have pointed out, that a unique opportunity to rapidly evaluate the energy amplifier concept at a realistic scale is offered by the planned year 2000 retirement of the LEP superconducting cavity electron accelerator presently used for research at the European Organisation for Nuclear Research (CERN). This accelerator can be modified to accelerate proton beams at a current of 20mA to energies above 1 GeV, which will make them suitable for an energy amplifier of up to 1500 MW thermal power. The proposal submitted for such a facility has been evaluated by a working group assigned by the European Commission DGXII. Its conclusion, which has been adopted by the Scientific and Technical Committee of the European Commission, is that the project should not be realised, except for small investigations aimed at getting rid of military nuclear waste, and which can be carried out with use of existing reactors (Pooley, 1997).

Nearly all the members of the working group are associated with the existing nuclear industry. Chairman Derek Pooley is with the UK Atomic Energy Authority (and by the way known as the ardent proponent of the nuclear industry during the debates in the late 1970ies, who seemed to use as a key argument something like "you can't be a Christian if you are against nuclear power"; Pooley, 1980), the other members are nuclear industry people from Framatome, Iberdrola, Ansaldo, a project manager at the British Sizewell B reactor, specialists from the Austrian nuclear centre at Seibersdorf, British Nuclear Fuels Laboratory, German Reaktor SmbH, the Swedish Nuclear Power Inspectorate, plus one accelerator specialist from CERN.

The group concludes, that to follow Rubbia's proposal will put nuclear power "back to square one", discarding all existing technology and building a novel one (which was indeed the intention), with required spendings as huge as those leading to the current nuclear technology, and with little hope that the public will understand the subtle difference between the old and the new nuclear power and better accept the latter.

The last statement of course just says, that the nuclear industry has lost so much credibility in the general populations that the working group does not think it can ever recover. It may be right about this and also that it will not be possible to raise support for funding a second effort in developing viable nuclear energy. However, the amounts of money spent on nuclear fusion points in the opposite direction. The accelerator-breeder would seem a much less risky project than nuclear fusion. It is quite possible, that the unwillingness of the existing nuclear industry to allow the newcomer (seen as a competitor?) to get the needed initial funding will speed up the final abolition of nuclear techniques in the energy sector. At least the prospects for realising a safe nuclear energy scenario seem very bleek.

The committee is of course right in pointing out, that if one goes on with the project, it is likely that unforeseen problems arise, and consequently that it would be a good idea to perform any possible small-scale experiments that can shed light on the amplifier project, before a full-scale demonstration is embarked upon.

The present construction of a global scenario based on the energy amplifier concept has shown, that if the energy amplifier project is indeed successfully developed, it would be possible to use nuclear energy on a much larger scale, globally, than envisaged for the present nuclear technology. The estimated resources of thorium makes it possible to sustain the thorium-cycle nuclear scenario at the level selected for some 1000 years, with a similar interval being possible for uranium-based concepts with a similar breeding ratio. The direct cost will certainly be higher than that of present nuclear reactor technologies, the reprocessing and the waste management costs considerably higher, and very uncertain since no solutions have yet been fully realised for handling the entire fuel cycle of current nuclear technologies.

Chapter 5

THE RENEWABLE ENERGY SCENARIOS

5.1 THE BACKGROUND

The interest in using renewable energy flows for energy supply is the desire to build sustainable energy systems, i.e. systems, where energy is borrowed from natural flows and returned to the stream of heat re-radiation from Earth to space (Sørensen, 1979 and 1999). The hope is in this way to minimise environmental impacts, at the same time as one eliminates the question of resource depletion.

A social paradigm, which is often intertwined with the quest for renewable energy, is that of decentralisation: Decentralisation meaning decentralisation of the physical energy conversion system as well as decentralisation of decision-making and control, from state or corporate level to local or even the personal level. One of the scenarios constructed here explores how far one can go in decentralising the renewable energy system, by placing energy collection and conversion devices integrated into buildings (solar collectors, fuel cells) or vehicles (ships, motor cars with these devices) or adjacent to buildings (such as individual wind turbines placed on farm land). The challenge is of course to accommodate the fluctuating renewable energy sources, leading to considering the issues of energy storage and transmission.

Relaxing the constraints of severe decentralisation leads to the second renewable energy scenario presented. For convenience of distinction, it is termed the centralised renewable energy scenario. However, it is not centralised in quite the sense of possessing conversion plants of large unit size: the renewable techniques are mostly modular (many 1 MW wind turbines rather than one gigawatt unit, solar panels consisting of modules of a few hundred watts, even if connected to a large desert-placed plant, an exception being hydro power plants, that exist in both small and very large sizes). The purpose of this scenario is to explore, if adding a modest amount of centralised energy production will make the decentralised scenario more resilient, both with respect to the time and space variations of resources and demand, but also with respect to changes in the demand levels. The latter issue is particularly important for the present work, because a single demand scenario is used throughout.

The work on the renewable energy scenario takes a somewhat different form than that of fossil or nuclear supply models. One reason is the role played by biomass resources. Using biomass in the energy sector may be done by dedicated crops (in which case competition with agriculture for land must be considered) or by diverting agricultural residues to the energy chain (and in contrast to current combustion uses of biomass returning the nutrients to the soil, and thereby making the use of biomass resources sustainable). In both cases, it is clear that an integrated analysis of agriculture and biomass energy use must be performed, For this reason, the present study has systematically included food energy in its assessment of the energy use by society. In the fossil and nuclear scenario, it has just been a disjoint energy flow, but in the renewable energy scenarios, important choices are connected with the way biomass resources are distributed on food, energy and possible other uses (e.g. as industrial feedstocks). The present Chapter thus includes a model for future handling of land resources and agricultural production.

In this connection, also marine biomass resources could be included. However, this is postponed to future work on the models, because of time restraints. The same is true for a number of renewable energy sources considered minor (geothermal, wave, ocean salinity and thermal gradient utilisation, etc.). In the case of geothermal it would only be the renewable flows that are relevant to renewable scenarios. Current use of geothermal hot springs does not constitute a renewable source, as the sometimes rapid decline in production at a particular installation demonstrates.

5.2 RENEWABLE ENERGY SUPPLY OPTIONS

The renewable energy sources and conversion technologies considered in the 2050 scenario are direct solar radiation used in flat-plate solar cells, wind energy converted by horizontal-axis turbines, hydro energy used in turbines power stations, and a range of bio-technologies, including food production from grain and other vegetable harvests and meats from animal raising, liquid biofuels such as methanol produced by thermal processes, or biogas produced by biological methods (Sørensen, 1979). For simplicity, some minor sources were left out (fish in the food sector, geothermal energy), although they would make a contribution in a more detailed and realistic scenario.

Solar thermal is an option that competes with photovoltaics for building roof and facade space. We have opted for the photovoltaic solution, even for covering low-temperature heating needs, because the efficiency of the solar-to-electricity-to-heat conversion route is high: Assuming 15% efficient solar cells and COP=3.33 heat pumps the total efficiency is 50%. Thermal solar collectors may have a direct efficiency of 50%, but the heat produced has to be stored, e.g. in communal storage systems, in order to satisfy demand when there is no solar radiation. Because most of the heating demand is at high latitudes, this means seasonal storage, which cannot claim a turn-around efficiency of more than of the order of 25%, at least if conventional heat-capacity storage is used. Thus the overall efficiency of the solar-to-heat-to-stored heat-to-useful heat is some four times lower than for the photovoltaic route. On the other hand, the expected cost reductions assumed for photovoltaic systems may turn out not to materialise, in which case the solar thermal option might again seem attractive.

For biomass, the option of direct combustion has not been considered, due to its environmental impacts similar to those of the fossil fuels that would be replaced. However, in a transition period it there may still be direct fuel uses of biomass, particularly if short-term reduction in net greenhouse gas emissions is considered important. Below the scenario assumptions for each energy source are discussed and the magnitude of the available resource is calculated under realistic assumptions of exploitation, considering both environmental and social constraints. First the assumptions on land use are presented, as they enter in all the considerations on the potential for using individual renewable energy technologies. For off-shore wind power, also sea-depth topology is important, as it would be for certain fish or kelp cultures. The land topography and roughness data could be used in estimating wind conditions, but we chose to base the wind resource estimate on measured data.

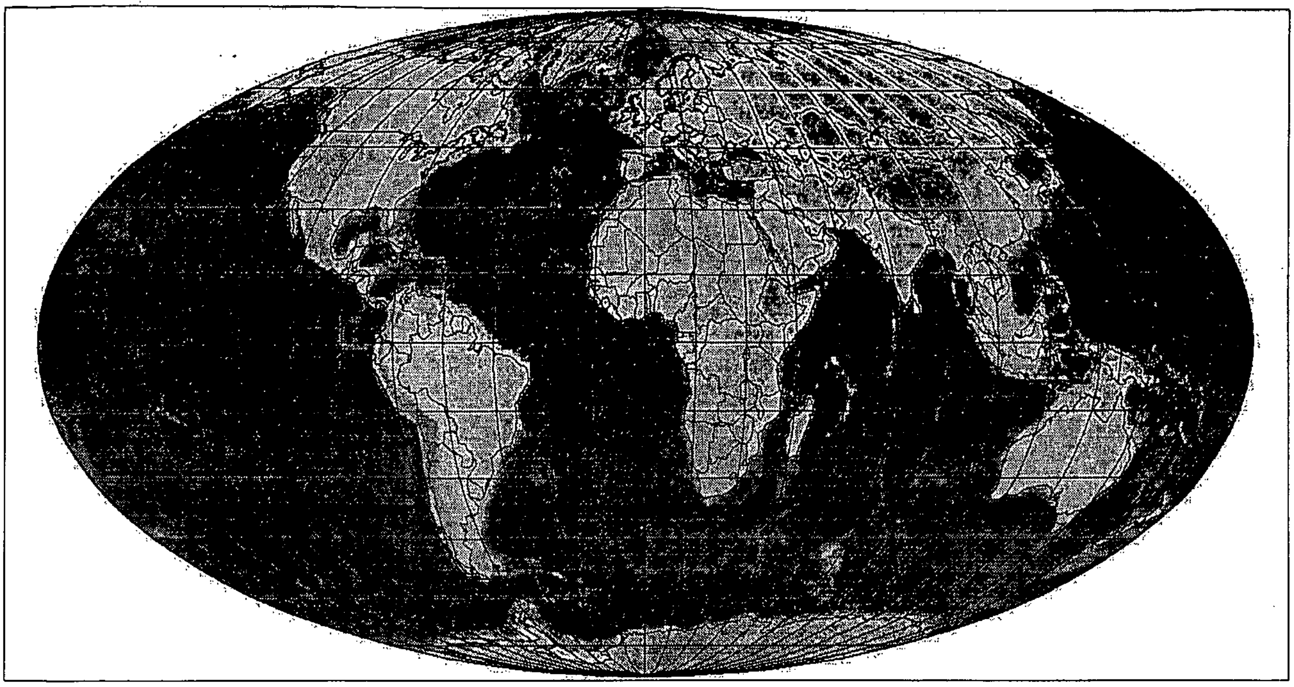


Figure 5.1a. Land and ocean topography (based on data from Sandwell et al., 1998) (scale given in Fig. 5.1b).

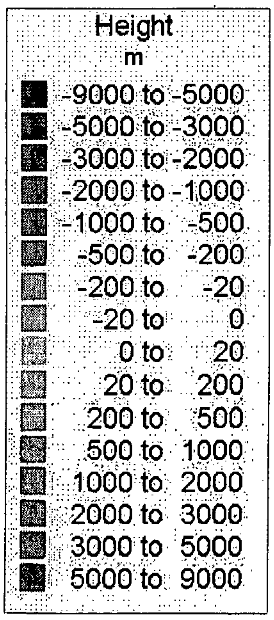


Figure 5.1b. Height scale relative to mean sea surface level (metres).

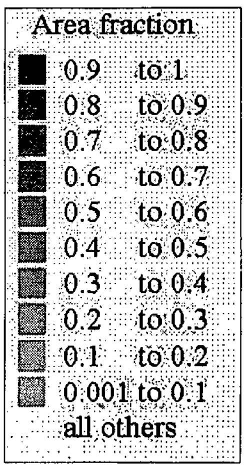


Figure 5.2b. Scale of area use fractions.

5.2.1 Topography and land use

The topography map shown in Figure 5.1 is used in estimating suitable sites for off-shore wind turbines. It is based on a latitude-longitude grid of 0.83°×0.83°, but is constructed from data on a much finer grid (Smith and Sandwell, 1997; Sandwell et al., 1998).

Land-use data are important in the description of agricultural yields, whether based on crop-land or grazing ranges, for forestry and possible energy crops, and for selecting land suited for

Table 5.1. Definition of area types relative to USGS classification

Definition used	USGS classification
Urban and built-up land	Urban and built-up land, however estimated with different algorithm
Cropland (including crop-land/pasture in rotation)	Rainfed and irrigated cropland and pasture plus 50% of cropland/grassland and cropland/woodland mosaic
Open cropland	Same as above except omitting cropland/woodland mosaic
Rangeland	Grassland and 50% of cropland/grassland mosaic and mixed scrub/grassland
Forest	Deciduous and evergreen broadleaf, needleleaf and mixed forests
Marginal land	Barren or sparsely vegetated land, scrubland plus 50% of mixed scrub/grassland
Water bodies	Water bodies
Other land	Savanna, wetlands, tundras and land covered by snow or ice

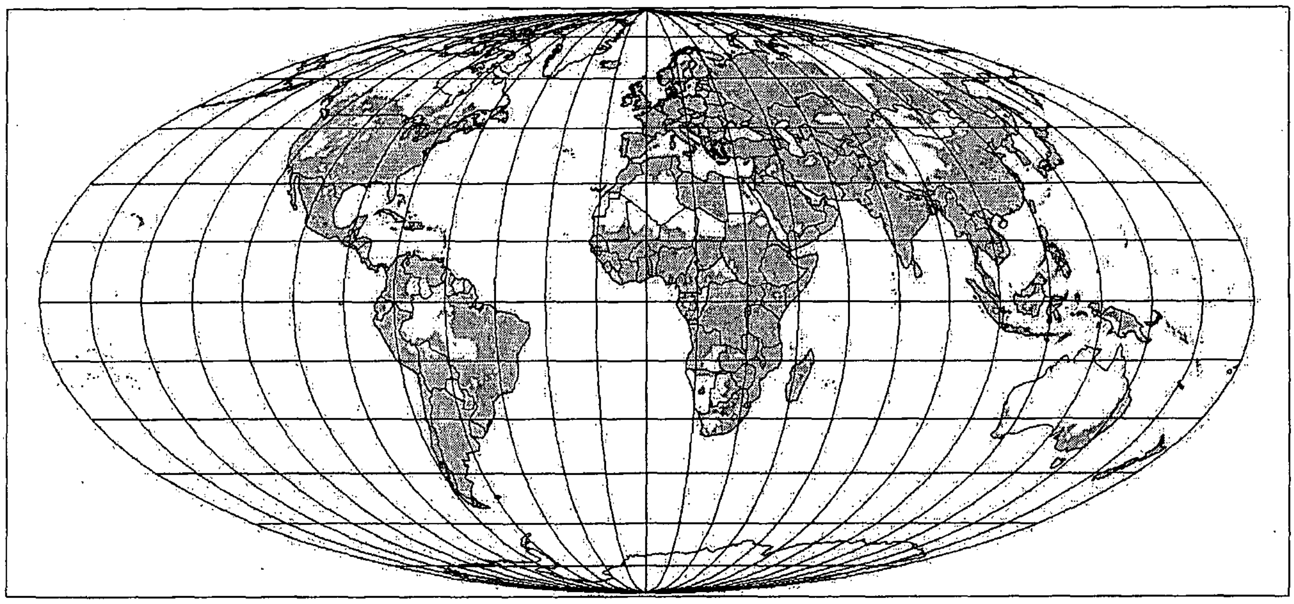


Figure 5.2a. Fraction of area constituted by urban or built-up land (scale given in Figure 5.2b on preceding page). Note that high-density city centres show up poorly on a global map.

placement of wind turbines and solar collector fields. The building-integrated photovoltaic systems require an estimate of suitable surfaces, for which data on urbanisation and dispersed farm densities are used. For the minimum grid size of 56km×56km (at the Equator) considered, there will typically be more than one type of land use inside each grid cell. A database is therefore constructed, giving fractions of each type of land use inside the grid structure used. There exist several land-cover databases in the literature. The one used is based upon 1km resolution radiometer data for the period April 1992 to March 1993 (US Geological Survey, 1997). The data are first converted from the Lambert Azimuthal Equal Area Projection to the latitude-longitude 0.5°×0.5° grid used here, with an algorithm developed by Evenden (1997). Then the land use data for all the 1km cells that have centres inside one of the 56km cells are

recounted. Of the several classifications offered by USGS the indigenous 24 category classification is selected (Anderson et al., 1976). This is then again simplified as shown in Table 5.1, in a way offering the categories needed for the energy model.

For the category of "urban and built-up area", a method is used that differs from that of the USGS database, which just copies data from a military map (the "Digital Chart of the World", US Defence Mapping Agency, 1992). Here it is assumed that the urban area is proportional to the population density raised to some power, inspired by Tobler et al. (1995) and Waggoner (1994): $U = A \times (P/P_0)^{-0.25}$, where U = urban and built-up area [m^2/cap.], P = population density [cap./km^2], P_0 = reference population density taken as 1 cap./km^2, and A as 1660 m^2/cap. for regions 1-4 (see Table 2.2) except Japan, Asian "tiger" countries, and the Middle East, and A=830 m^2/cap. for these exceptions and regions 5-6. The idea is to differentiate between regions where urban land is scarce and less scarce and to reflect diminishing per capita area use in areas of high-rise buildings. This *ad hoc* method gives reasonable agreement when checked with urban land use data for Buenos Aires, Lagos, Karachi and the regions of Bangladesh and Connecticut (Waggoner, 1994). Its prediction of roughly ten times higher urban and built areas than the Digital Chart of the World appears more realistic and suited for our purpose. Inside each cell, the other land use categories are adjusted proportionally to retain the correct total cell area.

Figure 5.2 shows the resulting estimated fraction of land area constituting urban or built-up sites in 2050. This on average gives 236 m^2 of urban/built-up land per world citizen or 4237 world citizens per km^2 of urban or built-up land. This seems consistent considering the urbanisation degree in 2050, whereas the significantly lower value obtained from the Digital Chart of the World is not.

Table 5.2 gives the regional sums of area use and Figs. 5.3-5.7 the additional land-use categories of interest to renewable energy planners. Figure 5.8 gives water body fractions, i.e. either rivers and inland lakes or ocean fractions included in the latitude-longitude cells at the edges of continents. Figure 5.9 gives the area fractions not belonging to any of the preceding categories. This includes wilderness and preservation areas, although some may be included in the other categories, notably forest and marginal land fractions.

5.2.2 Solar power

The solar radiation model employed is based on data for solar radiation incident on a horizontal plane. One set of data is based on an analysis (Pinker and Lazzlo, 1992) of satellite measurements of radiation, albedo (reflectance) cloud cover and attenuation of radiation in the air (NASA, 1997). Another study collects many types of weather and climate data (NCEP/NCAR, 1998) and uses balance equations and a global circulation model (horizontal resolution about 210 km and 28 vertical levels) to improve the consistency of data (Kalney et al, 1996). However, for solar radiation no ground-based observations are used, so this is again based on top-of-the atmosphere fluxes and various absorption, reflection and attenuation processes plus the balance requirements at the Earth's surface. The two types of analysis give similar results for solar radiation. The balance equations (difference between upwards and downwards short- and long-wavelength radiation and heat fluxes) do suggest a too high albedo over oceans, but the land data that we are using appear to be reliable. Figure 5.10 shows the radiation on a horizontal plane at the Earth's surface for selected months of 1997 (NCEP/NCAR, 1998).

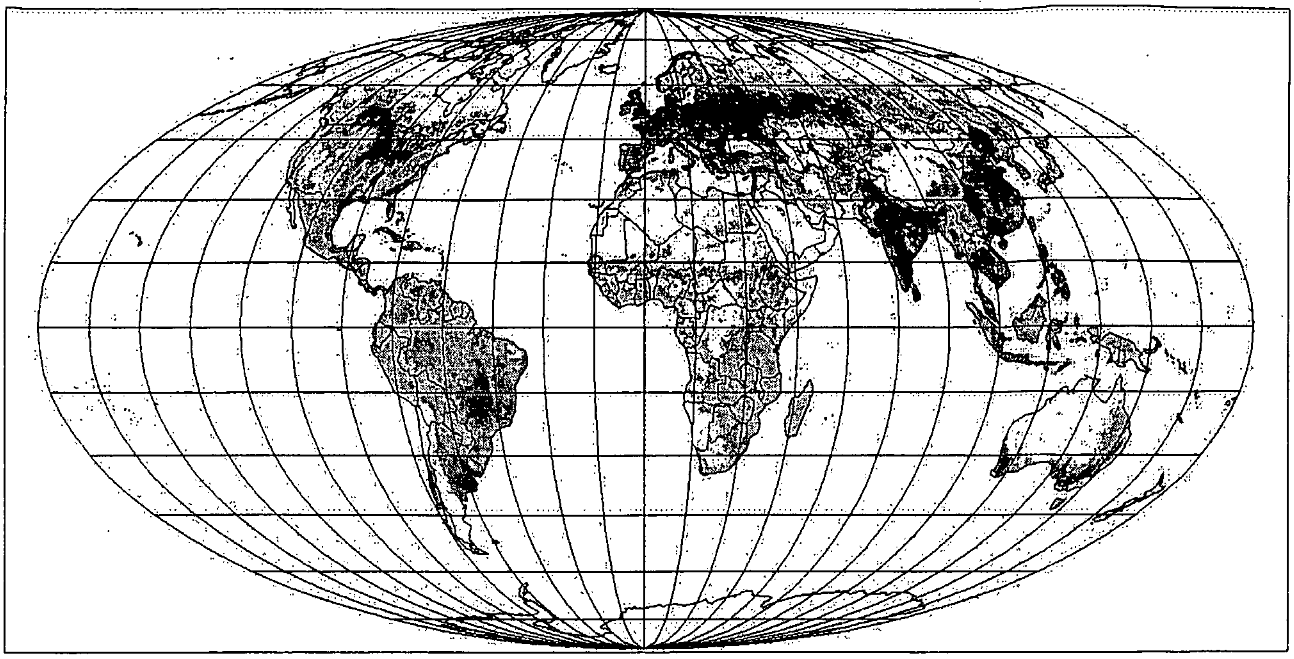


Figure 5.3. Fraction of area constituted by cropland and cropland in rotation (based on US Geological Survey, 1997; scale given in Figure 5.2b).

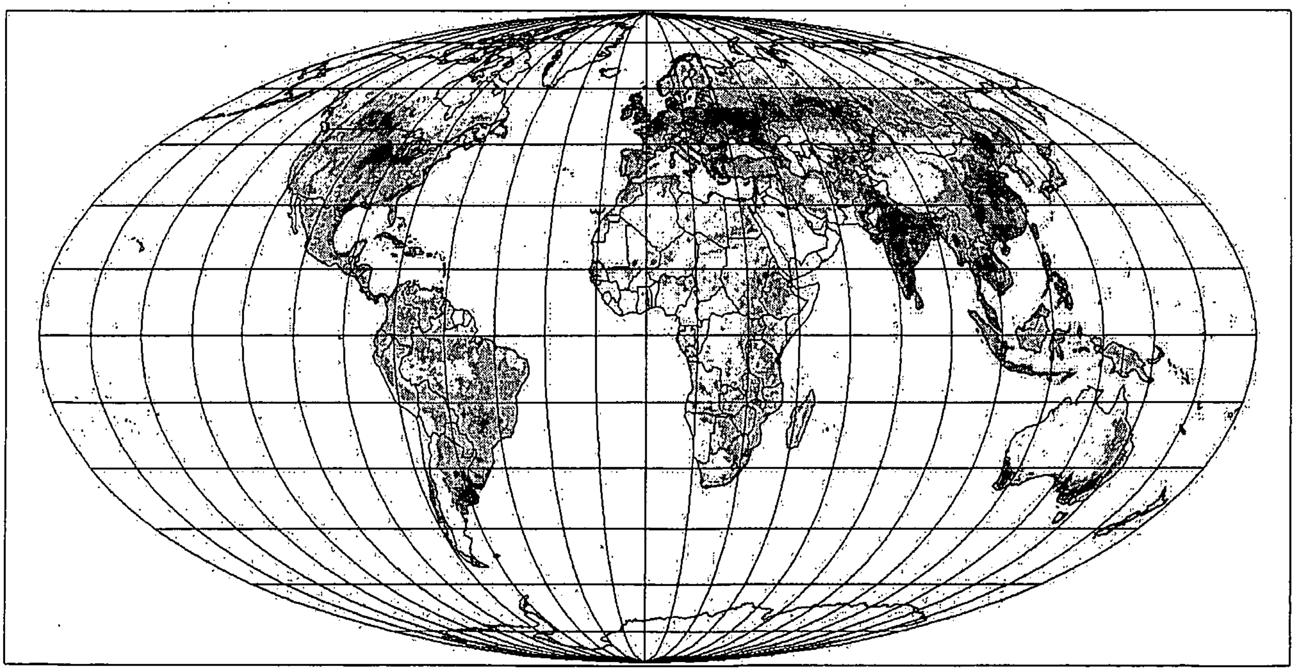


Figure 5.4. Fraction of area constituted by open cropland/cropland in rotation. This differs from the areas given in Fig. 5.3 by not including cropland in mixed crop/woodland mosaics, which would not be suited for wind power production due to high roughness levels (based on US Geological Survey, 1997; scale given in Figure 5.2b).

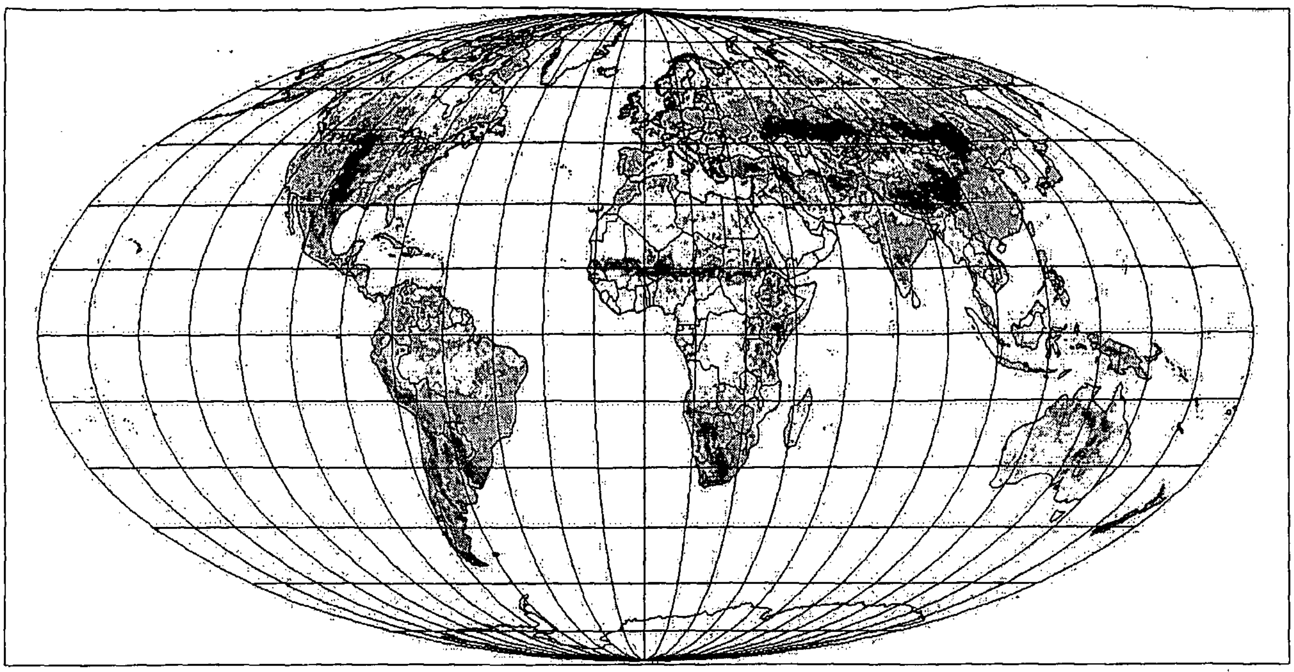


Figure 5.5. Fraction of area constituted by rangeland (based on US Geological Survey, 1997; scale given in Figure 5.2b).

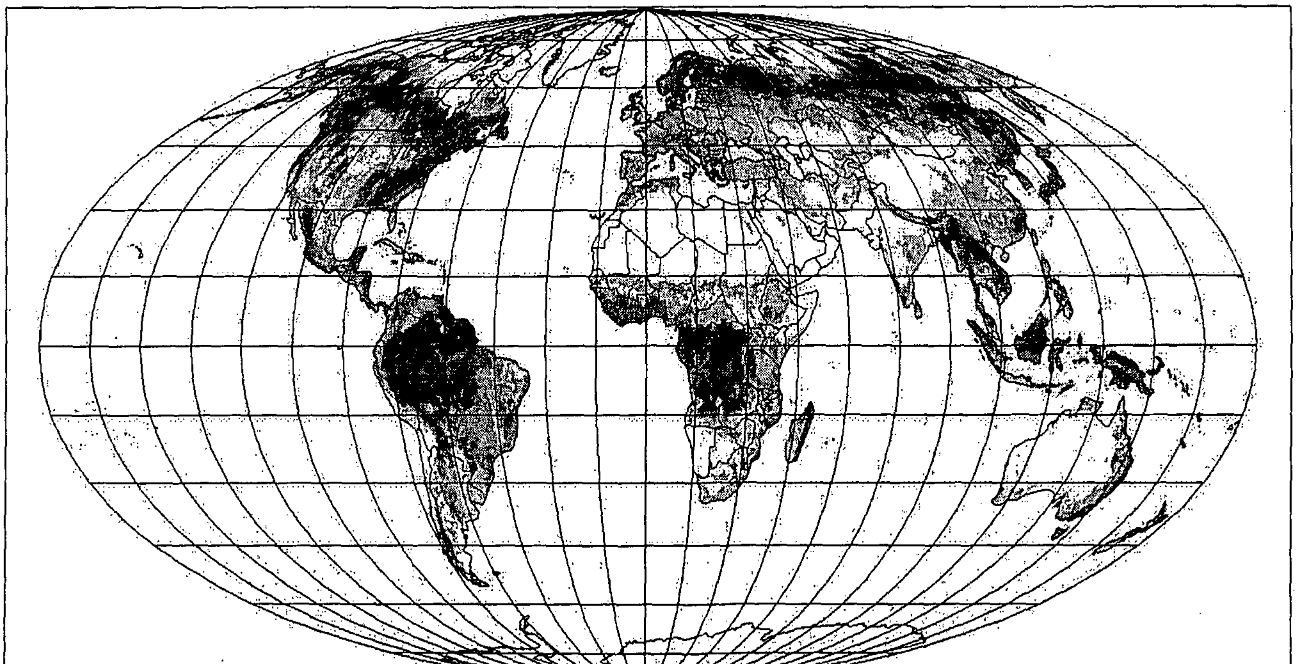


Figure 5.6. Fraction of area constituted by forest (based on US Geological Survey, 1997; scale given in Figure 5.2b).

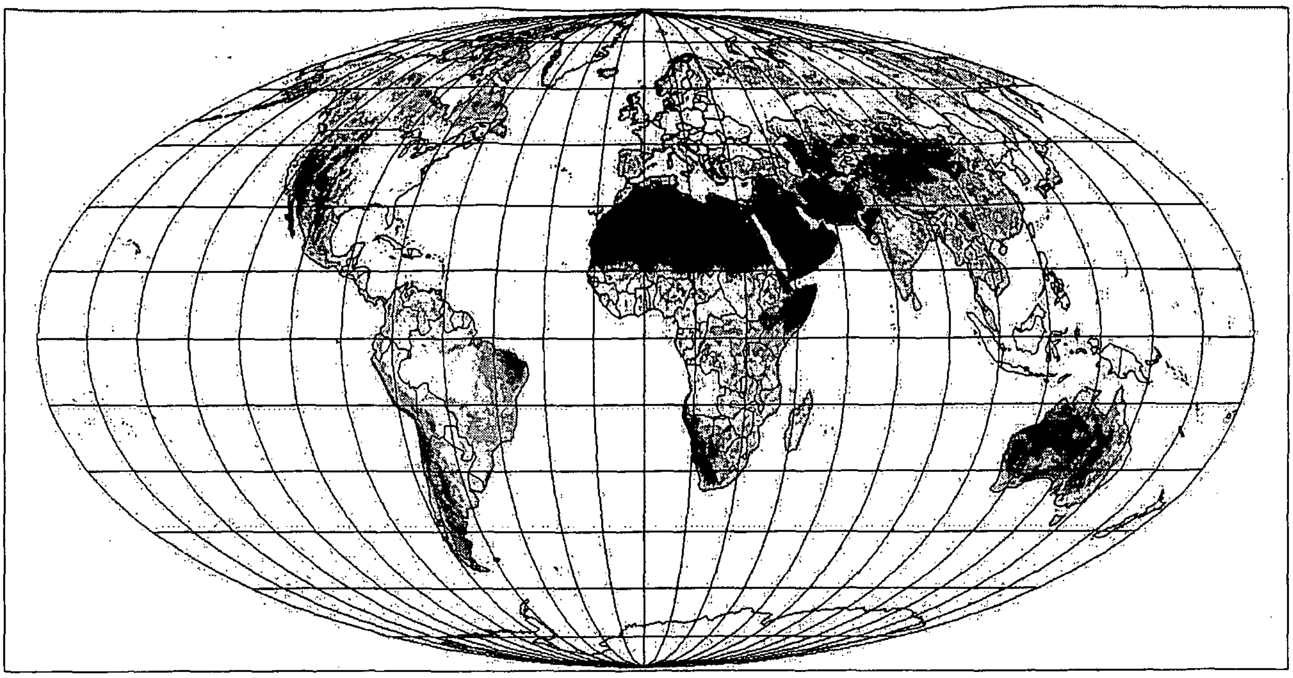


Figure 5.7. Fraction of area constituted by marginal land (based on US Geological Survey, 1997; scale given in Figure 5.2b).

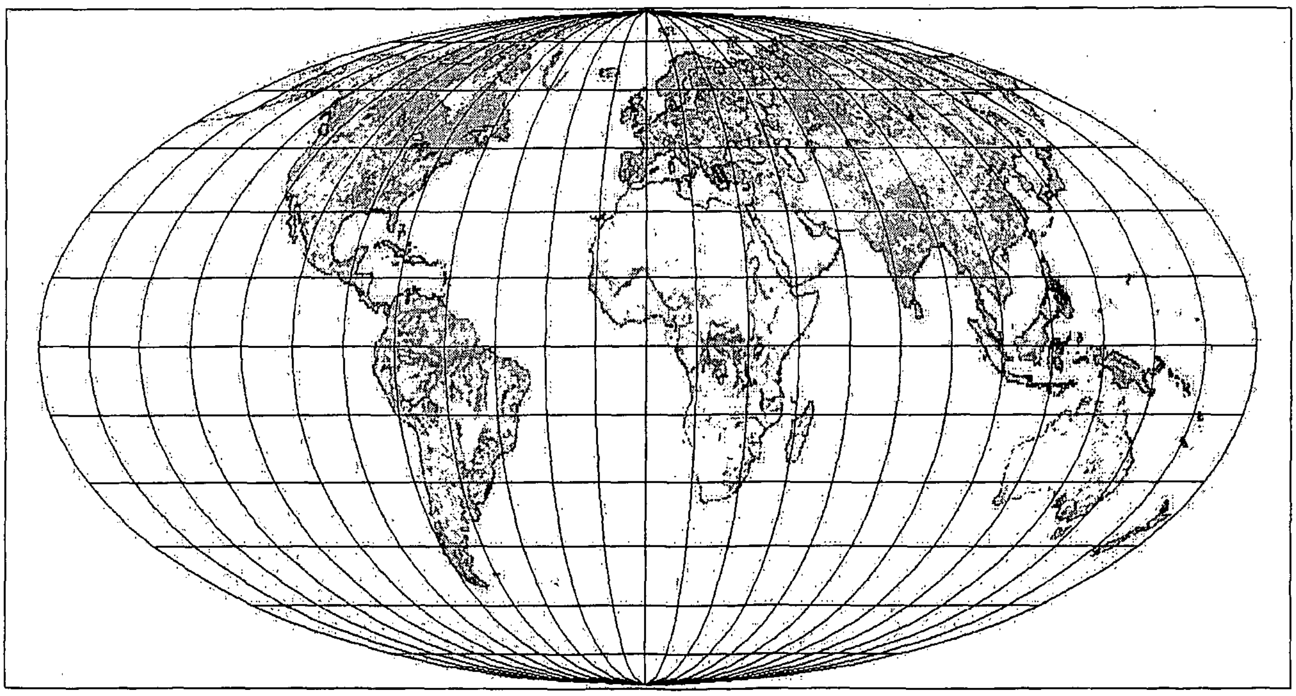


Figure 5.8. Fraction of "land" area constituted by water bodies (based on US Geological Survey, 1997; scale given in Figure 5.2b).

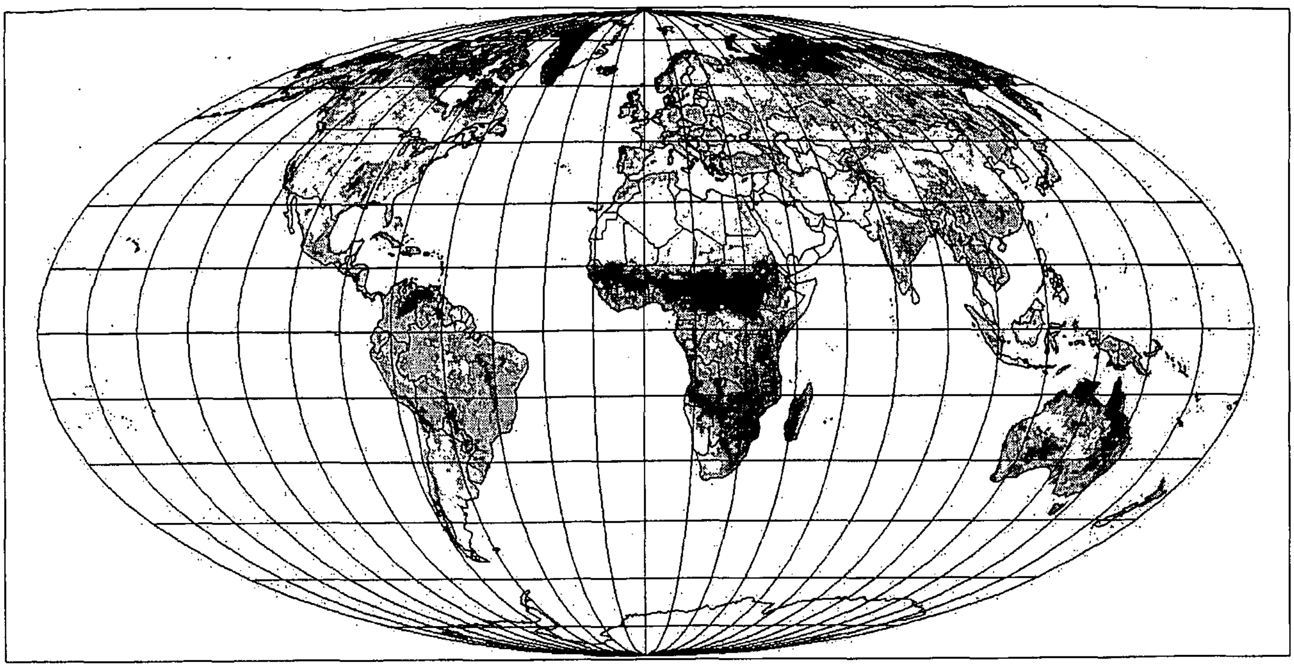


Figure 5.9. Fraction of area not covered by any of the categories shown in Figs. 5.2-5.8 (based on US Geological Survey, 1997; scale given in Figure 5.2b).

In order to calculate the solar radiation incident on inclined surfaces, such as the ones characterising most solar panel installations, one would ideally need hourly data for direct and scattered radiation (or equivalently for direct and total global radiation). One would then assume that the scattered radiation is uniform to calculate its value for differently inclined surfaces. For the direct part, ray calculations with the appropriate angles between the direction to the sun and the normal to the collector surface have to be performed hourly. Such calculations have been performed and compared with measurements on inclined surfaces at several major solar installations and some weather stations (Sørensen, 1979). Here global data are needed and only monthly average radiation data are readily available (at least with data sizes suitable for the present type of investigation), so an approximate relation has to be invoked.

The aim is to estimate the radiation on a surface tilted towards either North or South by an angle approximately equal to the latitude (as this gives the optimum performance) from the horizontal surface solar radiation data available. No great accuracy is aimed at, because the actual solar panel installations in the 2050 scenario will be of two types: *i:* Building integrated panels that will anyway be influenced by the structures at hand: some solar panels will be mounted on vertical facades, others on roofs being either flat or tilted, typically by angles 30°, 45° or 60°. In all cases the orientation may not be precisely towards South or North, although we estimate the resource as comprising only those buildings facing approximately correct and not being exposed to strong shadowing effects from other structures. The penalty of incorrect orientation and tilting angle is often modest and mostly influences the distribution of power on seasons (Sørensen, 1979). *ii:* Centralised solar farms will generally be oriented in an optimum way, using total production maximising for panels not tracking the sun. However, the majority of locations suited for central photovoltaic (PV) installations will be the desert areas of Sahara, the Arabian Peninsula, the Gobi desert and Australian inland locations. As these are all fairly close to the Equator, there is modest seasonal variations in solar radiation, and the horizontal surface data are often quite representative.

Table 5.2. Regional averages and sums of energy-supply related quantities

Region (cf. Table 2.2):	1	2	3	4	5	6	**Total**	unit
Region area	20.1	15.4	28.3	26.3	20.1	30.9	**141**	M km^2
Urban area fraction	0.0063	0.0133	0.0096	0.0178	0.0290	0.0122	**0.0147**	
Cropland fraction	0.0807	0.1324	0.1458	0.1714	0.2433	0.0472	**0.1368**	
Open cropland fraction	*0.0707*	*0.1020*	*0.1149*	*0.1107*	*0.2251*	*0.0240*	***0.1079***	
Rangeland fraction	0.0775	0.0430	0.0818	0.1115	0.1982	0.0632	**0.0959**	
Forest fraction	0.3514	0.1500	0.3051	0.4022	0.1305	0.1727	**0.2520**	
Marginal land fract.	0.1155	0.2166	0.1239	0.0999	0.3038	0.4058	**0.2109**	
Water body fraction	0.1043	0.1308	0.0625	0.1148	0.0465	0.0398	**0.0831**	
Other landtype fract.	0.2645	0.3141	0.2714	0.0824	0.0488	0.2589	**0.2067**	
Decentralised PV potential, January	38.9	40.5	71.3	146	164	109	**570**	GW
Decentralised PV potential, July	60.2	66.6	118	141	217	122	**724**	GW
Decentralised PV potential, ann. Av.	49.5	53.5	94.5	143	190	115	**647**	GW
Centralised PV potential, January	2220	7310	6680	4500	7910	18200	**46900**	GW
Centralised PV potential, July	3870	5990	9460	3980	11500	22700	**57500**	GW
Centralised PV potential, annual av.	3040	6650	8070	4240	9690	20500	**52200**	GW
Decentr. Wind power potential, January	66.3	40.8	454	156	118	85.0	**920**	GW
Decentr. Wind power potential, April	9.3	55.5	55.7	94.6	52.5	22.6	**290**	GW
Decentr. Wind power potential, July	37.6	41.2	52.7	189	153	49.6	**524**	GW
Decentr. Wind power potential, October	30.5	39.2	156	92.8	76.5	29.6	**425**	GW
Decentr. Wind power potential, ann. av.	35.9	44.2	180	133	100	46.7	**540**	GW
Off-shore/on-shore centralised wind power potential, January	28.6 28.4	59.6 93.5	66.5 82.0	138 45.5	10.2 42.6	8.7 309	**312** **601**	GW GW
Off-shore/on-shore centralised wind power potential, April	13.7 11.8	90.5 183	14.1 18.5	89.3 36.7	11.6 24.4	6.6 176	**226** **450**	GW GW
Off-shore/on-shore centralised wind power potential, July	7.9 5.8	98.5 265	21.4 169	139 103	50.3 99.4	21.7 539	**339** **1180**	GW GW
Off-shore/on-shore centralised wind power potential, October	17.0 17.4	61.2 46.0	11.5 30.5	82.6 46.6	9.0 16.9	5.3 245	**187** **403**	GW GW
Off-shore/on-shore centralised wind power potential, annual average	16.9 15.9	77.5 147	28.4 74.9	112 58.0	20.3 45.8	10.6 317	**266** **659**	GW GW
Hydro power potential	90.6	85.0	52.7	251	122	15.0	**616**	GW
Potential grain/vegetable food deliveries	153	176	215	369	546	90.7	**1550**	GW
Pot. animal food with use of crop fodder	38.4	43.9	43.0	92.2	46.8	4.5	**269**	GW
Pot. animal food from grazing animals	21.9	10.5	20.3	50.1	38.4	19.1	**160**	GW
Potential biofuels from forestry waste, crop residues and stable animal manure	299	184	263	987	327	356	**2420**	GW
Of which from forestry waste	208	80.4	154	769	157	333	**1700**	GW
Potential biofuels from energy crops	98.4	64.1	67.6	228	128	63.6	**650**	GW
Of which from prime cropland	25.5	29.3	0	61.5	0	0	**116**	GW

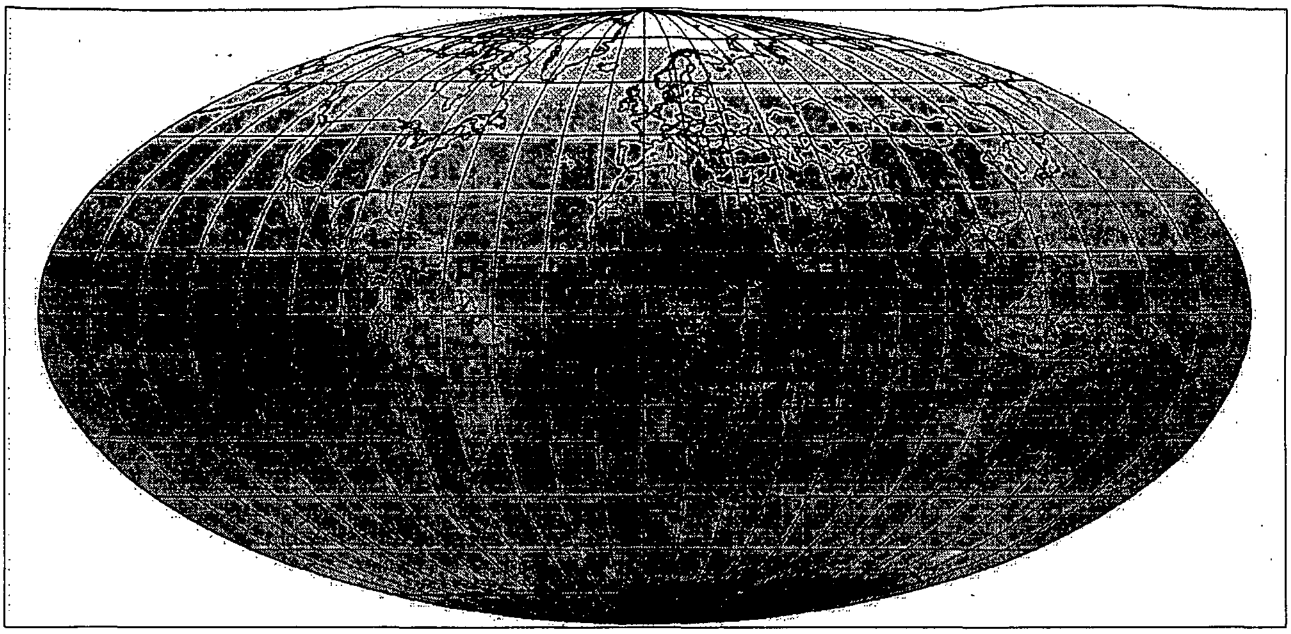


Figure 5.10a. January 1997 average solar radiation on horizontal surface (downward energy flux at Earth's surface) (based on NCEP/NCAR, 1998; scale given in Figure 5.10e).

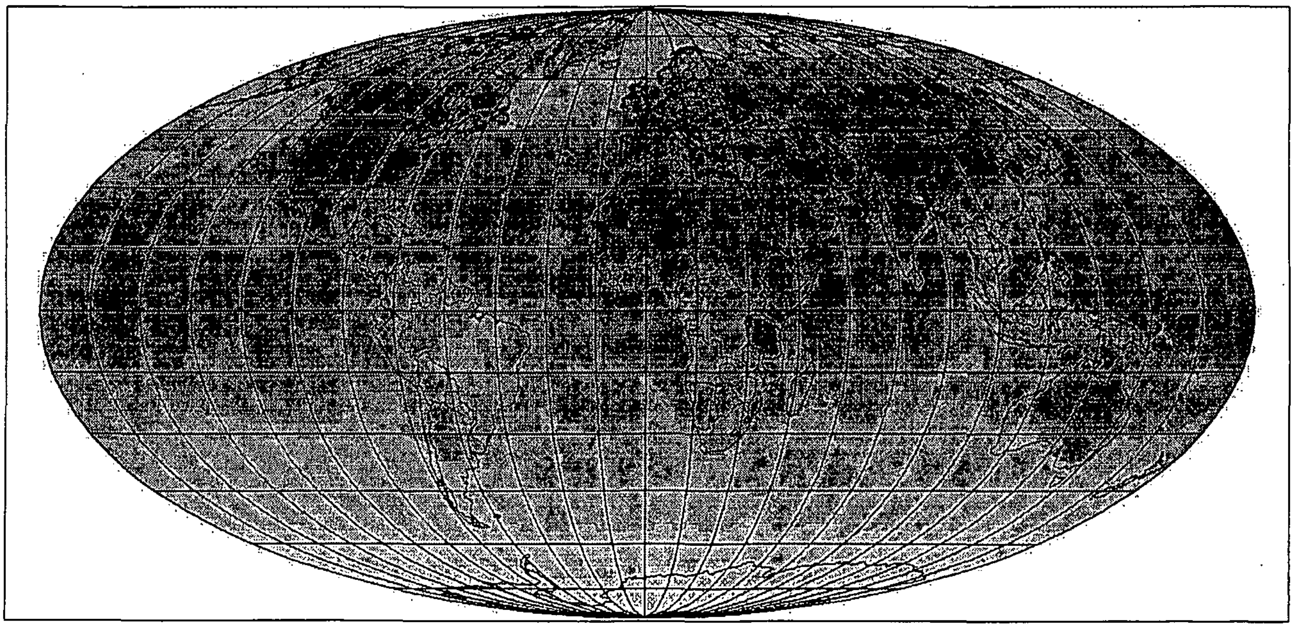


Figure 5.10b. April 1997 average solar radiation on horizontal surface (downward energy flux at Earth's surface) (based on NCEP/NCAR, 1998; scale given in Figure 5.10e).

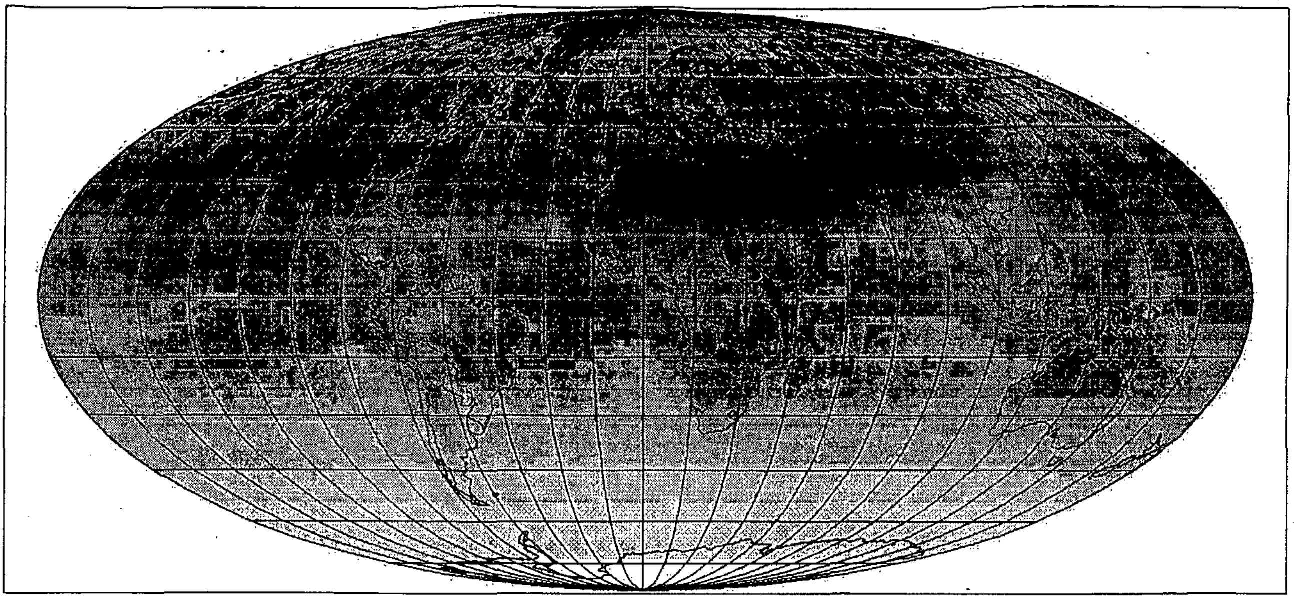


Figure 5.10c. July 1997 average solar radiation on horizontal surface (downward energy flux at Earth's surface) (based on NCEP/NCAR, 1998; scale given in Figure 5.10e).

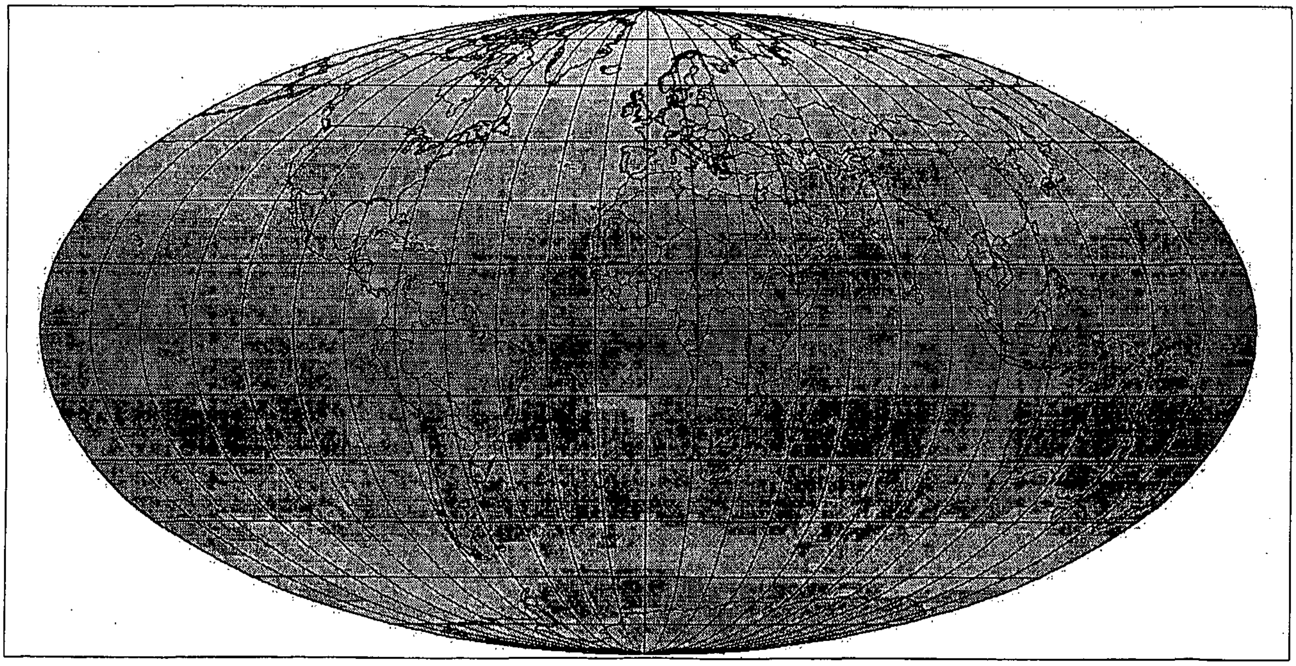


Figure 5.10d. October 1997 average solar radiation on horizontal surface (downward energy flux at Earth's surface) (based on NCEP/NCAR, 1998; scale given in Figure 5.10e).

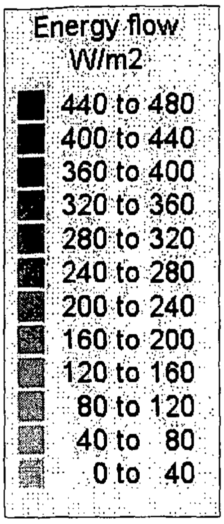


Figure 5.10e. Scale used for solar radiation (W/m^2).

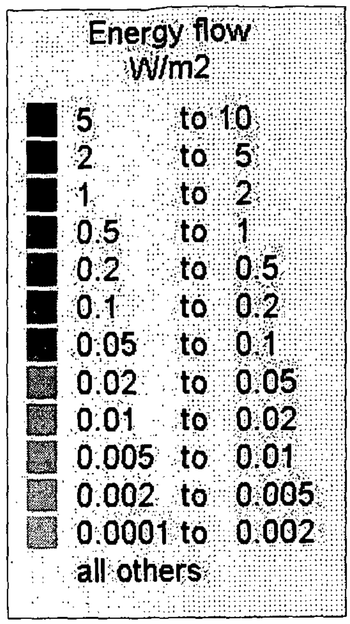


Figure 5.11d. Scale of energy flow (used for energy production and use) (W/m^2).

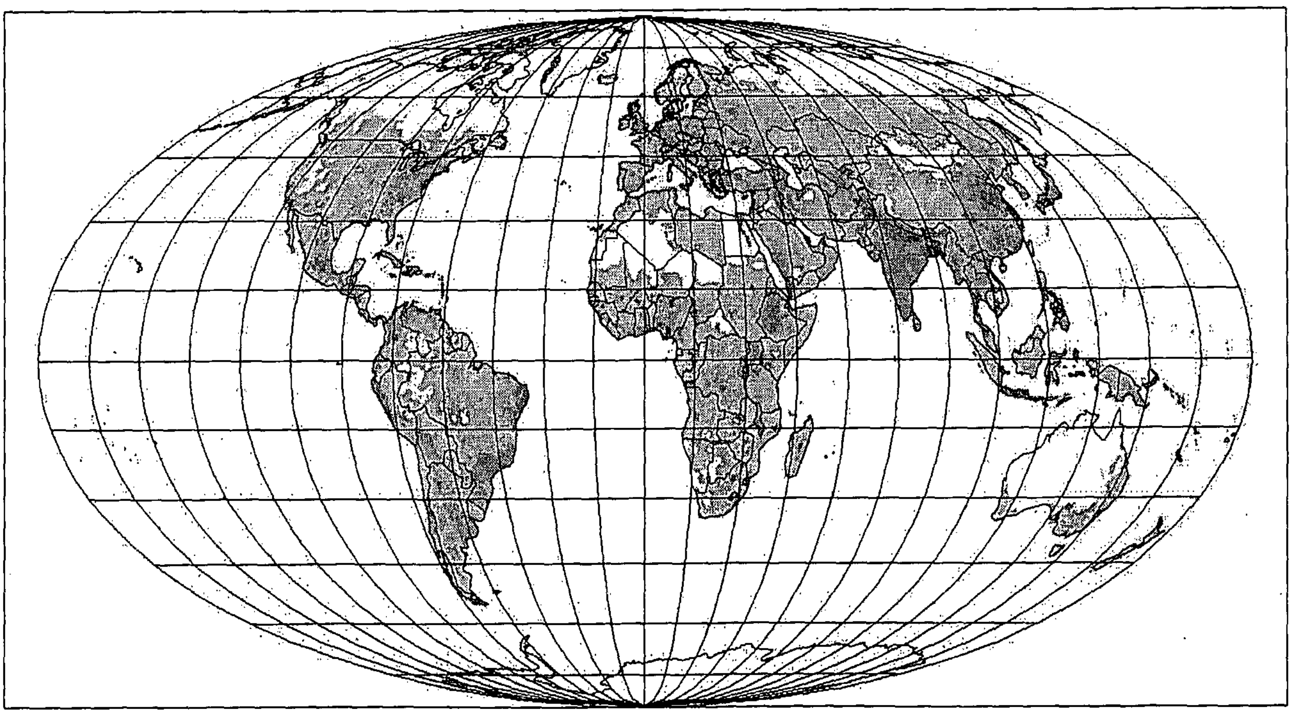


Figure 5.11a. January potential power production from building-integrated solar cells, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

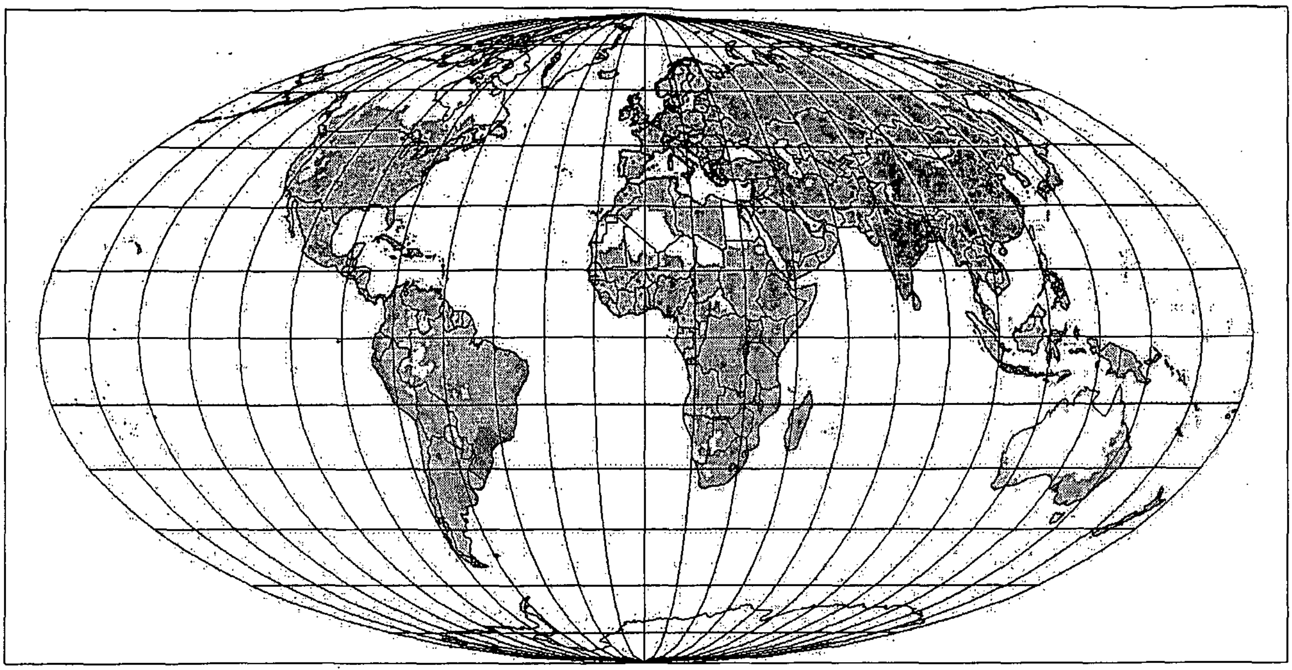


Figure 5.11b. April and October potential power production from building-integrated solar cells, with transmission and storage cycle losses subtracted (plain average of January and July values; scale given in Figure 5.11d).

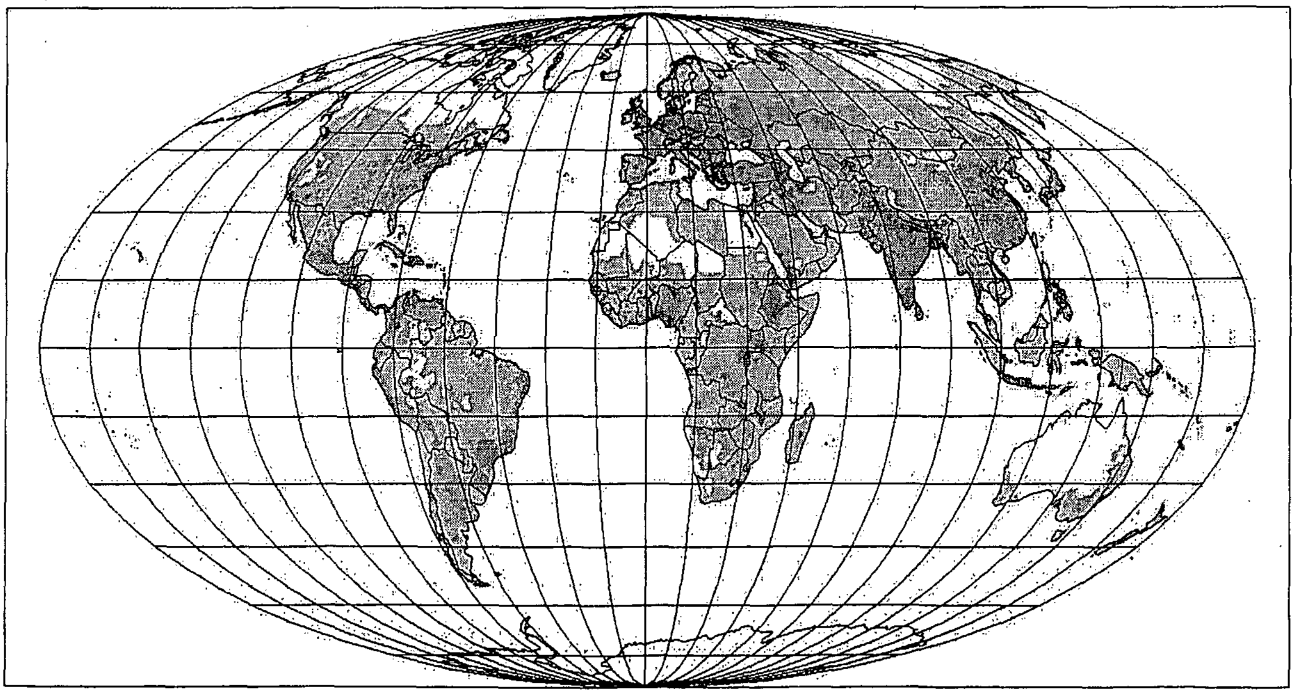


Figure 5.11c. July potential power production from building-integrated solar cells, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

Figure 5.11d: see before Fig. 5.11a.

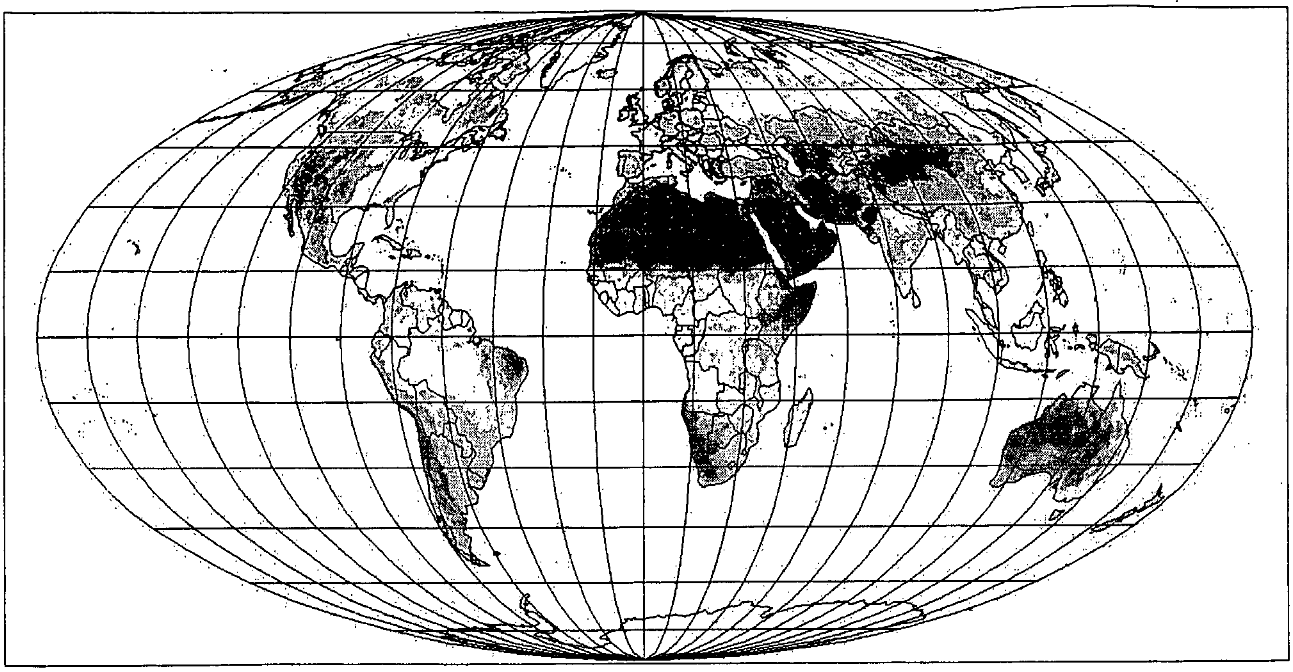


Figure 5.12a. Potential annual average power production from centralised photovoltaic plants on marginal land, with transmission and storage cycle losses subtracted. Seasonal variations are modest (scale given in Figure 5.12b).

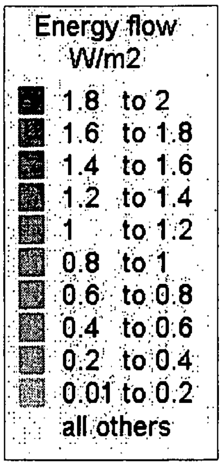


Figure 5.12b. Scale used for centralised photovoltaic production. Note that the scale is linear in contrast to the one used for decentralised power, e.g. in Figure 5.11 (W/m^2).

In consequence of the many unknown factors regarding the precise inclination of actual installations, the following simple approximation is used (it originates from an analysis of the Danish latitude 56°N data by Sørensen, 1979): The radiation on a latitude-inclined surface in January and July are noted to be very nearly equal to the horizontal radiation in October and April, whereas the horizontal surface data for January and July are lower and higher than the inclined surface measurements, respectively. It is therefore decided to use the October and April horizontal data as a proxy for January and July inclined surface radiation, and construct the April and October inclined surface values as simple averages of the January and July adopted values. Furthermore, this procedure, which works well for the Danish latitude, will be less inaccurate for low latitudes, because of the relative independence of seasons mentioned above, and we simply use it for all locations.

Figure 5.10 shows the NCEP/NCAR (1998) data for a horizontal surface. These have been checked against predictions of the European general circulation model HADCM2-SUL (Mitchell and Johns, 1997), and the 1997 monthly solar radiation values were found to be very similar.

In order to derive the actual energy extracted from PV solar panels, a fixed conversion efficiency of 15% is assumed, which is a fairly conservative estimate for year 2050 technology, considering that the current efficiency of the best mono-crystalline cells is above 20% and that of amorphous cells near 10%, with multicrystalline cells falling in between. The 2050 technology is likely to be thin-film technology, but not necessarily amorphous, as new techniques allow crystalline or multicrystalline material to be deposited on substrates without the complicated process of ingot growth and cutting. The efficiency of such cells is currently low, but as they are much less expensive than crystalline cells, they may be stacked in several layers and thereby still reach the efficiency envisaged here (Pacific Solar, 1997).

Finally, the availability of sites is estimated, for mounting PV panels either in a decentralised fashion or centrally in major energy parks: The decentralised potential is based on availability of suitably inclined, shadow-free surfaces. It is assumed that the area of suitably oriented surfaces that may be used for building-integrated PV energy collection is 1% of the urban horizontal land area plus 0.01% of the cropland area. The latter reflects the density of farmhouses in relation to agricultural plot sizes and is based on European estimates, roughly assuming that 25% of rural buildings may install solar panels. The potential PV production is thus taken as 15% of radiation times the fraction of the above two area types and the stated percentage for each. A final factor of 0.75 is applied in order to account for transmission and storage cycle losses, assuming about 5% transmission losses and that roughly half the energy goes through a storage facility of 60% round-trip efficiency (e.g. reversible fuel cells). The flow of energy reduced by all these factors represents the energy delivered to the end-use customers in the form of electricity. It is shown in Figure 5.11 for each season, with regional sums given in Table 5.2.

For centralised PV, the estimated potential is based upon 1% of all rangeland plus 5% of all marginal land (deserts and scrubland), again times 15% of the incoming radiation and times 0.75 to account for transmission and storage losses. As shown in Figure 5.12 and Table 5.2, this is a huge amount of energy, and it shows that such centralised PV installations can theoretically cover many times the demand of our 2050 scenario. Setting aside 1% of rangeland would imply an insignificant reduction in other uses of the land, even if this would rather be a small number of large plants. The same is true for desert and marginal land, where only the 5% most suited need to be invoked, which in reality might be 10% for the entire installation (including frames, access roads), of which the solar panels is only part. Because of the huge area of e.g. the Sahara desert this would suffice to supply more than the entire world need for energy. This would require the availability of intercontinental transmission, which may be quite realistic by year 2050, e.g. by use of superconducting trunk lines (Nielsen and Sørensen, 1996).

5.2.3 Wind power

The data used to assess potential wind power production are 1997 values from a reanalysis of meteorological station data and elevated data from balloons and aircrafts, analysed according to the method of Kalney et al., (1996), using a general circulation model to improve

consistency (NCEP/NCAR, 1998). From this, a simple average of pressure level 1000mb and 925mb data is assumed to represent the wind speeds at typical turbine hub heights of around 70m. However, as the data are monthly mean wind speeds $<v>$ constructed on the basis of zonal and meridional winds, a model is required for the relationship between $<v>^3$ and $<v^3>$ to go from wind speeds to power in the wind. Simple models imply a rough proportionality between these two quantities, as used e.g. in the US wind atlas prepared by the Pacific NW Laboratory (Swisher, 1995) and also apparent from the Weibull distribution approach of the European wind atlas (Troen and Petersen, 1989). Inspired by these sources, the relation between the power in wind P_w and the wind speed v (m/s) is estimated from the relation

$$P_w = 0.625 <v^3> \approx 1.3 <v>^3 \text{ W/m}^2.$$

The power in the wind obtained in this way is illustrated in Fig. 5.13, for four seasons.

Going from the power in the wind to the power that may be produced by a wind turbine, the non-linear response of wind turbines has to be taken into consideration. Turbines of modern designs aim at a high annual production and typically start producing only around 5 m/s and reach a fixed maximum production at around 12 m/s. Thus there would not be any production for a monthly average windspeed below 5 m/s, if this were made up of nearly constant values throughout the time range. However, actual time series of wind speeds reflect the passage of weather fronts and typically oscillates with periods of some two weeks, and actually entails some power production from the above type of wind turbine at practically all monthly average wind speeds, down to zero. The approach is then to parametrise the average power production from wind turbines as

$$W_p = \text{Minimum}(0.33\ P_w, 500) \text{ W/ m}^2,$$

representing the 21st century wind turbine constructions through a power factor slightly above the best of the current ones. A survey of power curves from existing wind turbines (Petersen and Lundsager, 1998) has been used as a basis for this estimate. This simple model is in reasonable agreement with data in regions of present wind exploitation. Due to the coarseness of the GIS grids used (for the wind speed data about 300 km cells at the Equator, diminishing by a cosine of the latitude towards the poles), the method does not at present compete with wind atlas methods available in certain parts of the world. It is, however, suited for planning purposes and can be refined as needed. The use of general circulation models in recalculating the data ensures that both surface roughness and general circulation determinants are included.

The wind power estimates calculated from the US data have been checked by performing a similar calculation using the HADCM2-SUL model of the European Hadley center (Mitchell and Johns, 1997; IPCC Data Distribution Centre, 1998), giving substantial agreement, within the variability from year to year which is of course different in the Hadley model from the NCAR model that is based on actual measurements. The year 1997 is about 10% under the long-term average for Danish locations (according to the data collected by Naturlig Energi, 1998), but the monthly variations are somewhat untypical. For instance the average of the four months included in our model is 20% under the long-term average. The previous year (1996) was the poorest wind year of the 20-year survey, and we wanted to include realistic seasonal variations in our data set and thus avoided further averaging. It should be said that the data from ground based stations (which has a substantial impact on the NCEP/NCAR data set due to the large number of such measurements relative to elevated data) may be a poor representation of actual wind conditions in a given area, due to the sheltered location of many meteorological measuring station. For this reason the European wind atlas used only selected station data believed to be more relevant for wind turbine exploitation. However, the comparison with the Hadley data, which only have a weak dependence on station data because they are generated from a general circulation model using topological features of wind roughness (friction), indicates that the method is quite reliable. The reason for this is presumably that pressure level data for both of the two lowest model pressure levels is employed here, rather than the 10m data also available in the NCEP/NCAR data base. The current type of calculation is also performed for the 10m data, yielding a considerably stronger dependence on the dubious ground level measurements.

The final step in estimating potential production from wind turbines is to appraise the locations suited for erection of wind turbines. There are three categories: Decentralised wind power production on farmland and centralised production in wind parks, either on-shore or off-shore. For the decentralised production, it is assumed that a (vertical) turbine swept area amounting to 0.1% of the crop- and rangeland areas may be used for wind production. Only the part of cropland designated as "open cropland" has been used (cf. Figure 5.4). This excludes mixed forest and cropland, where the trees are likely to impede wind flow. The assumed density of turbines corresponds roughly to the current density of wind turbines in many parts of Denmark, although the current average size is smaller than the turbines envisaged for the mid-21st century.

Current new turbines are typically of unit size 1.5MW and have hub-heights of 50-60m, while the average standing wind turbine is around 500kW with a hub-height of around 40m. Due to the combination of swept area increasing as the square of the linear dimension, and wind speeds increasing with height, the 2-4MW turbines envisaged in the 2050 scenario will not be conspicuously larger than those of the current generation. It is therefore assumed that visual intrusion aspects will allow a turbine density similar to the present one. Other environmental concerns such as noise are very minor, as the present generation of turbines can be heard only a few rotor diameters away at levels significantly exceeding the background noise (wind passing trees and structures such as power lines, highway signs and buildings) (Sørensen, 1995; 1997). In terms of ownership, the density of decentralised turbines would correspond to one out of 5-10 farmers owning a wind turbine (with large variations due to farm size variations between regions). Current wind power utilisation in the country with highest per capita wind power production, Denmark, are still dominated by farm-attached wind turbines, while in many other countries, the emphasis has been on centralised production from turbine clusters. The amounts of decentralised wind power potentially available is shown in Fig. 5.14 and summarised on a regional level in Table 5.2.

By centralised wind power is meant power not produced in connection with individual farms. For land-based wind parks, only placement on marginal land is accepted in the present scenario. In contrast to photovoltaic power, there is a fundamental limit to the fraction of land that can be used for wind power extraction, due to shadowing and interference between wake flows that create turbulence and reduce the power output. This limit would be a vertical swept area of about 1% of the horisontal land area (Sørensen, 1995). The assumption is that only 10% of the marginal land areas will be used for placement of wind turbines at such spacing, implying a maximum wind swept area constituting 0.1% of the land area. This is small enough not to interfere with other uses of the marginal land, such as the solar cell parks considered in section 5.2.2. Figure 5.15 gives the seasonal and annual production that potentially may be derived from such wind parks, with regional summaries in Table 5.2.

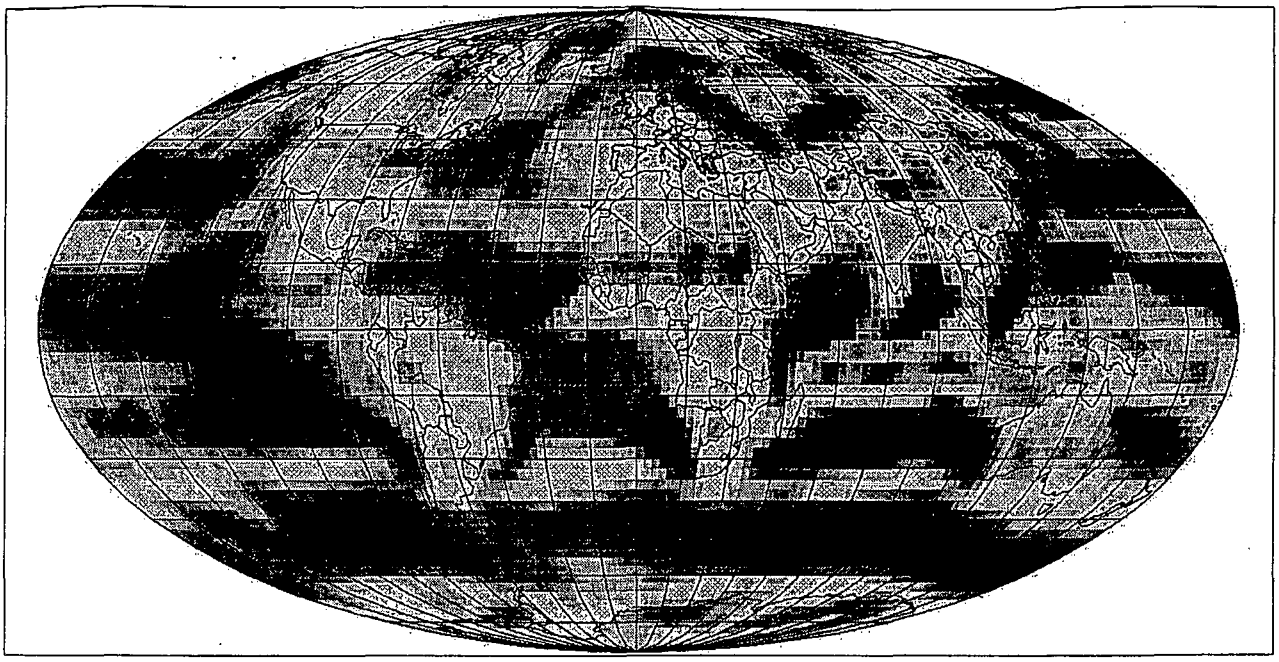


Figure 5.13a. Average January 1997 power in the wind at typical wind turbine hub height (about 70m; based on the average of 1000mb and 925mb horizontal winds from NCEP/NCAR, 1998) (scale given in Figure 5.13e).

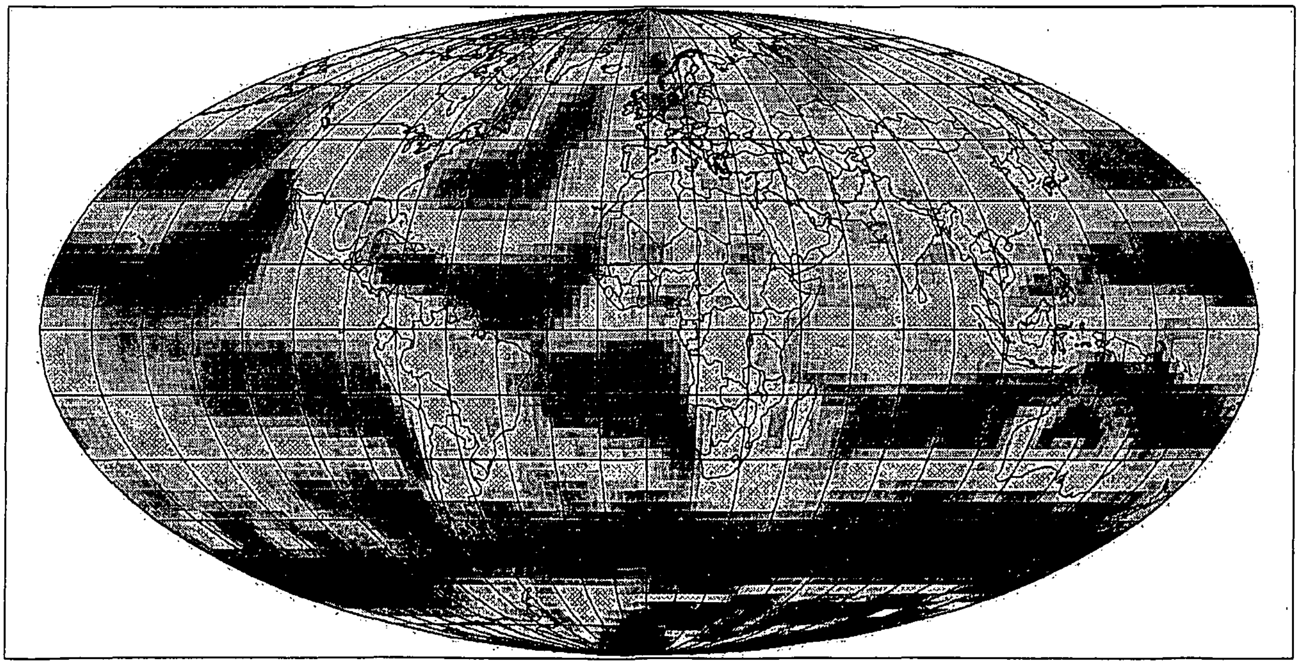


Figure 5.13b. Average April 1997 power in the wind at typical wind turbine hub height (about 70m; based on the average of 1000mb and 925mb horizontal winds from NCEP/NCAR, 1998) (scale given in Figure 5.13e).

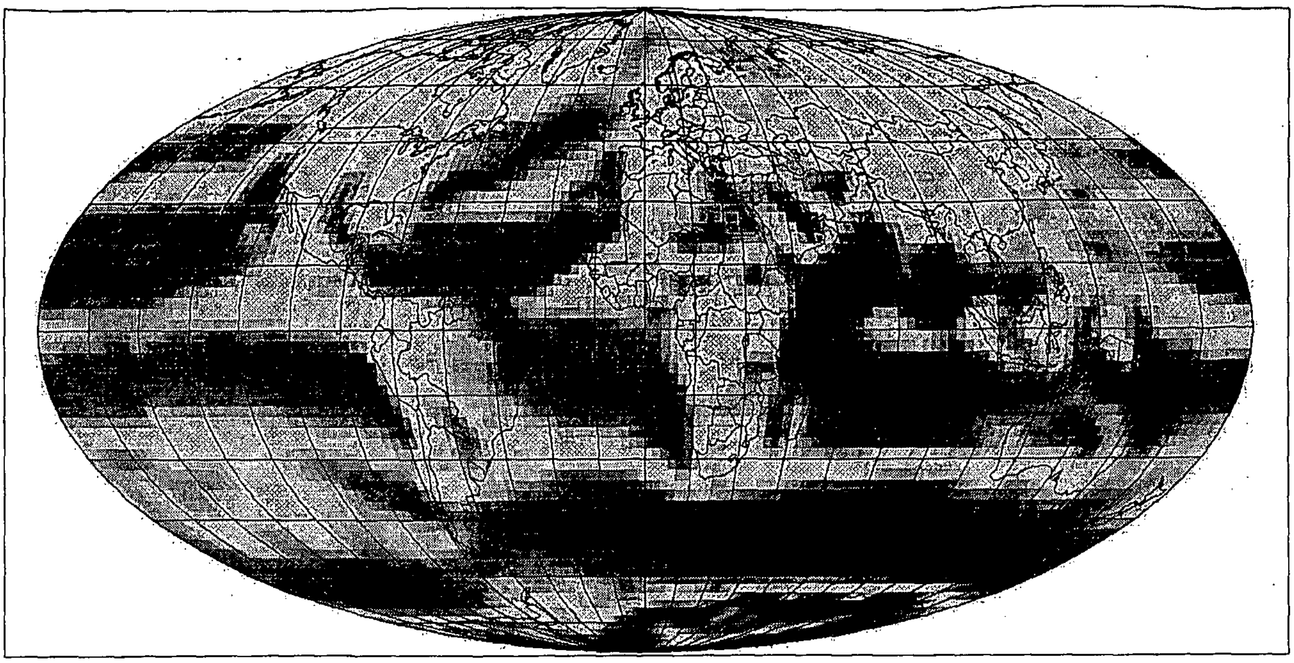


Figure 5.13c. Average July 1997 power in the wind at typical wind turbine hub height (about 70m; based on the average of 1000mb and 925mb horizontal winds from NCEP/NCAR, 1998) (scale given in Figure 5.13e).

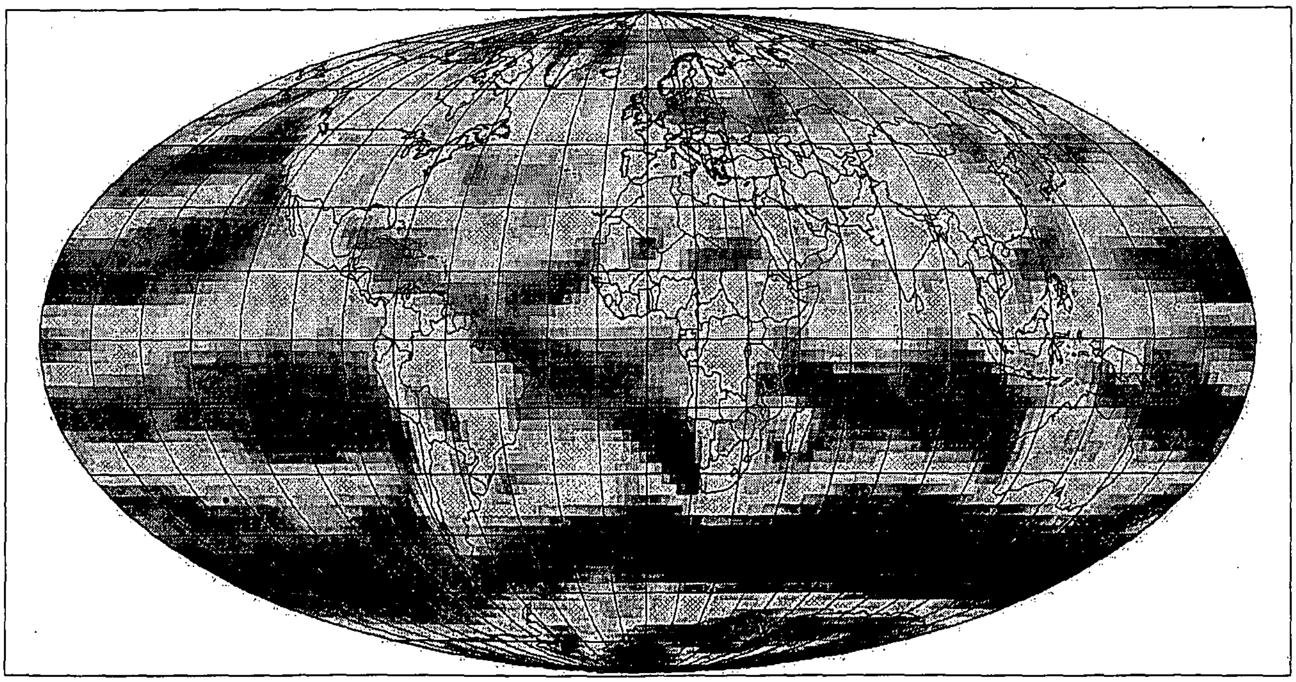


Figure 5.13d. Average October 1997 power in the wind at typical wind turbine hub height (about 70m; based on the average of 1000mb and 925mb horizontal winds from NCEP/NCAR, 1998) (scale given in Figure 5.13e).

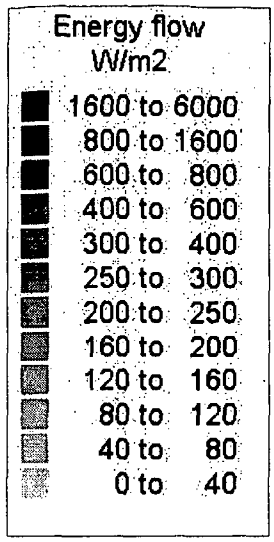


Figure 5.13e. Scale used for power in the wind (W/m^2).

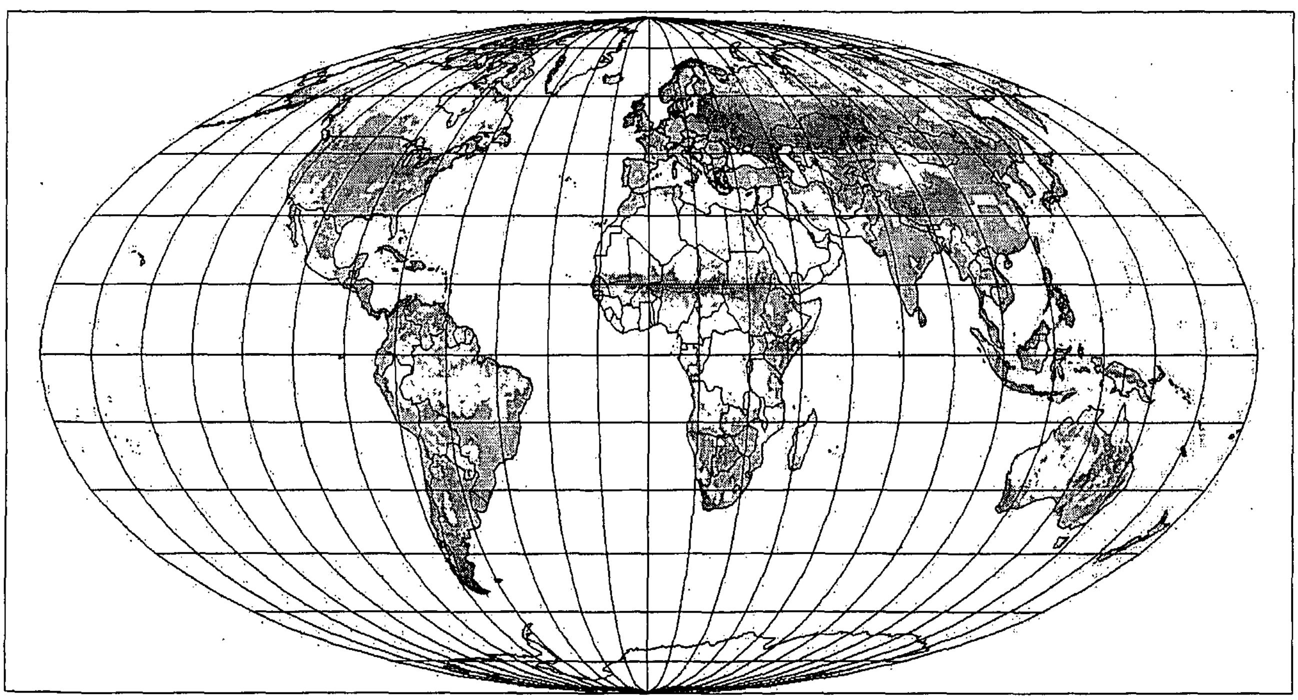


Figure 5.14a. Potential January average power production from decentralised wind turbine plants near farms, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

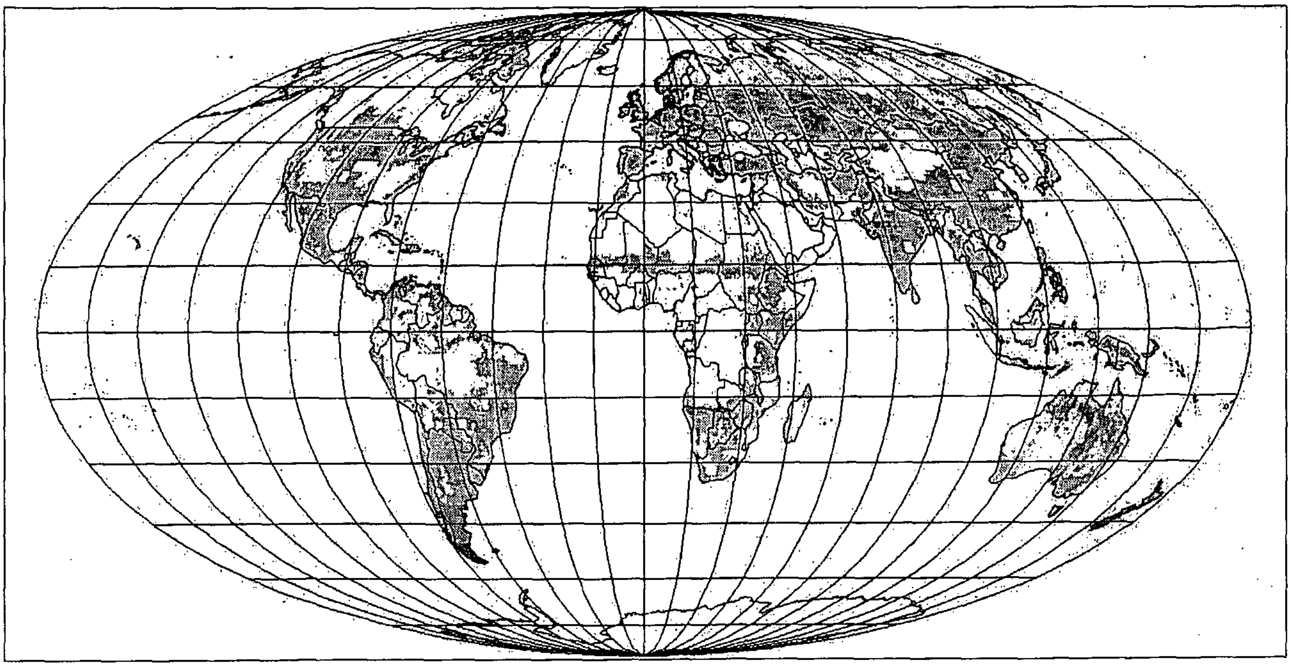


Figure 5.14b. Potential April average power production from decentralised wind turbine plants near farms, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d.

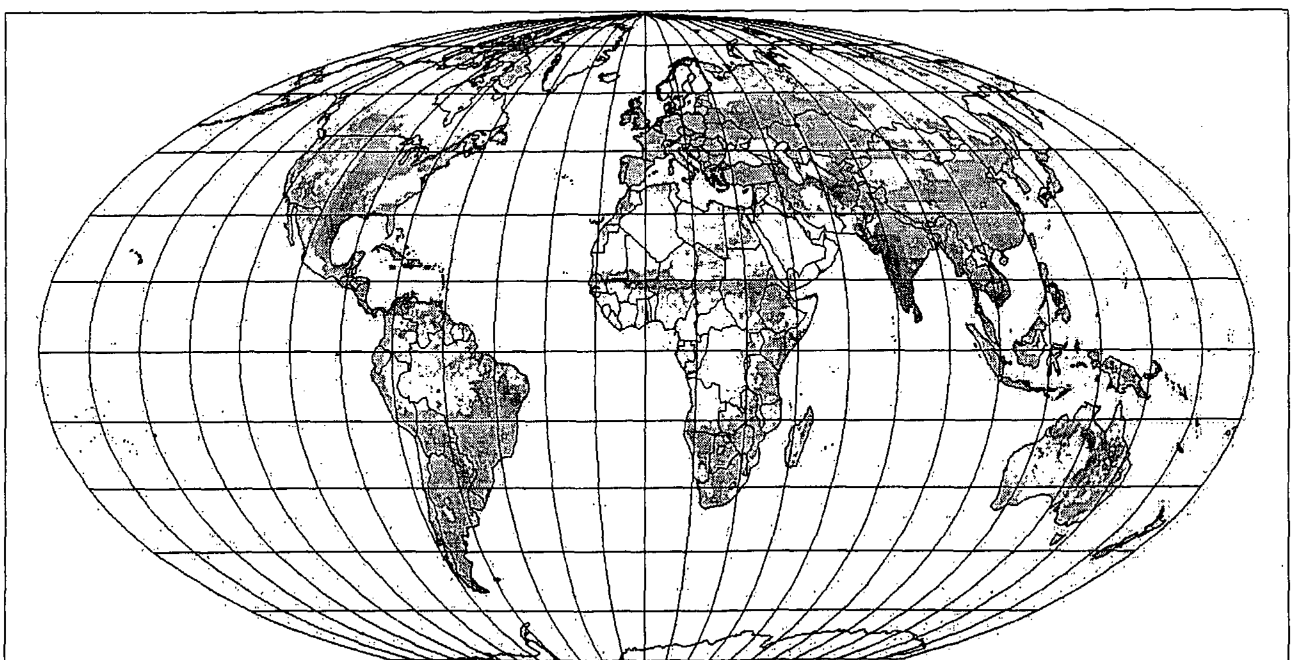


Figure 5.14c. Potential July average power production from decentralised wind turbine plants near farms, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

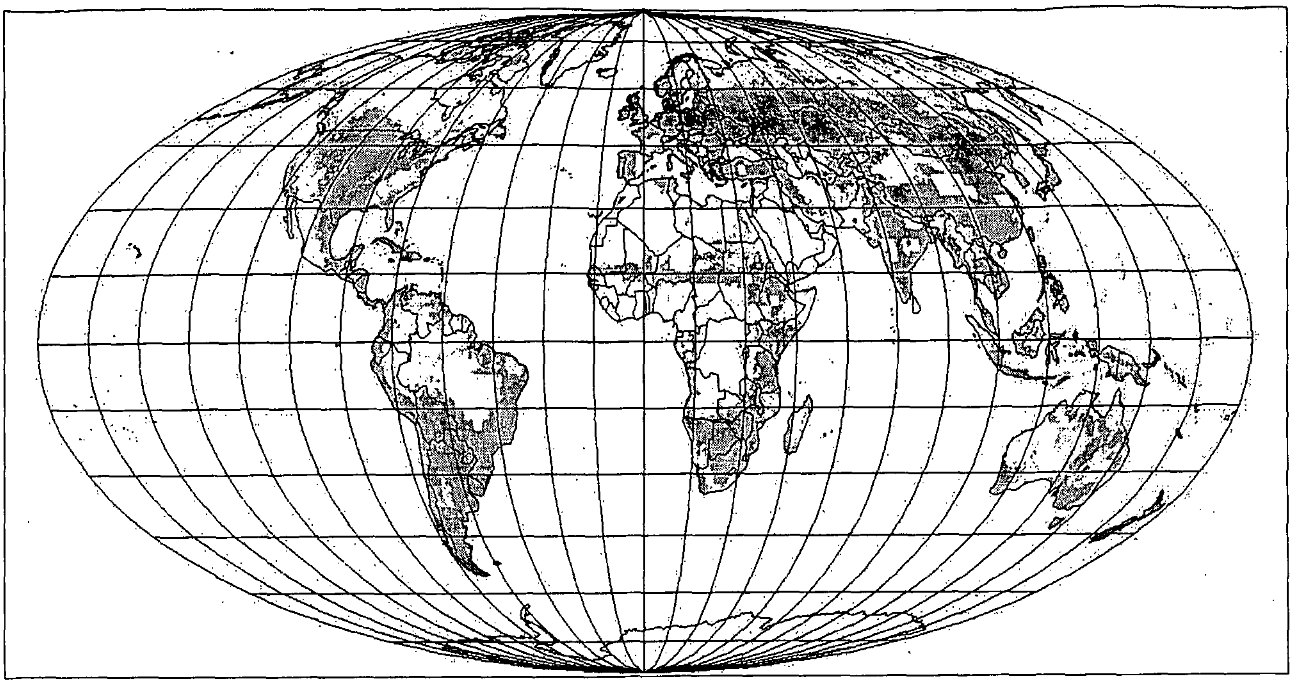


Figure 5.14d. Potential October average power production from decentralised wind turbine plants near farms, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

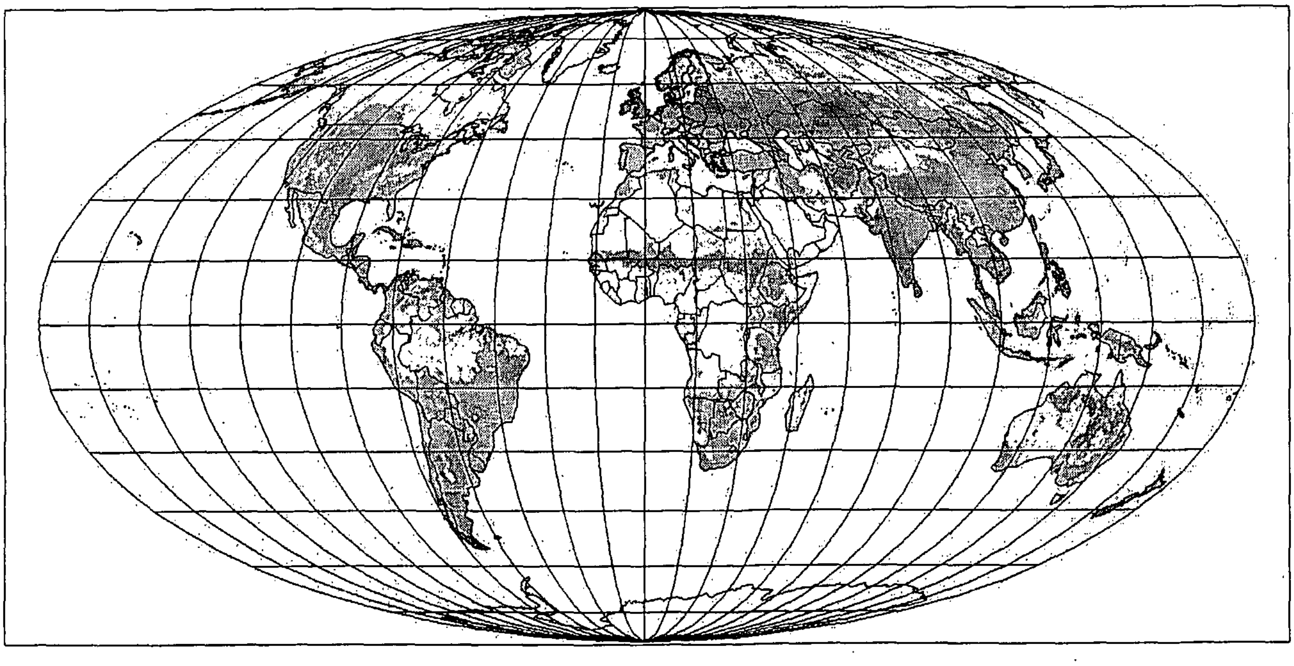


Figure 5.14e. Potential annual average power production from decentralised wind turbine plants near farms (on crop- and rangeland), with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

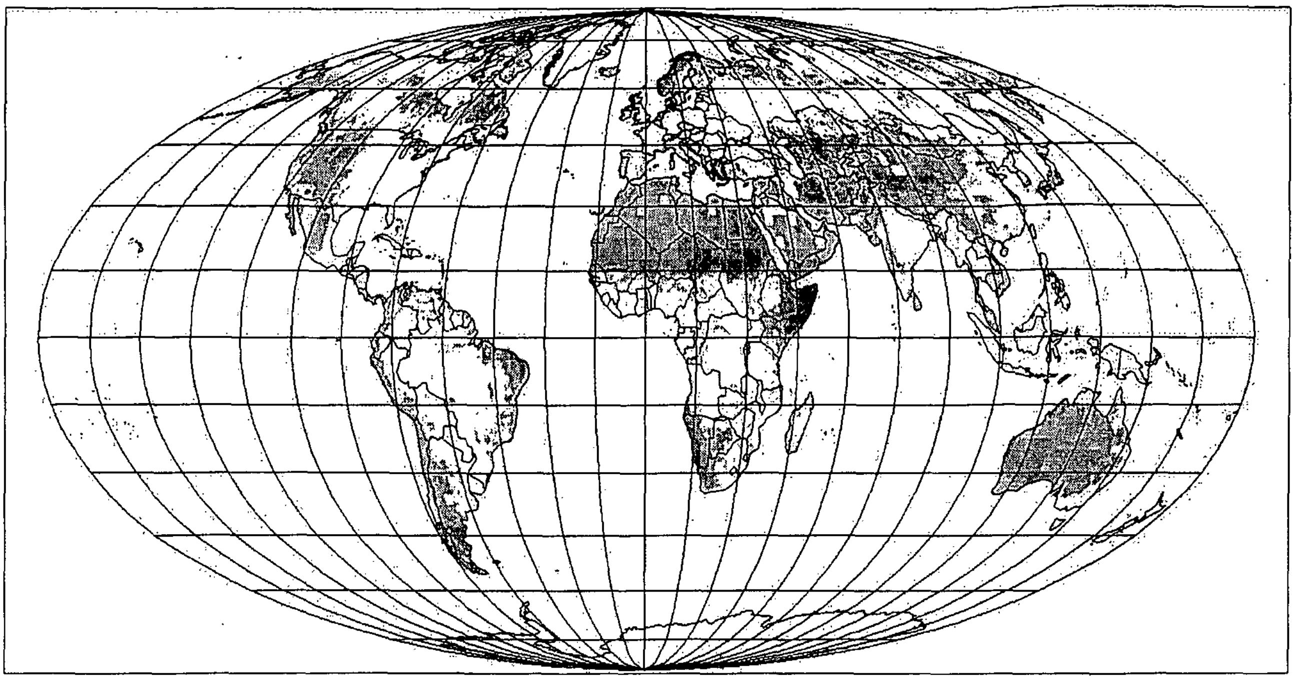


Figure 5.15a. Potential January average power production from centralised wind turbine parks on marginal land, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

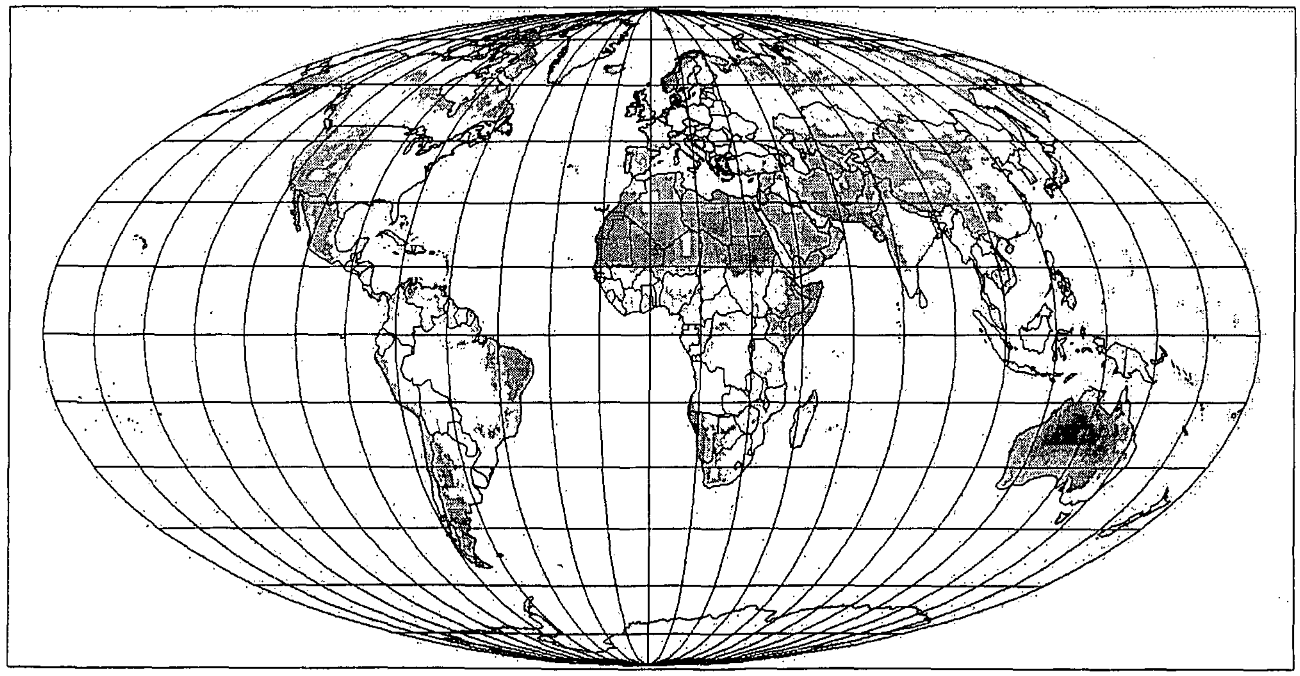


Figure 5.15b. Potential April average power production from centralised wind turbine parks on marginal land, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

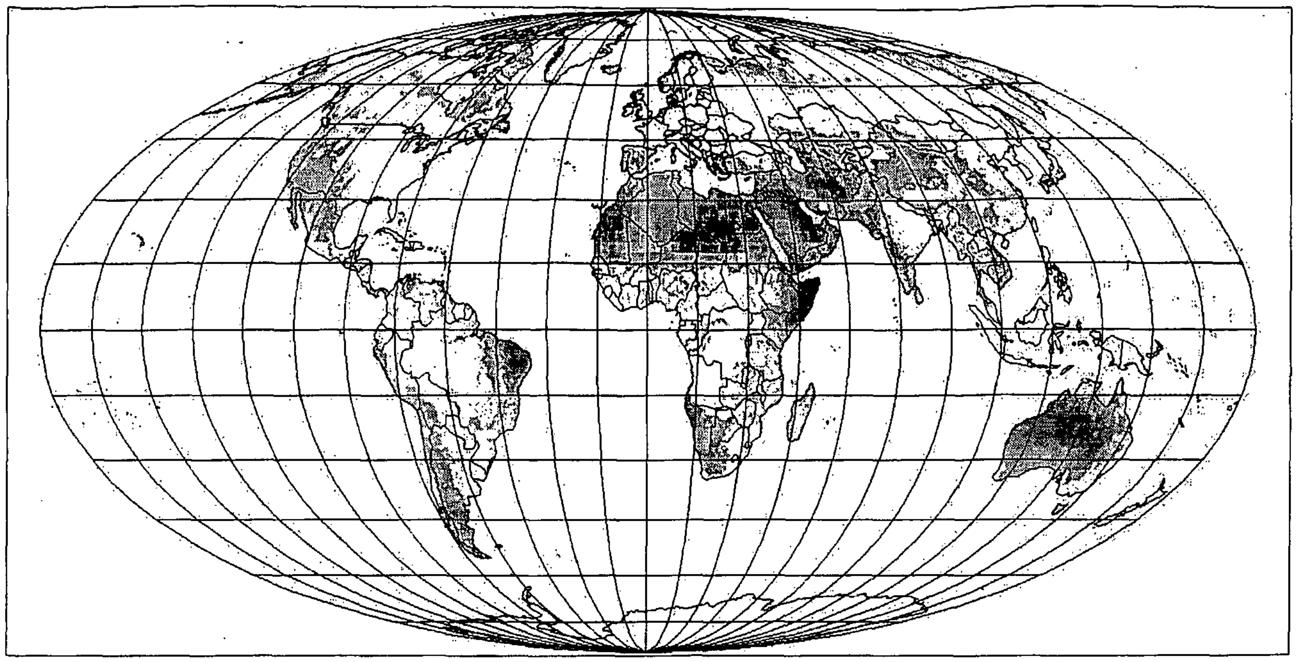


Figure 5.15c. Potential July average power production from centralised wind turbine parks on marginal land, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

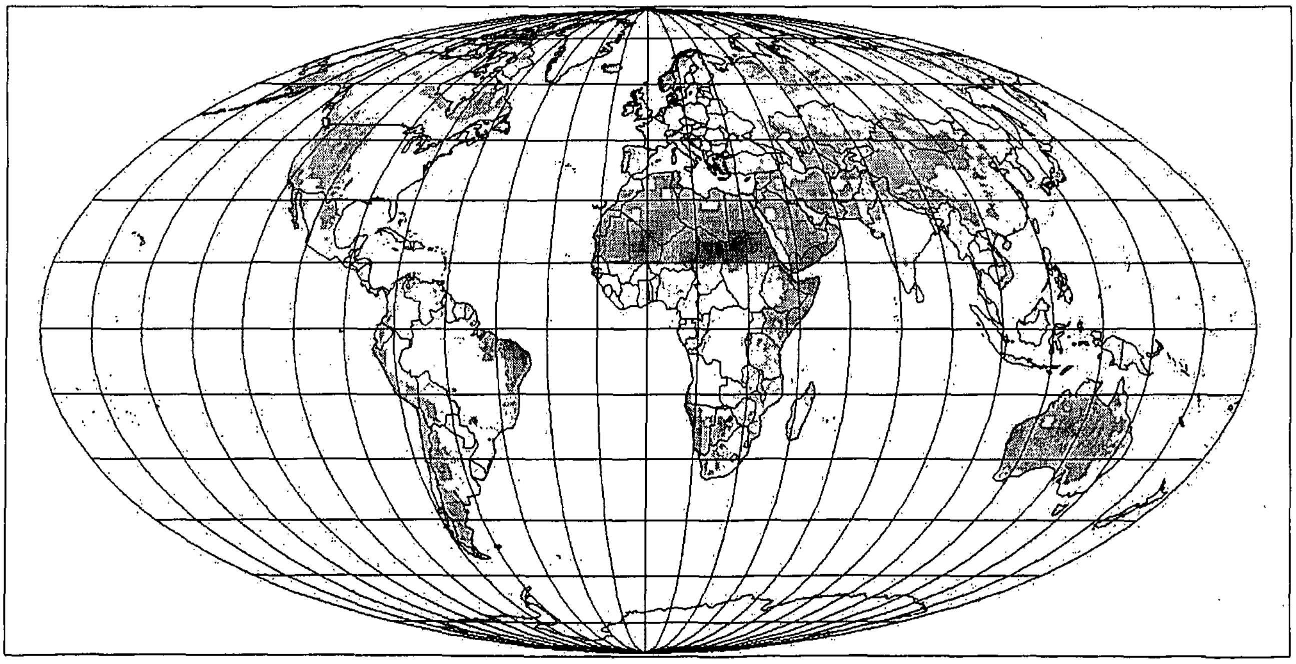


Figure 5.15d. Potential October average power production from centralised wind turbine parks on marginal land, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

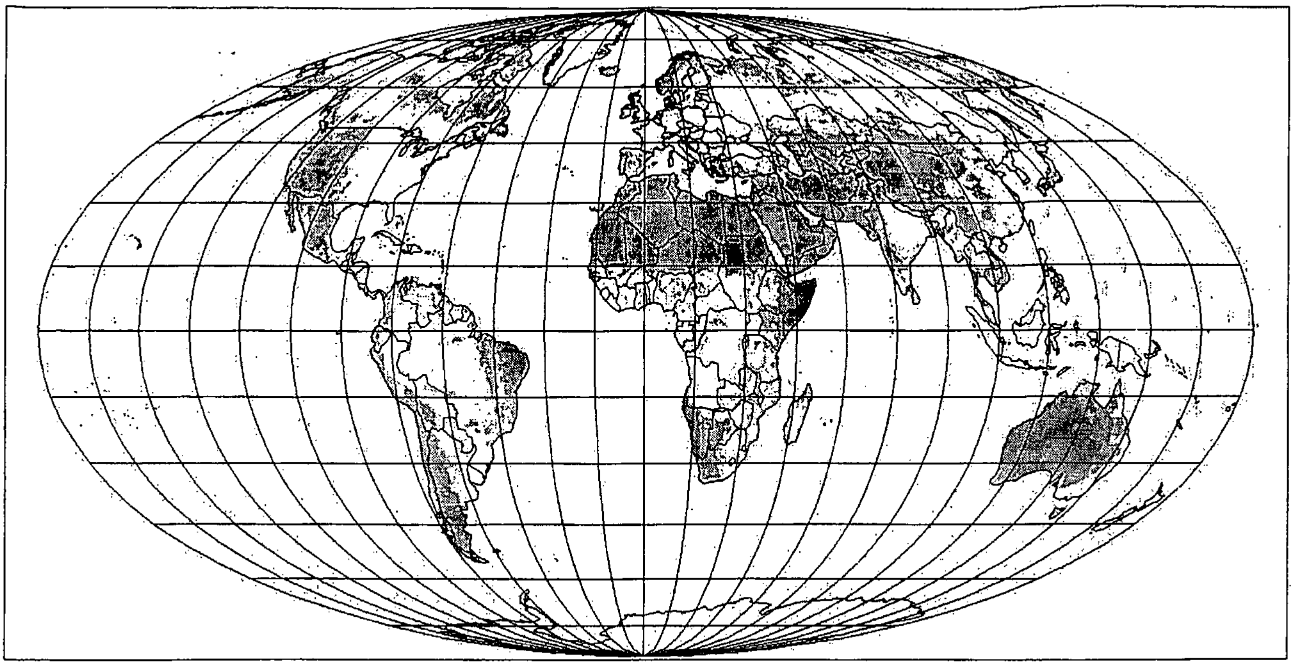


Figure 5.15e. Potential annual average power production from centralised wind turbine parks on marginal land, with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

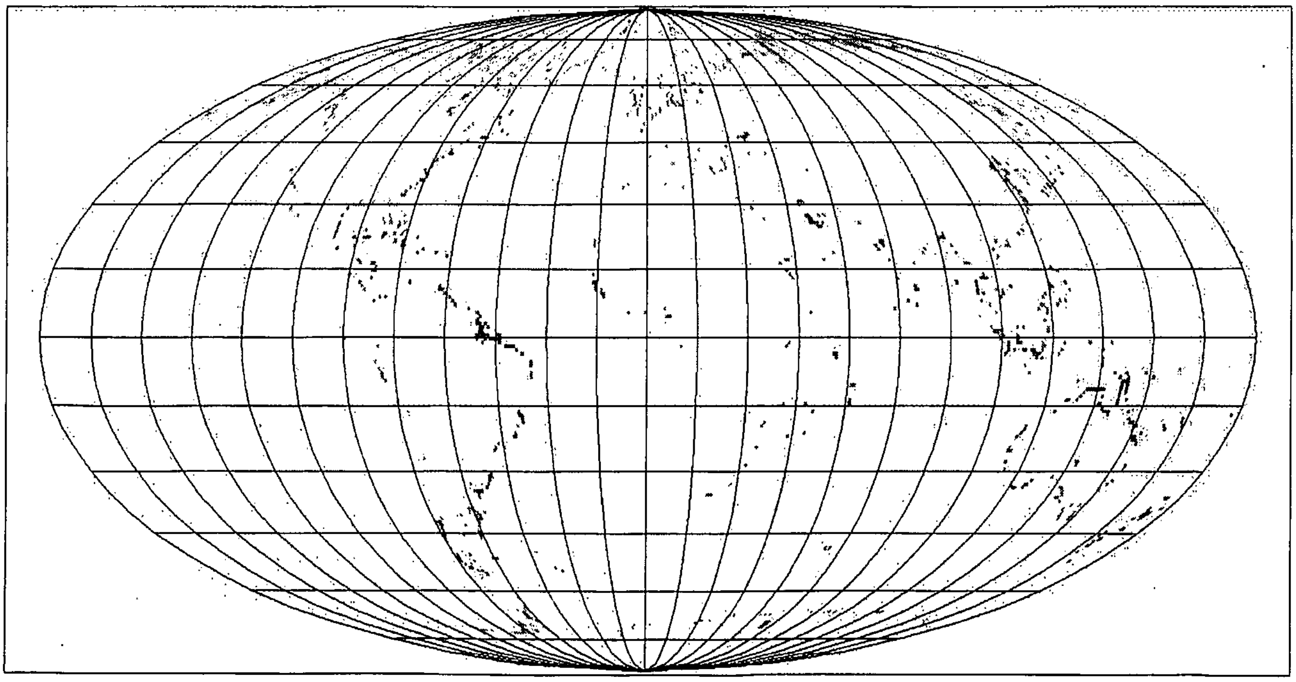


Figure 5.16. Potential annual average power production from centralised off-shore wind turbine parks (water depth under 20m), with transmission and storage cycle losses subtracted (scale given in Figure 5.11d).

Finally, there are off-shore wind parks, meaning turbines placed in shallow waters at a distance from the shore that minimises visual impacts. This mode of wind utilisation has become popular in recent years, as innovative low-cost solutions to the off-shore foundation problem have been found (Sørensen, 1995). The potential is here estimated by first identifying all off-shore water bodies with a depth under 20m (Figure 5.1a). Of these, it is assumed that only 10% can be used for wind power generation, due to competing uses (fishing, military, ship routes, etc.). Taking again the 1% maximum utilisation rate imposed by turbine interference into account, one arrives at a 0.1% maximum use of off-shore locations for wind power extraction. The average amount of power that can be derived from these locations is shown in Fig. 5.16 and summed up on a regional basis in Table 5.2. As indicated in the area fraction data of Table 5.2 and in Fig. 5.8, there are an additional number of inland water bodies that could also be used for wind power production. These are disregarded as candidates for wind production, because such lake and river areas are often of great recreational value.

5.2.4 Biomass energy

The largest current use of renewable energy sources is in agriculture. Although the primary aim is food production, increasing amounts of residues are made useful for energy purposes and as feedstock in manufacturing industries. The same is true for fisheries and silviculture, where again the aim is to make productive use of the entire variety of products associated with biomass. The technologies employed have also changed in response to environmental concerns, from simple burning of straw and woodfuel to production of new bio-derived fuels, e.g. ethanol, methanol, methane and hydrogen. Here, it will generally be assumed that biomass used in a "decentralised" mode means using the land areas already devoted to agriculture and forestry, possible for other crops than those grown today and farming in a more efficient manner. Like for solar and wind power we then add some further potential uses that we denote "centralised", meaning in the biomass case cultivation of dedicated energy crops or energy forest.

The general model used for the biomass sector is shown in Fig. 5.17. It is a refinement of a model developed earlier (Sørensen et al., 1994; Sørensen, 1995b). Below each part of the model is explained and the numerical assumptions made are discussed.

Food production

The land area used for food crops is considered to be the same in 2050 as now. This primarily includes the cropland area fraction (*AF* in Fig. 5.17) given in Figure 5.3, and for grazing also the rangeland shown in Fig. 5.5. Some of the latter is today used for grazing in a little intensive way, in contrast to the use of cropland in rotation for occasional grazing. Crop cultivation on the cropland fraction is in some areas (e.g. Africa) little intensive, and present yields strongly reflect the agricultural practices of each region. As an indication of the potential biomass production on these areas, the calculated net primary production data from the "Terrestrial Ecosystem Model (TEM)" of the Woods Hole group is used (Melillo and Helfrich, 1998; model evolution and description in Raich et al., 1991; Melillo et al., 1993; McGuire et al., 1997; Sellers et al., 1997). Global warming may induce increased primary production in a fairly complex pattern and the borders of natural vegetation zones will change, sometimes by several hundred kilometres (IPCC, 1996).

No consideration is made of greenhouse warming induced change in area fractions, because it is considered that diligent farming practices will allow a gradual replacement of the crops

cultivated in response to such altered conditions, which are anyway long-term compared to the lives of annual crops. The present model does not specify which crops will be cultivated at a given location, but simply assumes a productivity consistent with growing crops suited for the conditions. The TEM data are for a mature ecosystem, and they take into account natural water, humidity and nutrient constraints along with solar radiation and temperature conditions. Annual crops are likely to have smaller yields, because of only partial ground cover during part of the year and the corresponding smaller capture of radiation. On the other hand, the crops selected for cultivation may be favourably adapted to the conditions and therefore give higher yields than the natural vegetation at the location. Furthermore, irrigation may prevent yield losses in dry periods, and application of chemical fertilisers may improve overall yields.

The value basis driving the 2050 scenario implies restrictive use of these techniques and suggests a move towards increased use of the ecological agriculture principles currently showing at the 10% level, area-wise, and mostly in Europe. The basis for the scenario will be what is called "integrated agriculture" (Danish Technology Council, 1996), a concept where use of pesticides is banned and recycled vegetable residues and animal manure are the main sources of nutrient restoration, but where biological pest control and limited use of chemical fertilisers are not excluded. The yield losses implied by this method of farming is under 10%, according to current experience.

On cultivated land (including grazing land and managed forests) in regions such as Denmark, characterised by modest radiation and good soil and water access, the average annual biomass production is 0.62 W per m^2 (of which 0.3 W/m^2 are cereal crops; Sørensen et al., 1994). This is exactly the value for a grid cell in Denmark given in the TEM database for mature natural productivity. In Southern Europe the current production is about half (Nielsen and Sørensen, 1998), while the TEM database gives a slightly higher value than for Denmark. The reasons for this are less intensive agricultural practice in Southern Europe and water limitations for the growth pattern of the crops cultivated (limitations that would be less severe for a mature ecosystem). It thus seems reasonable in the scenario to use the TEM as a proxy for cultivation yields, provided than one assumes better farming techniques used by year 2050, and assumes that irrigation and chemical fertilisers are used when necessary. These are precisely the assumptions stated above as the basis for the scenario. The net natural primary production data of the TEM are thus used globally, but without adding further increases on the basis of irrigation (which in dry regions can double agricultural output) and use of chemical fertilisers (which can provide a further doubling, if the soil is poor in nutrients or nutrients are not returned to the fields). In other words, one offsets the disadvantage in going from mature vegetation to annual crops against the advantage of reducing limiting factors related to water and nutrients. In Fig. 5.17, this means disregarding the irrigation and fertiliser parameters *IF* and *FI*, and proceeding with the potential production *PP* taken from the TEM database.

The TEM global biomass production estimates for *PP* are shown in Fig. 5.18, expressed in energy units (1 gram carbon per year is equal to a rate of energy production of 0.00133 W).

Currently, in Denmark only about 10% of this energy is contained in the food consumed domestically. The indication from this is, that there is room for altered management of the system, by diverting residues to energy extraction and later returning the nutrients to the fields. One may also note, that the current system is based on high meat consumption and the associated emphasis on animal raising, and in the Danish case export. By even the modest change in vegetable to animal food consumption ratio assumed in the demand scenario described in Chapter 2, it is possible globally to divert substantial amounts of biomass to energy purposes,. without jeopardising the need to provide food for a growing world population.

It is not assumed that the intensive agricultural practices of Northern Europe will have been adopted globally by year 2050. The agricultural efficiency factor *AE* in Fig. 5.17 is taken as unity only for regions 1 and 2 (cf. Table 2.2). For Africa (region 6) it is taken as 0.4 and for the remaining regions as 0.7. The fraction of the biomass production actually harvested is taken globally as *HF* = 0.4. The remaining fraction consists of roots and residues plowed down in order to provide natural fertilisation for the following growth season.

Regarding the land areas classified as cropland, we assume the distribution on uses given in Table 5.3, based on cropland scarcity and traditions for animal raising. The low animal fodder value for Africa reflects the fact, that the African tradition for animal raising is based on rangeland, not cropland providing fodder.

Table 5.3. Parameters used for cropland biomass production in 2050 scenario (cf. Fig. 5.17)

Region	AE(cropland)	HF	UF (veget. food)	UF (fodder)	UF (energy crops)
1	1	0.4	0.4	0.5	0.1
2	1	0.4	0.4	0.5	0.1
3	0.7	0.4	0.5	0.5	0
4	0.7	0.4	0.4	0.5	0.1
5	0.7	0.4	0.7	0.3	0
6	0.4	0.4	0.8	0.2	0

The amounts of vegetable type food that can potentially be produced and delivered to the end-users in this scenario can now be calculated on an area basis, assuming the losses in going from vegetable food produced to vegetable food delivered as 25% (*IE(veg. products)* = 0.75 for vegetable food products in Fig. 5.17),

Delivered vegetable food = AF(cropl.)×PP[W/m2]×AE×HF×UF(veg. food)×IE(veg. prod.),

where *AF* and *PP* depend on the precise geographical location, the others only on region. The calculated distribution of vegetable food delivered to the consumers is shown in Fig. 5.19, and the regional totals are given in Table 5.2.

For food from animals, such as meat, milk and eggs, the average efficiency in transforming biomass to delivered animal products is assumed to be *IE(animal products)* = 0.15, a value reflecting a typical average of a smaller efficiency for meat production and a higher one for milk and eggs (Sørensen et al., 1994). The amounts of animal-based food using cropland-derived fodder and delivered to the consumer is thus

Delivered animal food(1) = AF(cropl.)×PP[W/m2]×AE×HF×UF(fodder)×IE(anim. prod.).

The distribution of potential animal food deliveries based on the route where livestock is fed fodder produced on cropland is shown in Fig. 5.20 and summarised in Table 5.2.

The other part of animal food is from animals grazing on rangeland, where we shall assume that livestock grazes *HF* = 0.4 of the biomass production per unit of area, and put *AE* = 1. The use of rangeland is assumed to be 50% for grazing and 50% for other purposes (such as energy crops or no commercial use). Thus the utilisation factor is taken as *UF(grazing)* = 0.5:

Delivered animal food(2) = AF(rangeland)×PP[W/m2]×HF×UF(grazing)×IE(anim. prod.).

The distribution of potential animal foodstuff delivered to the end-users through the route of rangeland grazing is shown in Fig. 5.21 and again summarised in Table 5.2. The ratio of the two contributions (crop feeding and grazing routes) is determined by the area set aside for each. The resulting fraction of animal food derived from rangeland grazing is 37%, in terms of energy content.

The efficiency in the end-user's making use of the delivered food, denoted *EE* in Fig. 5.17, has for all the bioenergy routes been included in the definition of gross demand in Chapter 2.

Biofuel production

A number of fuels may be produced from biomass and residues derived from vegetable and animal production, or from forestry and dedicated energy crops, ranging from fuels for direct combustion over biogas (mainly methane mixed with carbon dioxide) to liquid biofuels such as ethanol or methanol, or gaseous fuels such as synthesis gas (a mixture of mainly carbon monoxide and hydrogen, also being an intermediate step in producing methanol) or pure hydrogen. The production of biofuels by thermochemical processes is based on high-temperature gasification and various cleaning and transformation processes (Jensen and Sørensen, 1984; Nielsen and Sørensen, 1998).

Whether the biofuel production is by thermal or biological processes, the expected conversion efficiency is of the order of *FE* = 50% (cf. Fig. 5.17). This is to be compounded with a factor describing the ability of the biofuel production industry to collect the necessary feedstocks. This collection efficiency factor, which is called *CF*, describes the efficiency in collecting biomass for such industrial uses. For vegetable foods, it is assumed that *CF(veg. waste)* = 25% of the gross production is available for energy production (some of this would come from the food industry losses of *(1-IE(veg. prod.))* = 25%, some from the subsequent household losses of 30%, cf. the previous section and section 2.3). The overall yield of biofuels from vegetable crops is then

Biofuels from vegetable foodcrops =

AF(cropl.)×PP[W/m2]×AE×HF×UF(veg. food)×CF(veg. waste)×FE.

Considering manure, this would be available only when livestock are in stables or otherwise allows easy collection. The assumption is here that grazing animals leave manure in the fields and that this is not collected (although it could be in some cases), but that animals being fed fodder from crops will be in situations where collection of manure is feasible. Furthermore, although the 85% of animal biomass not ending up in food products will both be used to maintain the metabolism of livestock animals and the process of producing manure, it will also contain a fraction that may be used directly for fuel production (e.g. slaughterhouse wastes). Combined with manure this is assumed to amount to *CF(anim.)*= 0.6, giving for the fodder to animal route to biofuels:

Biofuels from manure and other animal residues =

AF(cropl.)×PP[W/m2]×AE×HF×UF(fodder)×(1-IE(anim. prod.))×CF(anim.)×FE

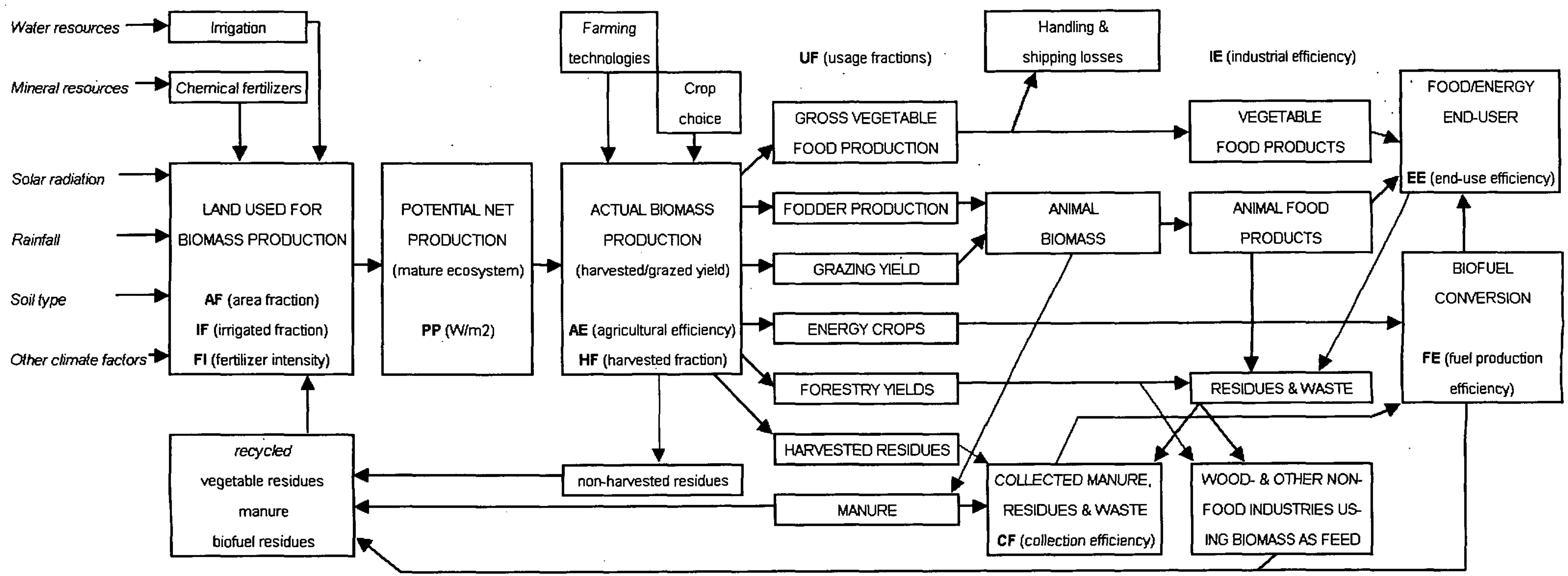


Figure 5.17. Overview of the model used for the agricultural and silvicultural system.

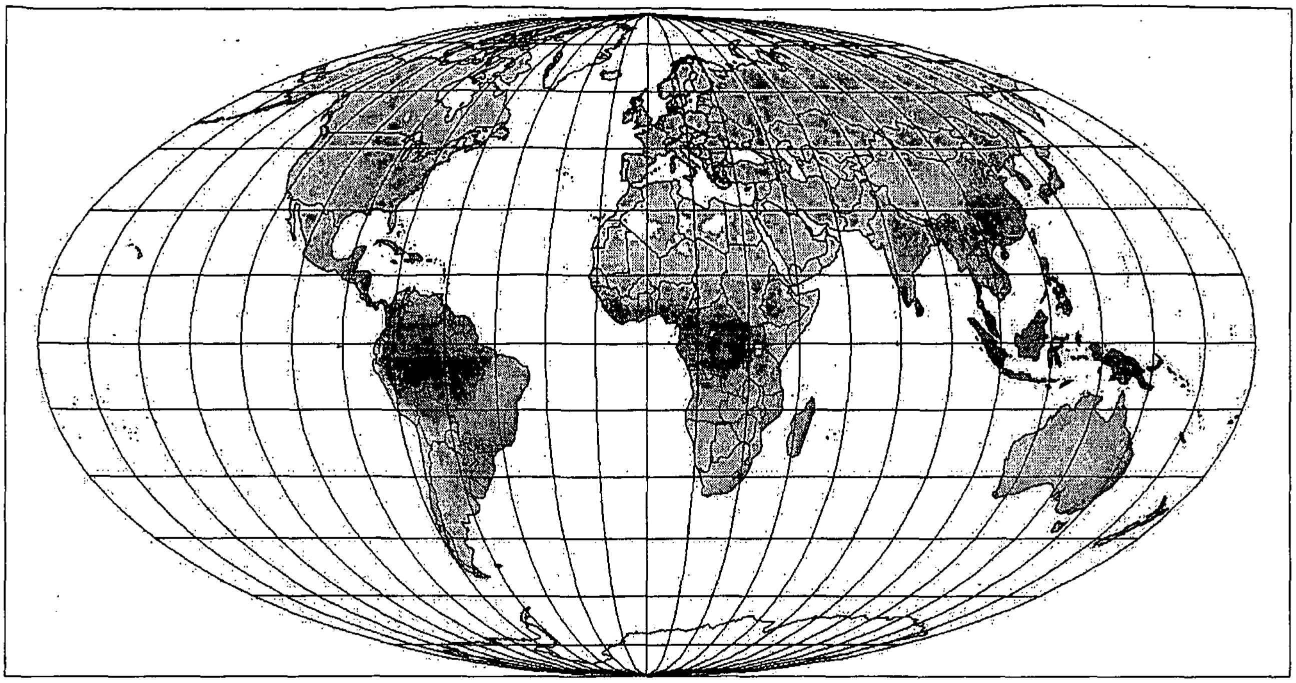
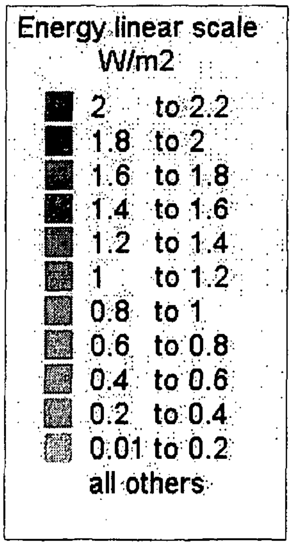


Figure 5.18a. Annual average energy content of potential net biomass production in mature ecosystems (based on Melillo and Helfrich, 1998; scale given in Figure 5.18b).

Figure 5.18b. Net primary production energy scale (W/m^2, the scale is linear).



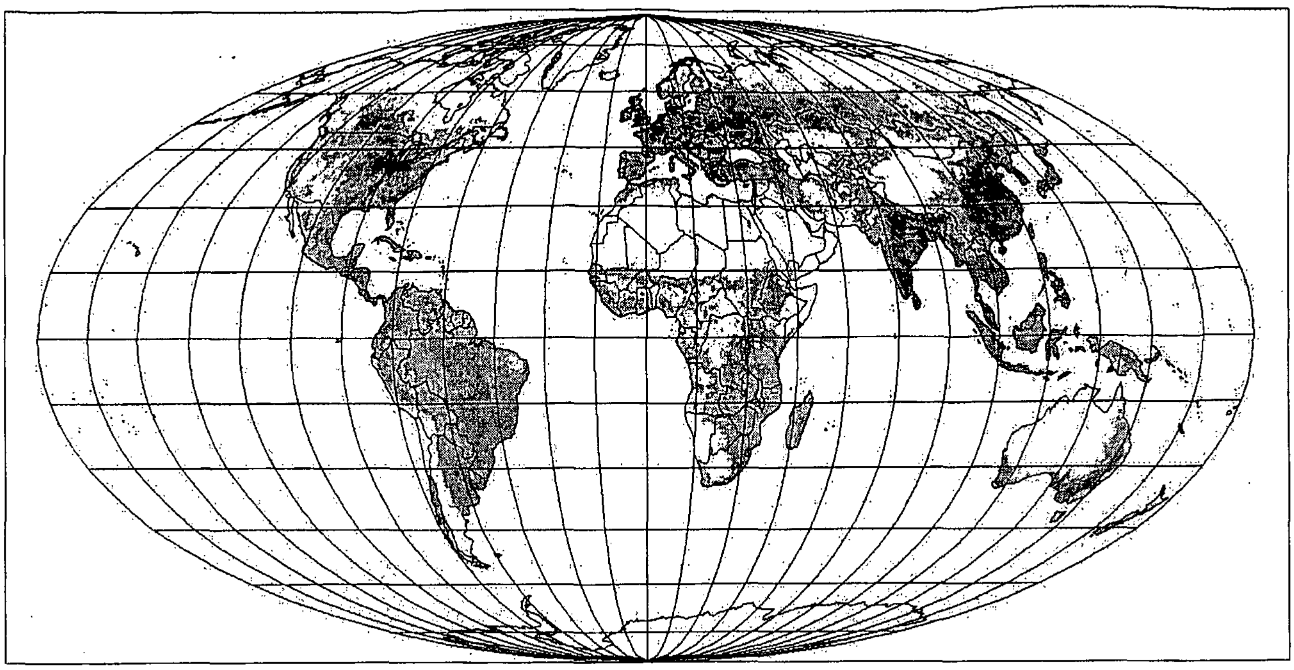


Figure 5.19. Potential vegetable food delivery to final consumers in 2050 scenario, derived from cropland production and expressed by annual energy content (scale given in Figure 5.11d).

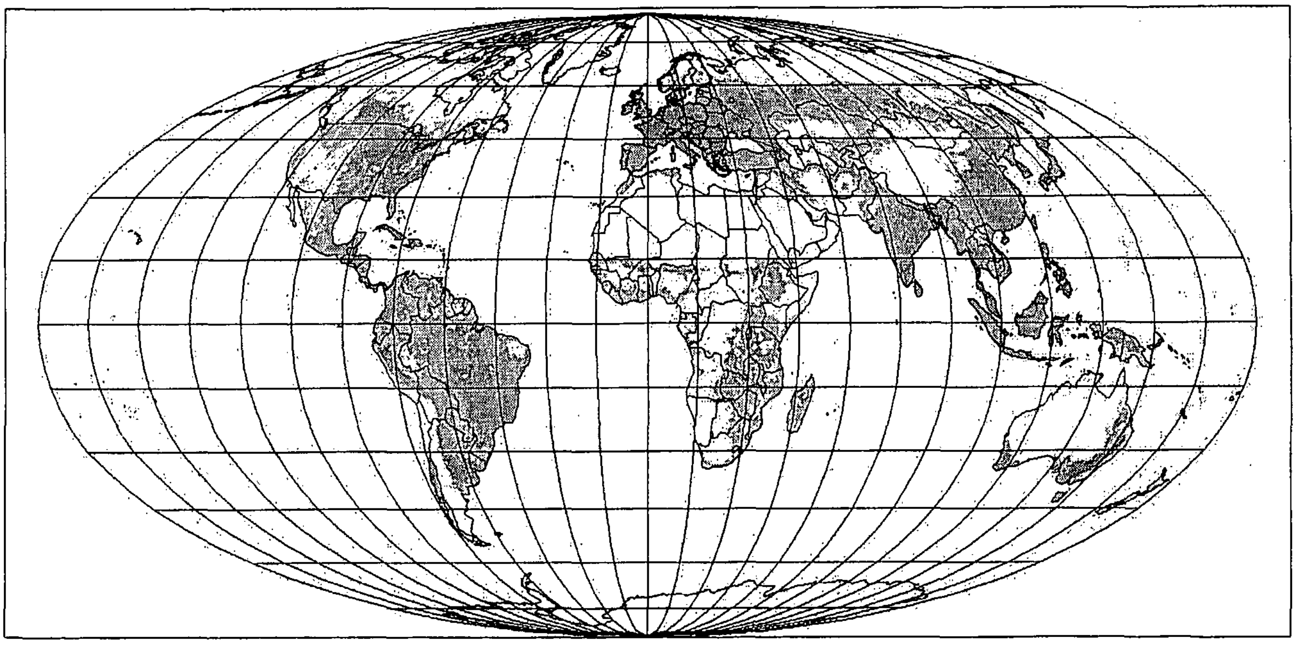


Figure 5.20. Potential animal food delivery to final consumers in 2050 scenario, for the fraction of animals being fed fodder grown on cropland, expressed by annual energy content (scale given in Figure 5.11d).

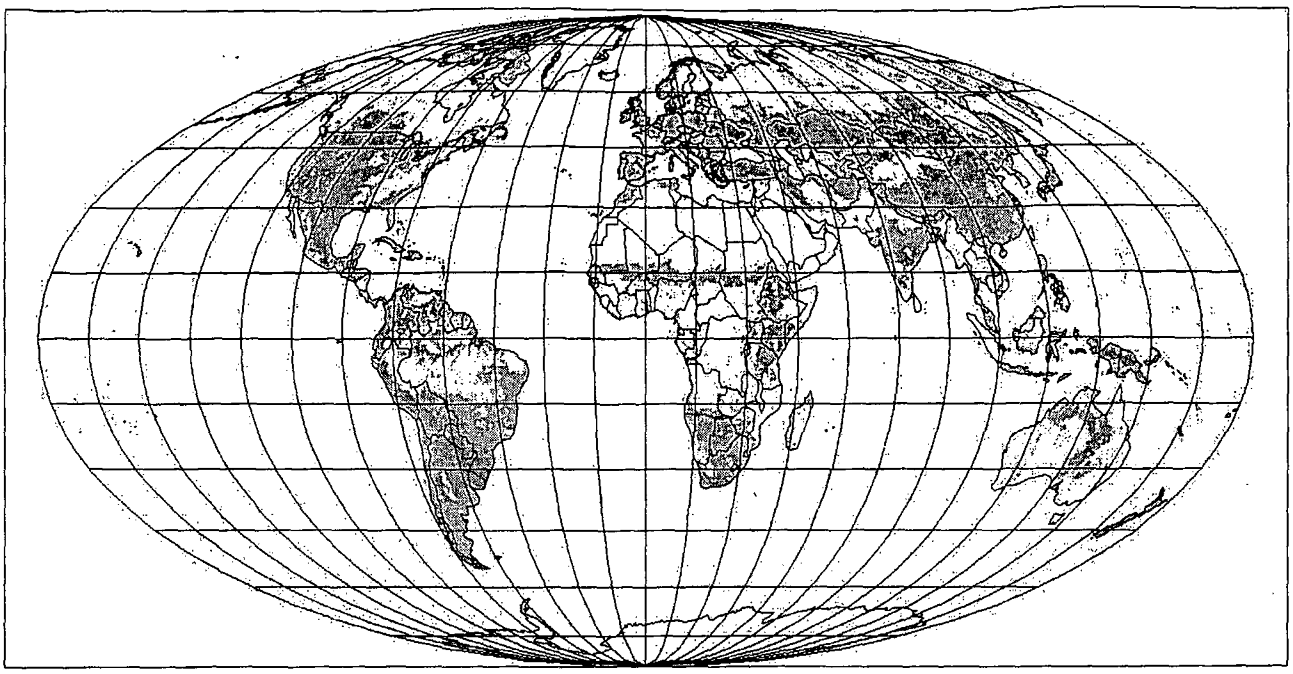


Figure 5.21. Potential animal food delivery to final consumers in 2050 scenario, for the fraction of animals grazing on rangeland, expressed by annual energy content (scale given in Figure 5.11d).

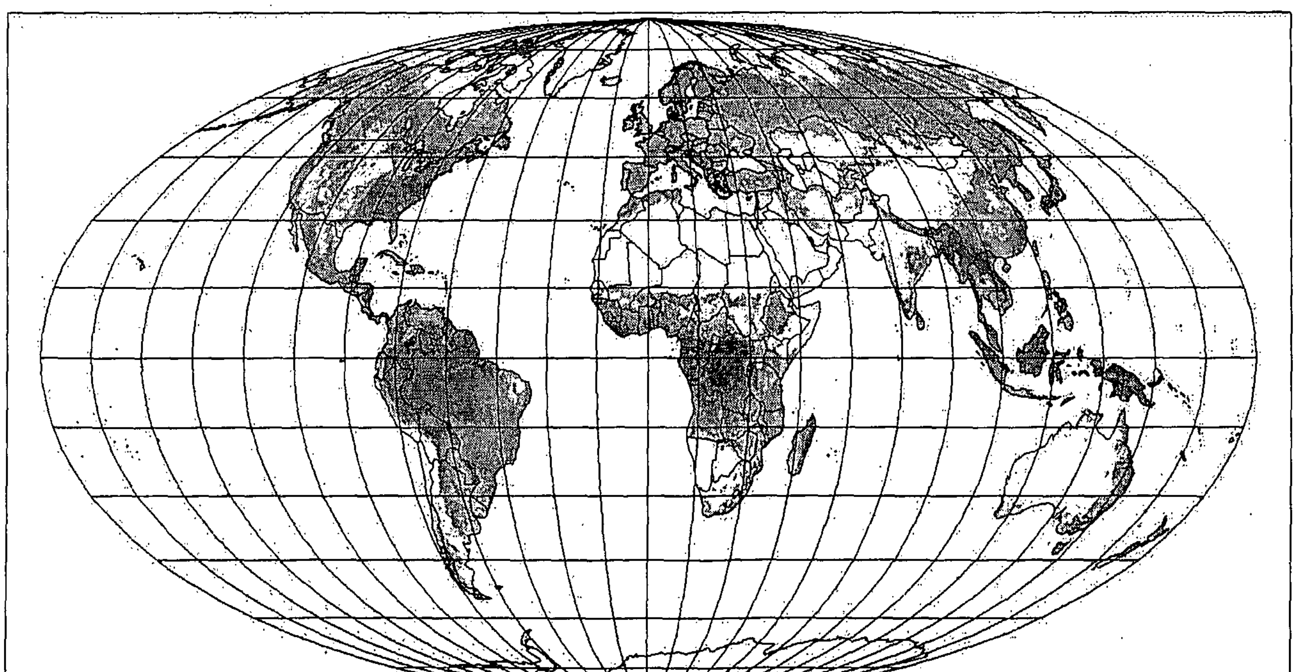


Figure 5.22. Potential biofuels produced and delivered to final consumers in 2050 scenario, from use of forestry residues and wood waste, expressed by annual energy content (scale given in Figure 5.11d).

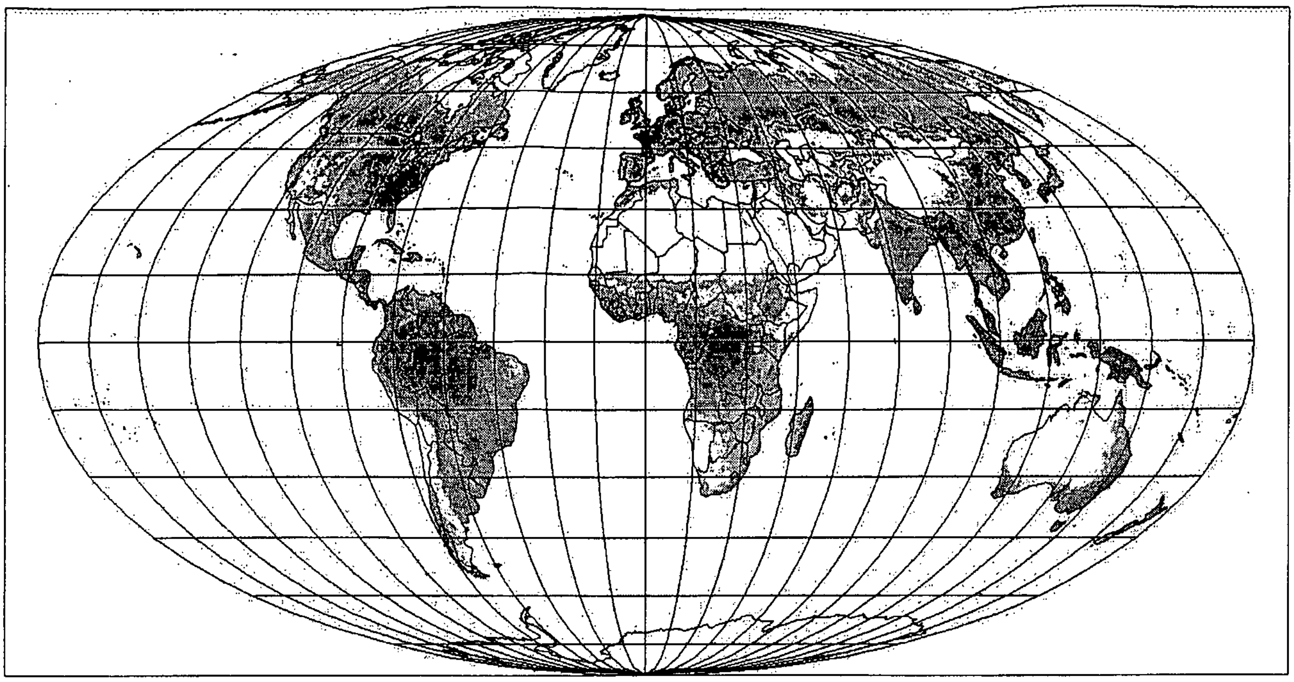


Figure 5.23. Potential delivery of biofuels to final consumers in 2050 scenario, from forestry (cf. Figure 5.22) and from agricultural residues, manure and waste from households and food industry, expressed by annual energy content (scale given in Figure 5.11d).

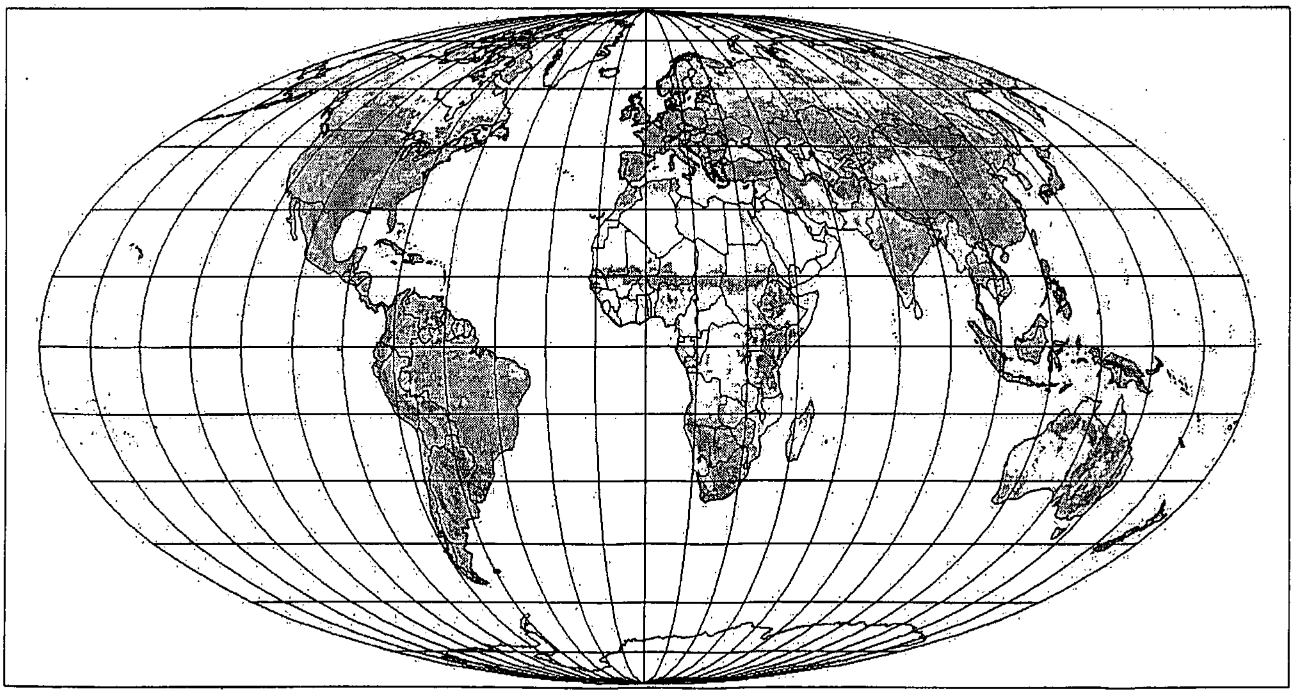


Figure 5.24. Potential delivery of biofuels to final consumers in 2050 scenario, from centralised production, i.e. special energy crops grown on part of rangeland and minor parts of cropland, expressed by annual energy content (scale given in Figure 5.11d).

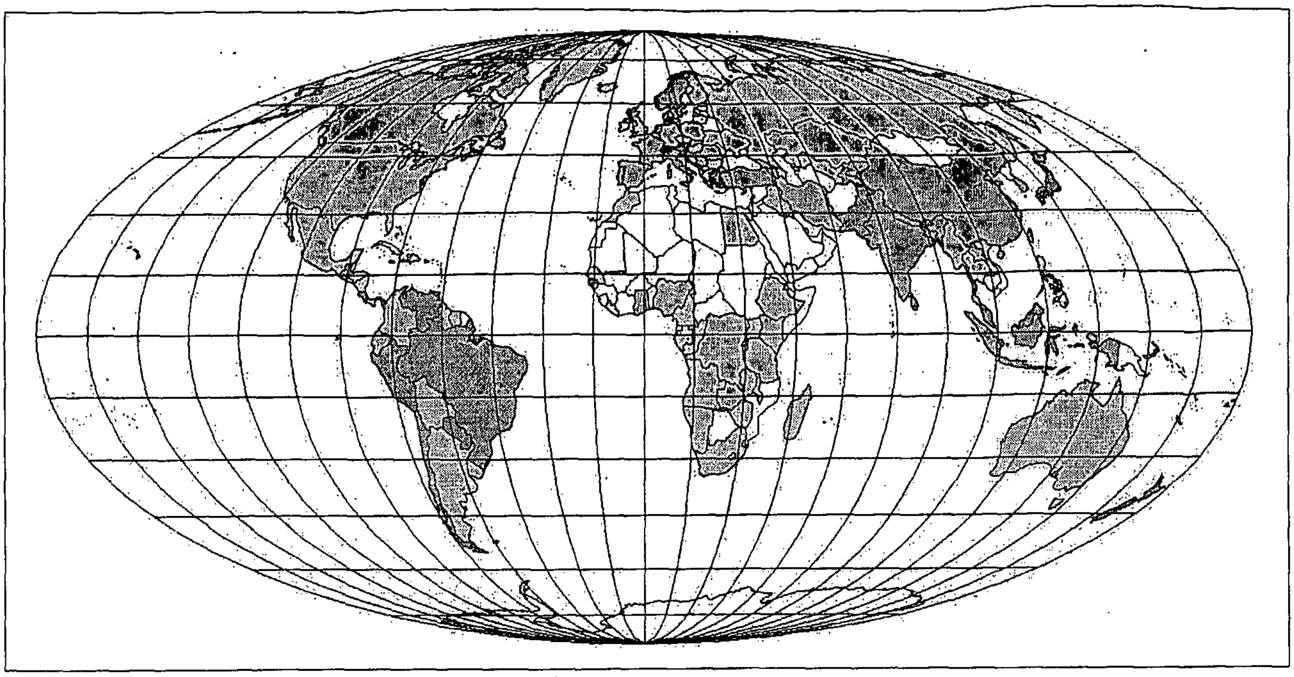


Figure 5.25. Potential delivery of hydropower to final consumers in 2050 scenario (scale given in Figure 5.11d).

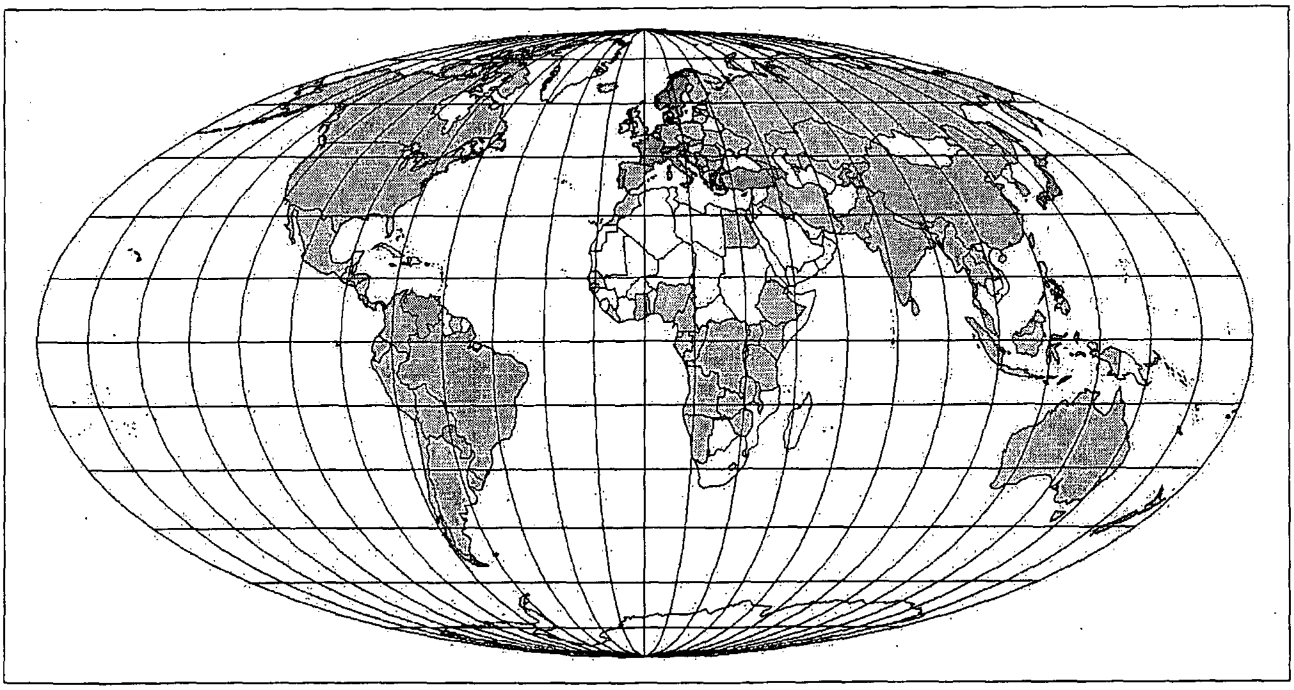


Figure 5.26. Annual average production of hydropower at existing hydropower plants plus estimated production from plants under construction (scale given in Figure 5.11d).

The further possibility of producing biofuels from forestry residues (either scrap derived from the wood industry or residues collected as part of forest management) may be described by a factor *CF(forestry)* = 0.3, defined as a percentage of the total forest biomass production. This is the fraction collected, expressed in energy units. For managed forests it depends on the fraction of wood being suitable for the wood manufacturing industry (furniture etc.), which again depends on the tree type. Adding wood scrap from industry and discarded wooden items, as well as from forest management would in many regions exceed 30%. However, as the basis is an enumeration of all forests including the rainforests and other preservation-worthy forest areas that are not suggested to be touched, and considering only managed forests that deliver to wood industries, 30% is probably a maximum for year 2050. The forest residue to biofuel route is then

Biofuels from forest management =

$$AF(forestland) \times PP[W/m2] \times HF \times UF(fodder) \times CF(forestry) \times FE$$

The potential amounts of biofuels that could be derived from forestry are shown in Fig. 5.22, and the sum of the three routes to biofuels described above are given on an area bases in Fig. 5.23. This is denoted "decentralised fuel production", although forestry may not be seen as entirely decentral in nature. However, it is an ongoing activity and distinct from producing biofuels from land used exclusively for energy crops. Two energy crop routes are included:

While the biomass production on rangeland does not give rise to biofuel production because manure from grazing livestock is not collected, some of the rangeland may be suited for cultivation of dedicated energy crops. As only 50% has been assumed used for grazing, the remaining 50% shall be regarded as potentially exploitable for energy purposes, in the scenario versions where centralised energy schemes are found acceptable (i.e. *UF(rangeland energy crops)*=0.5). On cropland it is further assumed that 10% may be set aside for energy crops in areas of generous resources, such as Western Europe and the Americas (see the *UF(cropland energy crops)* values of 0.1 or 0 in Table 5.3). The potential biofuel production from these areas is

Biofuels from energy crops on cropland =

$$AF(cropl.) \times PP[W/m2] \times AE \times HF \times UF(cropland\ energy\ crops) \times FE,$$

Biofuels from energy crops on rangeland =

$$AF(rangeland) \times PP[W/m2] \times HF \times UF(rangeland\ energy\ crops) \times IE(anim.\ prod.).$$

The area distribution of these two potential sources of biofuels from energy crops is shown in Fig. 5.24, with regional sums in Table 5.2.

5.2.5 Hydro power

For hydro power, which in the past has often been used in a way not compatible with environmental considerations (flooding areas of high landscape value, dislocating people, etc.), it is here considered that it is a renewable energy source worthy of inclusion in a sustainable scenario, provided that it is used with proper considerations. These include modular construction of large plants (cascading the water) allowing a highly reduced disturbed area, and planned location of reservoirs in locations where there is little conflict with preservation concerns, even if the water transport layout may become more complex and expensive. The 2050 scenario includes all existing plants and plants under construction (because attempts to close plants and revert to pre-hydro landscapes have proved to entail negative environmental effects quite similar to the original change in the opposite direction, due to the already completed adaptation of flora and fauna to the changed conditions). Also included are small-scale hydro installations planned in several countries, considering the impacts to be acceptable for most schemes. As regards total potentials identified and actual schemes proposed but not started, a modest inclusion is made of only those for which actual proposals including environmental statements exist. As a source for such appraisals of the potential hydro generation we have used a survey made by the World Energy Council (1995). Including all their categories would roughly double the current hydro power generation. Figure 5.25 show the distribution of this potential power generation on countries. A large fraction of the installations are or will be reservoir-based, so no additional storage cycle is considered necessary (although pumped hydro would be an obvious option). Figure 5.26 shows the average generation from existing hydro plants plus those under construction, again averaged over country areas.

It is not attempted to show the actual reservoir areas on the maps. They simply spreads the power production evenly over each country. In any case most hydro is a centralised resource, that is not (and largely cannot be) used by the local population. The regional sums in Table 5.2 show that South America is the most endowed region, implying that the utilisation choices made in this region will be decisive.

5.3 MATCHING SUPPLY AND DEMAND

The construction described above has made available a demand scenario for the year 2050, and estimates of potential renewable energy generation for the same period of time, divided into decentralised and centralised supply. Both are on a geographical basis. The next task is to match supply and demand, adding new system components if necessary, e.g. when the energy form supplied is not that demanded, and pointing out requirements for energy imports and exports, when the location of supply and of demand is not the same. In practice the form of transport will depend on the type of energy (electricity transmission, gas piping, heat in district lines, or fuels to be moved e.g. by vehicle or ship). Also temporal mismatch can be identified, and energy storage requirements determined. In many cases, there is already incorporated some storage cycle in the supply estimates, notably for those renewable energy sources where the source variability already indicated a storage need. The supply-demand matching will first be performed using only those amounts of renewable energy that are estimated to be available locally, in a decentralised form (as pointed out in the resource appraisal of section 5.2), and then look at possible advantages of including also centralised production.

5.3.1 Decentralised renewable energy 2050 scenario

The demand categories have already, as shown in Table 2.6, been simplified under the assumption of an abundant fraction of the supply being in the form of electric energy. We now determine the sources of supply for each demand type.

For the vegetable food-fraction, the results of comparing local supply and demand are shown in Figs. 5.27 and 5.28, where Figure 5.27 shows the amount of surplus for those geographical grid cells, where supply exceeds demand, and Figure 5.28 shows the amount of deficit for those local cells where demand exceeds supply. Regional sums are given in Table 5.4, while the sums of individual contributions to demand and supply are given in Tables 2.6 and 5.2. It follows that on average, worldwide supply exceeds demand by 35%. This must be considered reasonable, as there has to be room for variations in crop harvests and thus food production from year to year, and further the transportation required for evening out supply and demand will entail some additional losses. As today, there is surplus vegetable food production in the Americas and Western Europe (regions 1, 2 and 4), and by year 2050 also in region 3 (including Russia), due to substantial improvements in agricultural practices assumed for this region. Region 5 (including China and India) will be just self-sufficient by year 2050, whereas Africa (region 6) will have a deficit that must be covered by imports. In the scenario, Africa is the only region that by 2050 is in a development situation where it may offer labour at lower expense that the other regions, and thus there will be the possibility of paying for food imports by industrial revenues, provided that an education policy is pursued, that will give the working force the necessary skills. In addition to inter-regional exchange, Fig. 5.27 and 5.28 indicate scenario requirements for transport of vegetable food within regions, especially from farming areas into cities. The scenario assumptions for inter-regional trade in food are indicated in Figs. 5.44-5.49, where the regional exports have been selected from the surpluses available. The substantial needs for both vegetable and animal foods in Africa are uniformly imported from regions 1-4.

For animal-based food from either rangeland or fodder-fed animals, the surpluses and deficits are shown in Figs. 5.29 and 5.30. The picture is similar to that of vegetable foods, with surpluses in the first 4 regions, but here with deficits in both region 5 and 6. This is due to the increase in the meat and milk fractions of diets assumed for Asia (Table 2.6), but the amounts are easily covered by imports from other regions, as indicated in Figs. 5.44-5.49. Overall, the animal food supply exceeds demand by 27%, which again is considered adequate, e.g. in view of additional transportation losses. Here variations between years are smaller than for primary crops (because of the storage functions performed by livestock), but fairly frequent epidemics of animal disease are known to require a reserve.

Figures 5.31 and 5.32 show the surplus and deficit of potential liquid biofuels derived from agriculture and silviculture, relative to the energy demand for transportation. The assumed fraction of biofuels used in this way is 48.5% (chosen such that the global average demand is covered), the remaining is considered going into industrial uses such as medium-temperature process heat, where it is assumed used with 90% efficiency. When constructing the demand scenario, it was left open to which extent electric vehicles would be used, but the availability of liquid biofuels is such, that they could cover all transportation needs (with methanol use in fuel cells determining the assumed conversion efficiency). However, the regional supply-demand situation is such, that substantial energy imports into region 5 are necessary. As will be seen below, this requires that as much energy trade as possible is based on biofuels, and hence dictates a large electricity use in the transportation sector of the exporting regions.

The deficits in Fig. 5.32 are in urban areas and areas without biomass growth (e.g. Andes and Saudi Arabia), and in large parts of India. On average globally surplus and deficit balance, as seen from Table 5.4 or by comparing Tables 2.6 and 48.5% of the potential biofuel from decentralised sources estimate given in Table 5.2. There is surplus only in South America and Africa, while the numbers for North America balance, those for region 3 almost balance (and are remedied in the scenario shown in Fig. 5.46 by increasing the fraction going into the transportation sector), whereas region 5 (including China and India) has a deficit of some 65%. The high production value for South America is related to the high forest productivity,

and one may consider part of this as difficult to realise, without imposing on (what should be) preservation areas. However, as will be seen, exports from South America of biofuels to the lacking regions in Asia are essential. Other areas of the model, such as regions 2 and 3 which also have average deficits, would have to import from regions 1 and 4; albeit on a smaller scale. As explained below, the actual scenario will not use the 48.5/51.5 % split of the biofuel use, notably because electric vehicles take over some of the transportation demand.

The remaining energy produced is in the form of electricity. Figs. 5.33-5.42 show surplus and deficit, for each of the four seasons and as an average, in produced electricity plus the 51.5% of biofuels that in the initial assessment is not used by the transportation sector, relative to demand for electricity and all other energy not covered above. The regional summaries are given in Table 5.4. Although annual totals are in balance, there are very large mismatches both on a spatial and temporal scale. Consistent surpluses of electricity production occur in the Americas and Africa, and large, consistent deficits in region 5 (notably India and China). Western Europe exhibits small deficits, and region 3 strong seasonal variations, adding up to a substantial annual surplus. The reason is seen from Table 5.2 to be the variation in wind power production, which it ten times higher in January than in April. This is true for the year 1997, from which wind data were taken, but variations between years are large, implying considerable instability of power supply in region 3. A reason is that continental winds in the Eurasian continent are less persistent than West European coastal ones. The implication of the low wind power production in April in region 3 is that there is a substantial global deficit of power, affecting mostly region 5, which might have depended on imports from region 3.

Both the Figures and Table 5.4 shows, that the large exchange of decentralised power that would solve the global mismatch problem would have to be from North and South America and Africa to South-East Asia. This is a little feasible proposition, unless a global, superconducting transmission grid would be established before year 2050. It would also appear that this level of inter-continental exchange is contrary to the idea of mainly local supply underlying the decentralised scenario. In the following subsection, it will be investigated to which extent an easement of the uneven supply situation can be expected, if also a certain amount of centralised renewable energy production is permitted.

In constructing the actual scenario, the first aim is to make as much biofuels available for export to region 5 as possible, because fuels can easily be transported over long distances (by ship), in contrast to electricity, where it is assumed that neither conventional nor superconducting transmission will by 2050 be feasible for distances as long as from South America to India or China. The regional scenario details shown in Figs. 5.44-5.49 indicate the assumed regional shift in biofuel and electricity use, that allows larger amounts of biofuels to be exported to region 5. Basically, electricity is allowed to enter the transportation sector through electric vehicles used for all urban transport as well as track-based regional transport, except for region 5, which has to use the biofuels imported. As even the necessary electricity demand in region 5 is larger than what can be produced locally, the decentralised scenario can only be realised if there is enough biomass (after imports) in region 5 to allow the missing electricity to be generated from biofuels. Since there is a loss in converting fuels to electricity, and since there was just enough biofuels available globally before redistribution, according to the assumptions of the decentralised scenario, this simply cannot be done. A solution would be to relax the assumptions restricting the decentralised energy production, or alternatively to introduce a little centralised energy.

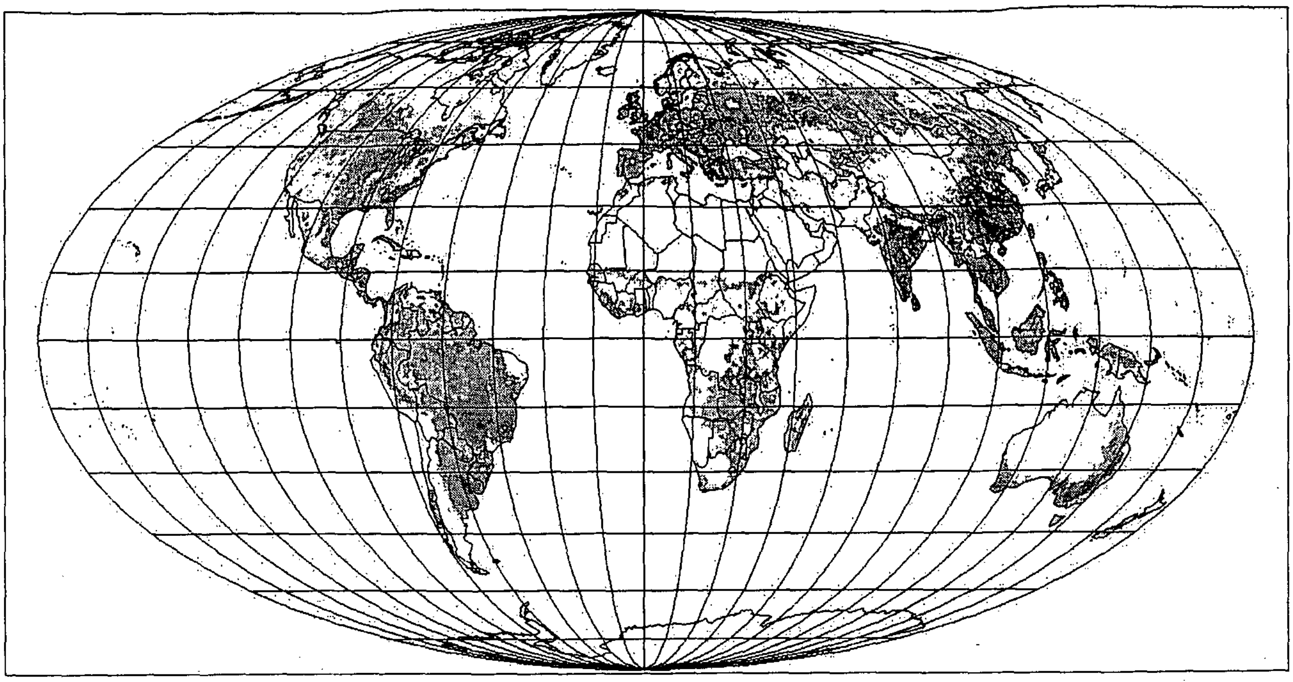


Figure 5.27. Local surplus of vegetable food supply over demand on an area basis, valid for both decentralised and centralised 2050 scenario. (annual average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

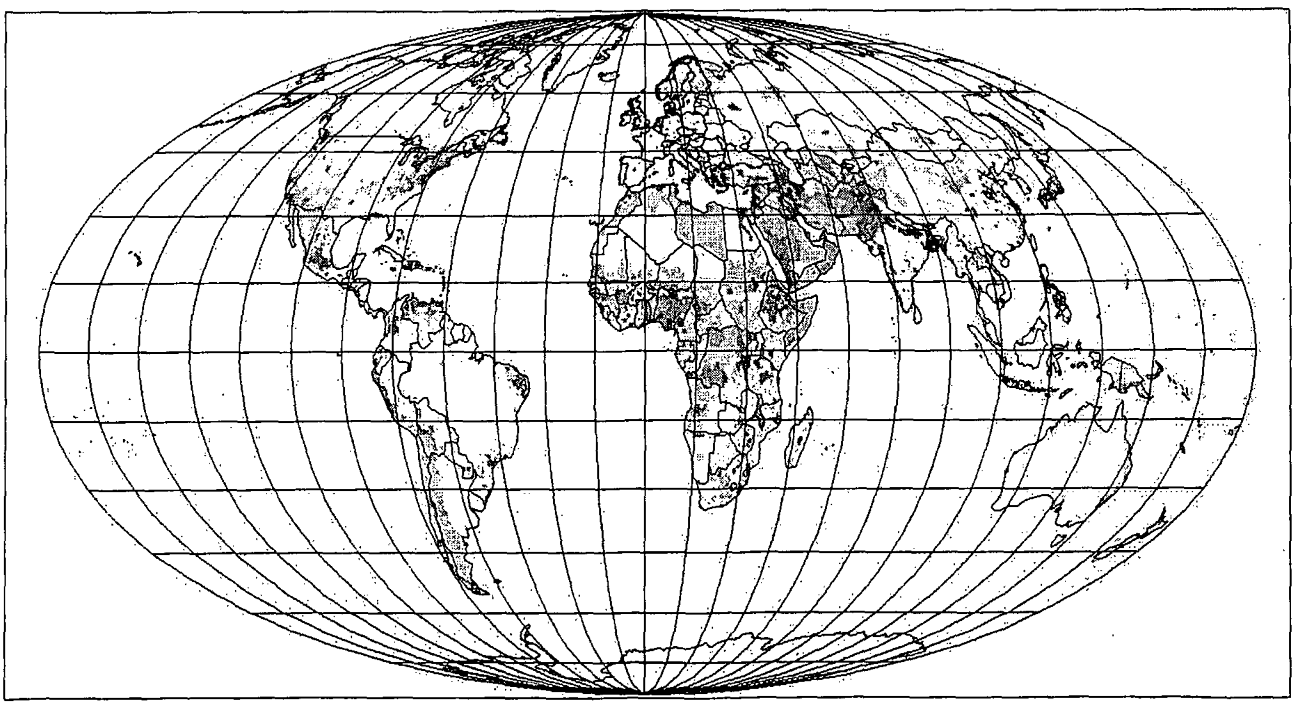


Figure 5.28a. Local deficit of vegetable food supply relative to demand on an area basis, valid for both decentralised and centralised 2050 scenario. (annual average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

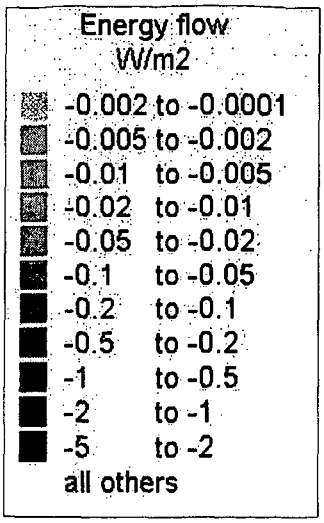


Figure 5.28b. Scale of negative energy flows (such as deficit in rate of supply relative to demand; note that scale is logarithmic and similar to scale of positive energy flows shown in Figure 5.11d; unit: W/m^2).

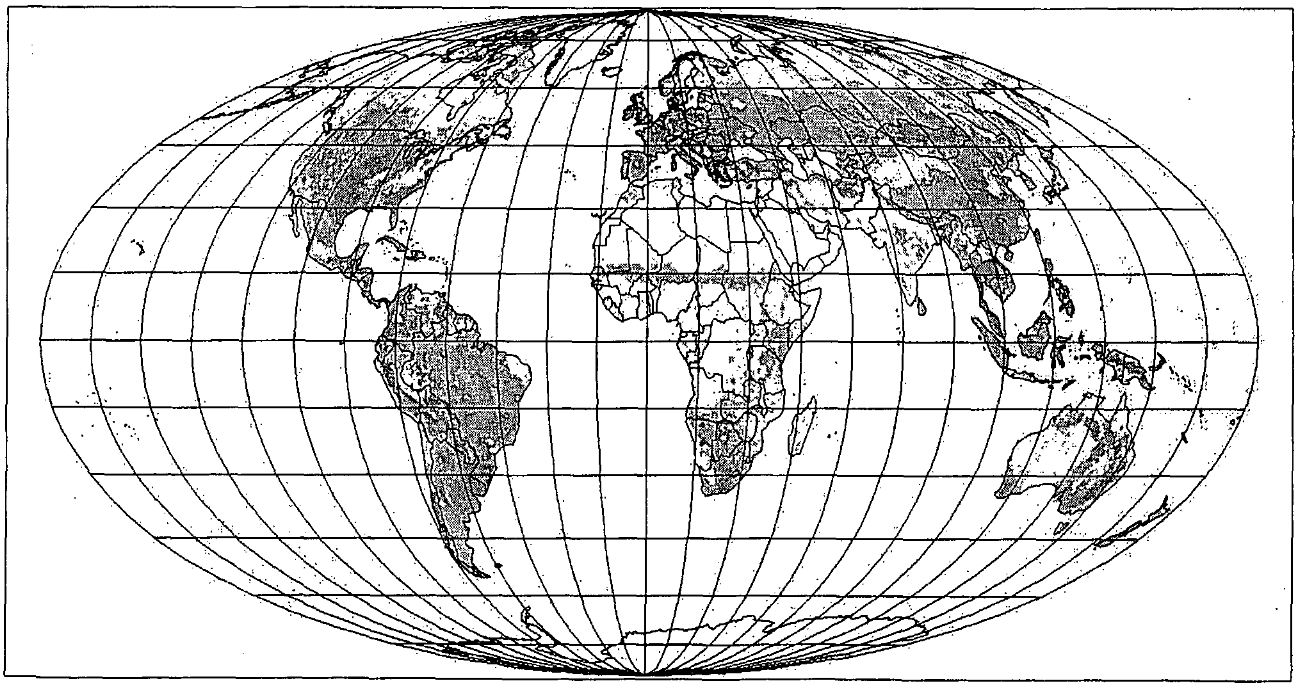


Figure 5.29. Local surplus of animal-based food supply over demand on an area basis, valid for both decentralised and centralised 2050 scenario. (annual average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

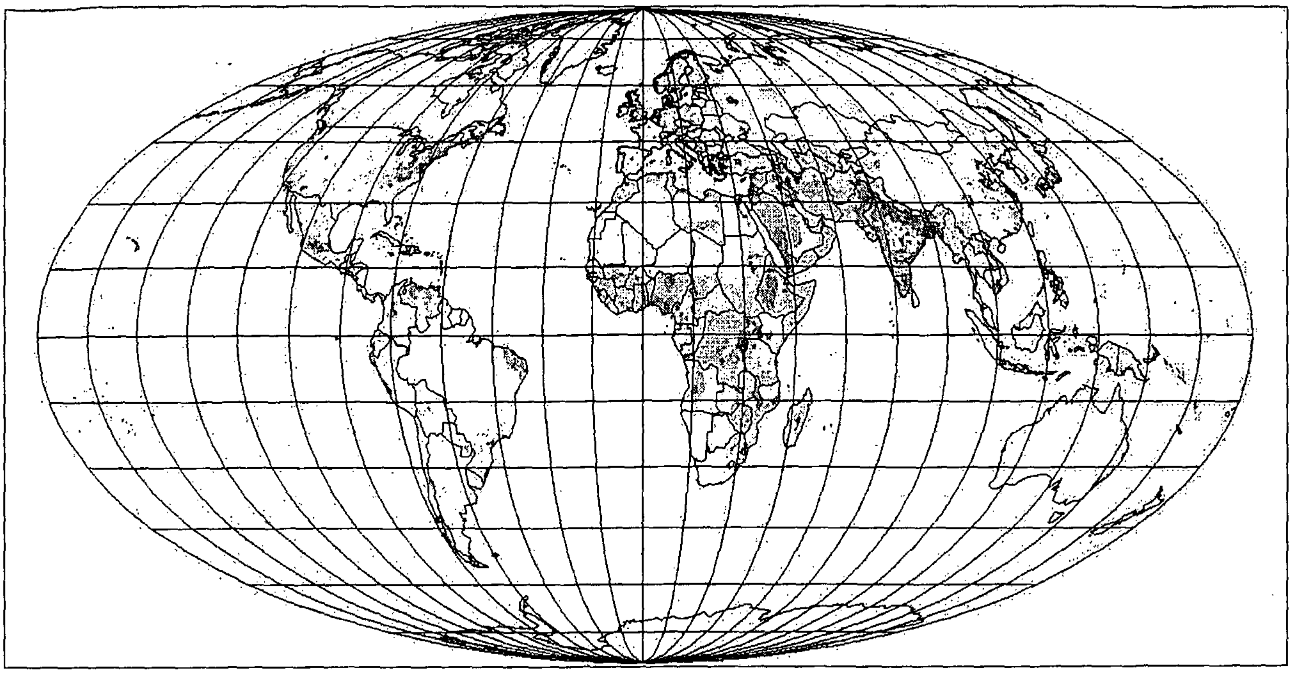


Figure 5.30. Local deficit of animal-based food supply relative to demand on an area basis, valid for both decentralised and centralised 2050 scenario. (annual average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

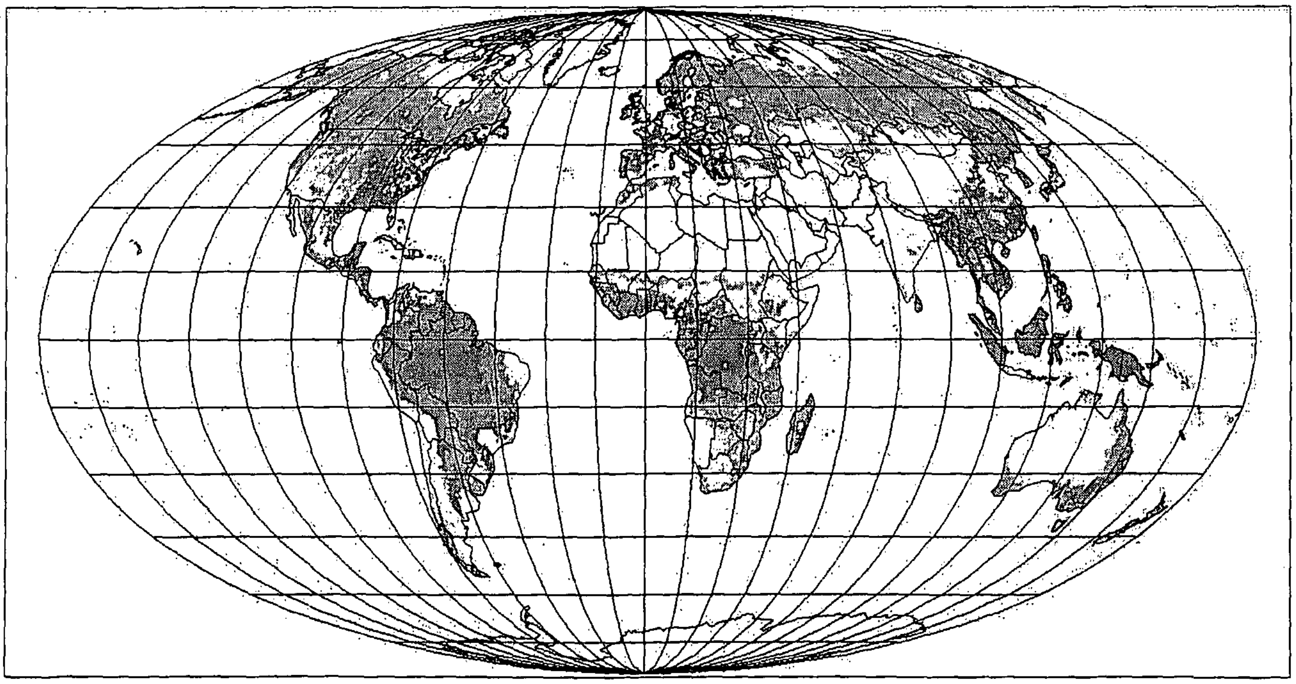


Figure 5.31. Local surplus of biofuel supplies (such as methanol) over demand for transportation fuels on an area basis, according to the decentralised 2050 scenario. (annual average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

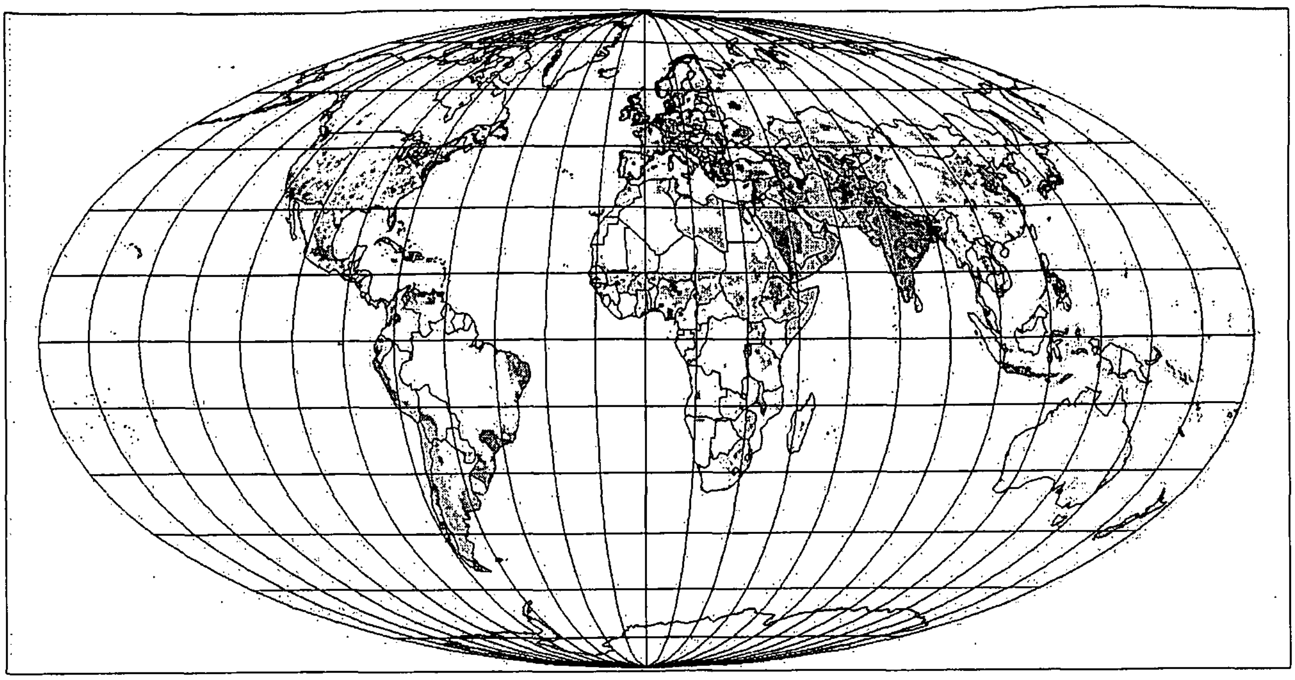


Figure 5.32. Local deficit of biofuel supplies (such as methanol) relative to demand for transportation fuels on an area basis, according to the decentralised 2050 scenario. (annual average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

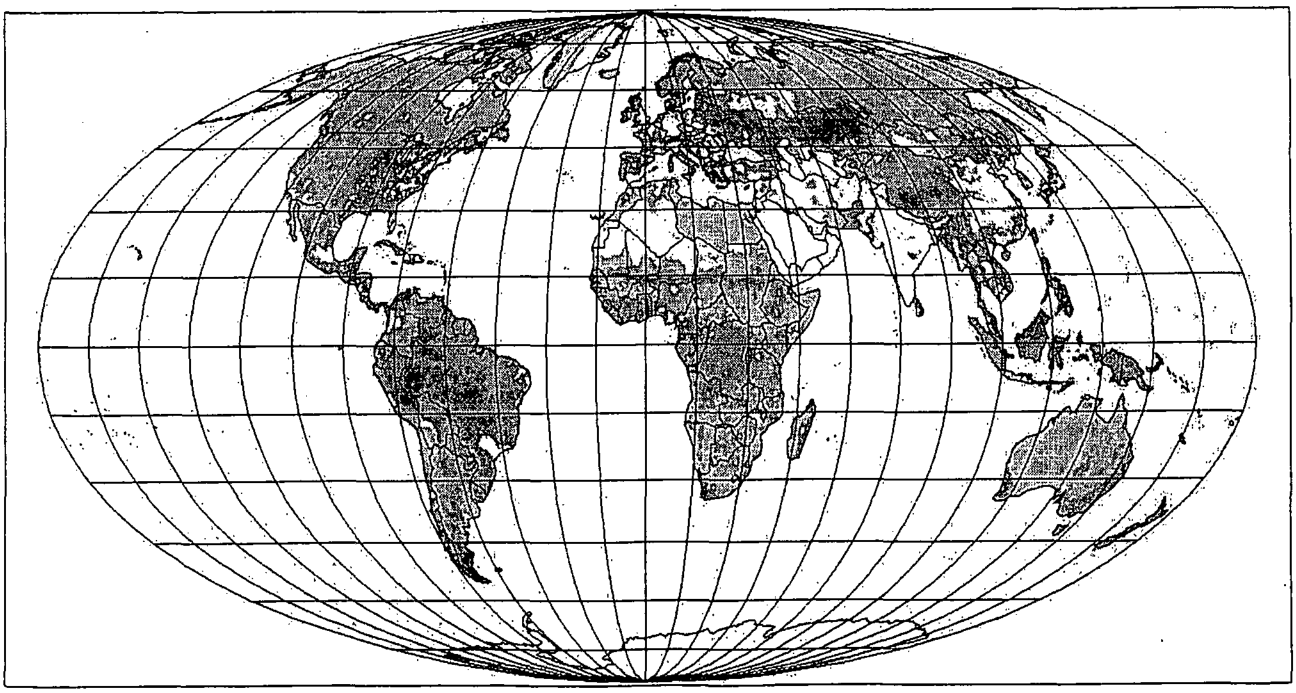


Figure 5.33. January local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

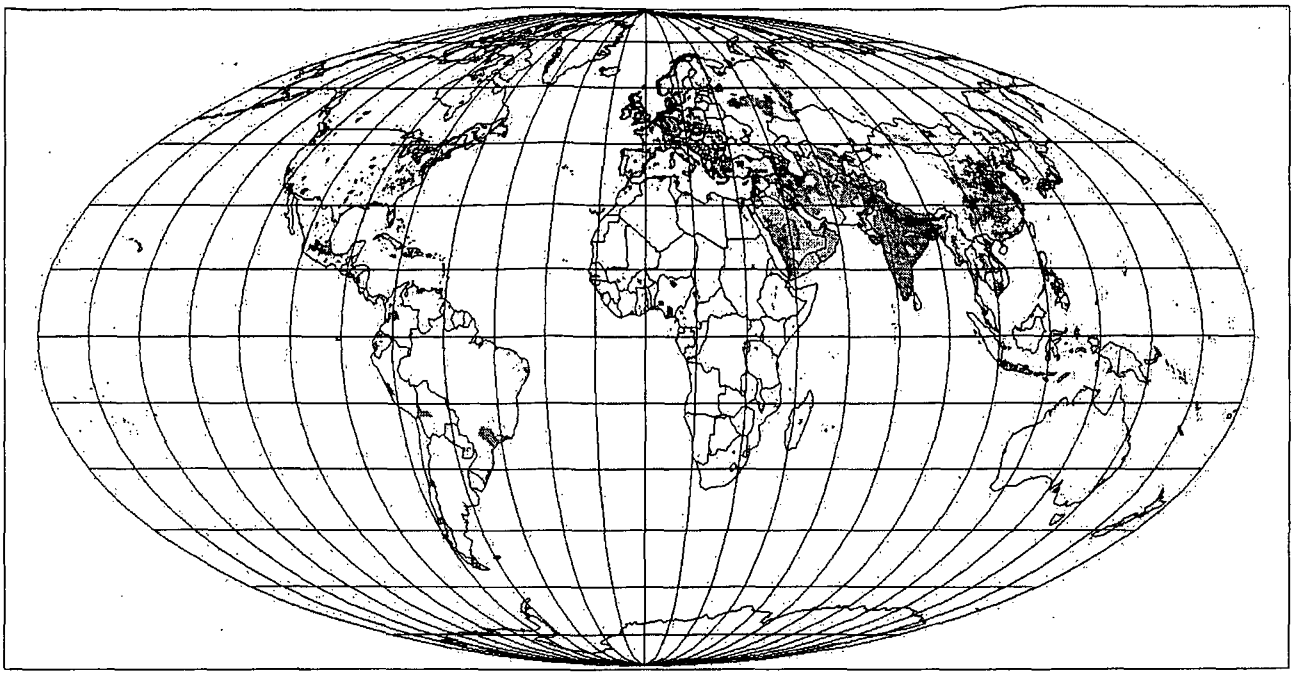


Figure 5.34. January local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

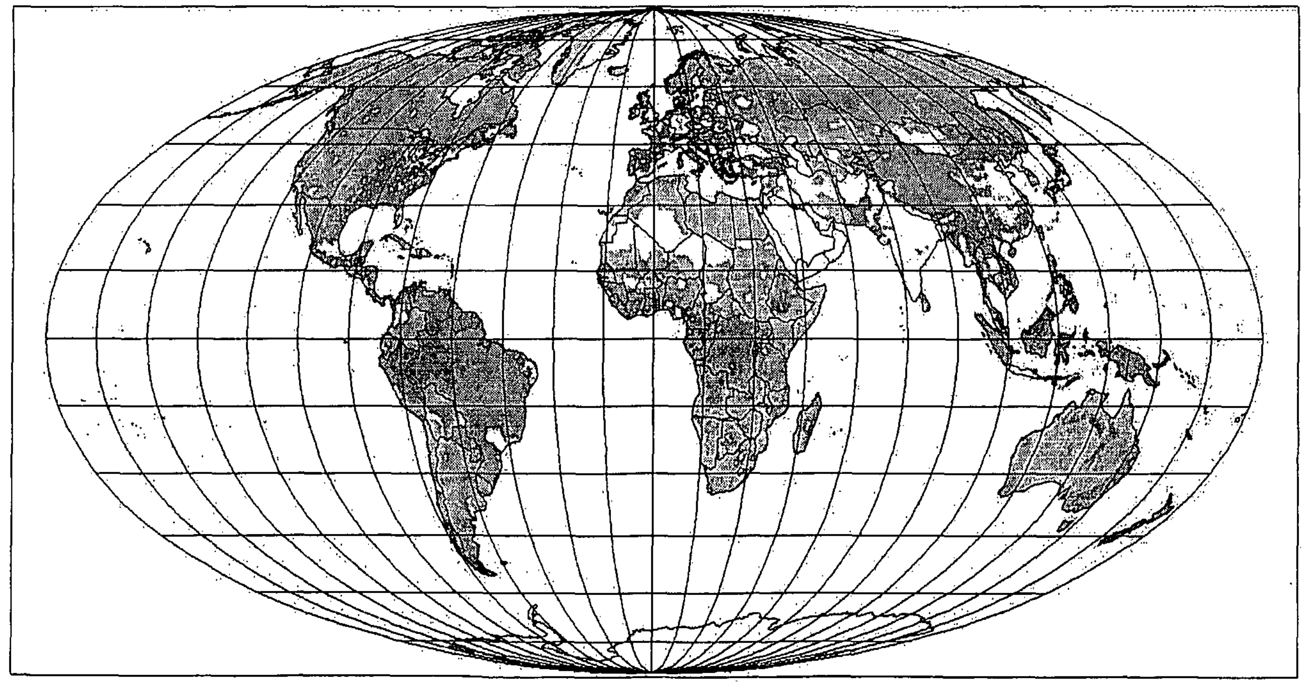


Figure 5.35. April local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

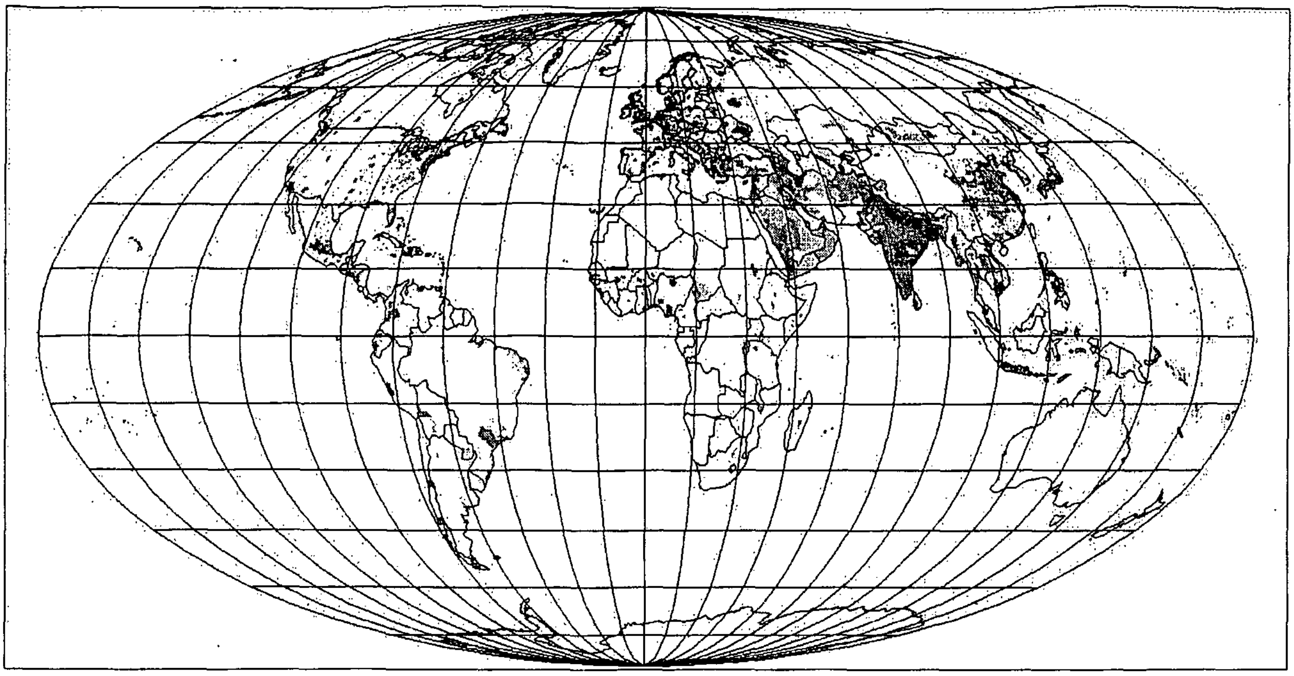


Figure 5.36. April local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

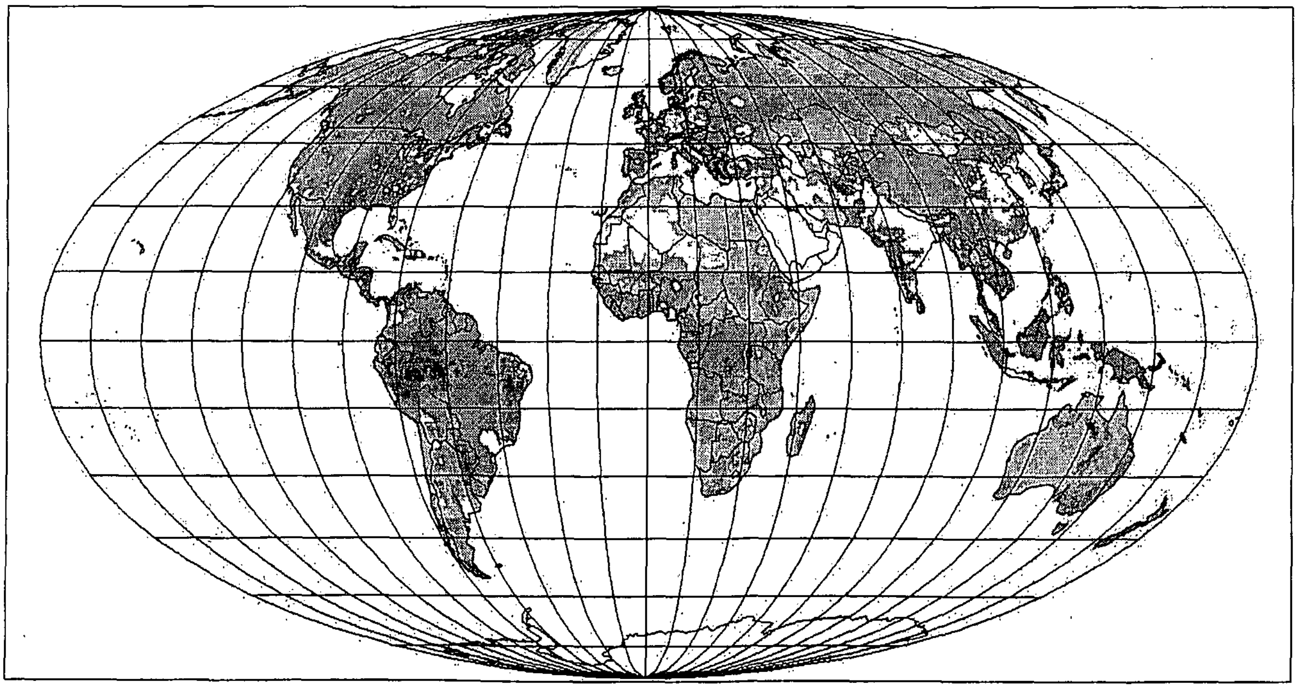


Figure 5.37. July local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

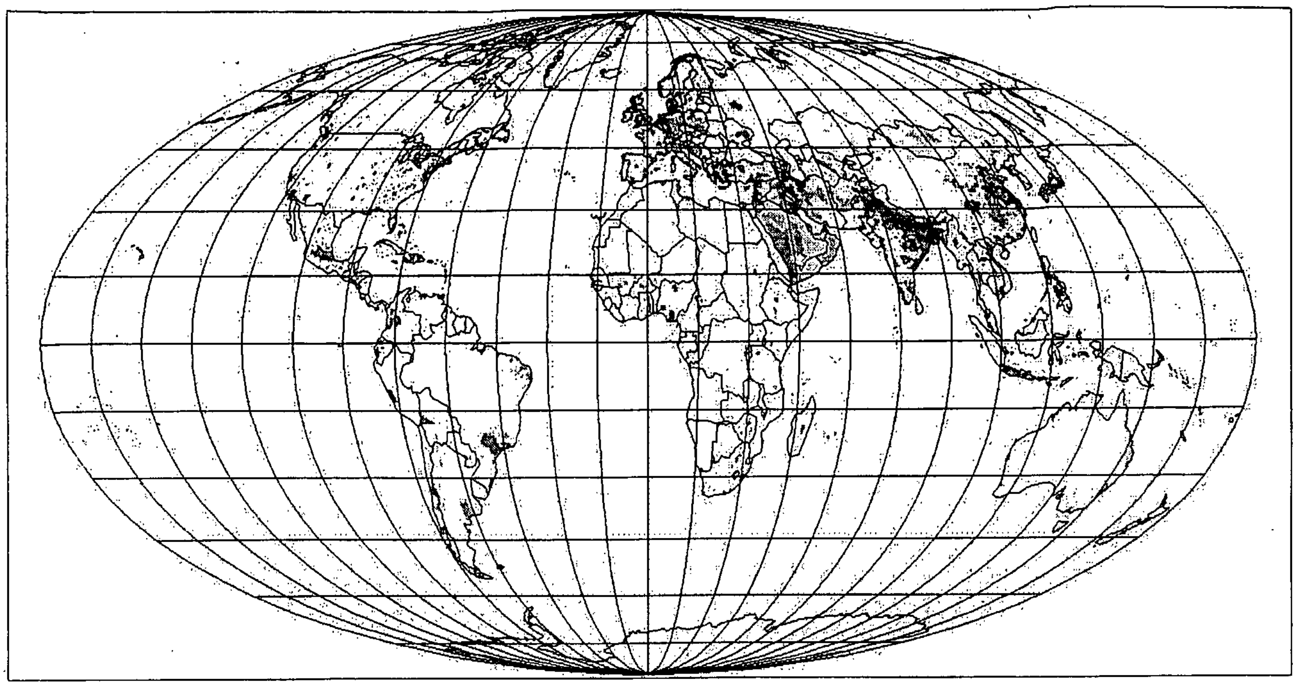


Figure 5.38. July local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

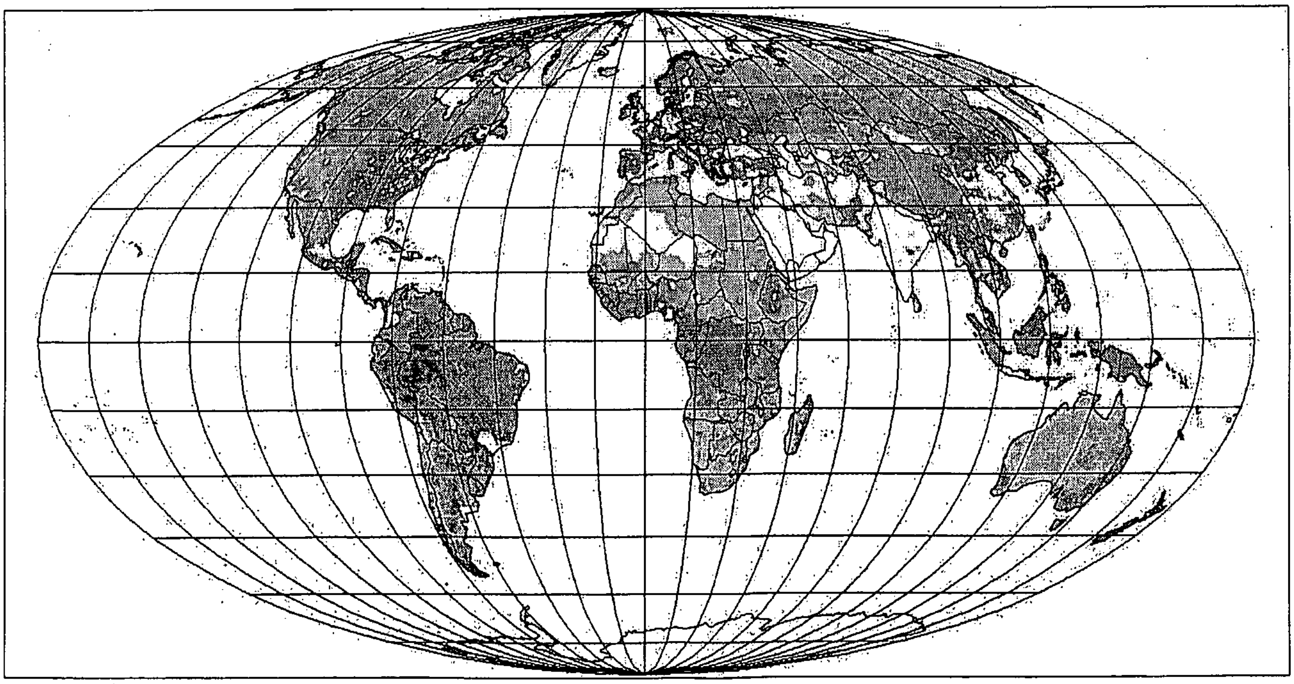


Figure 5.39. October local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

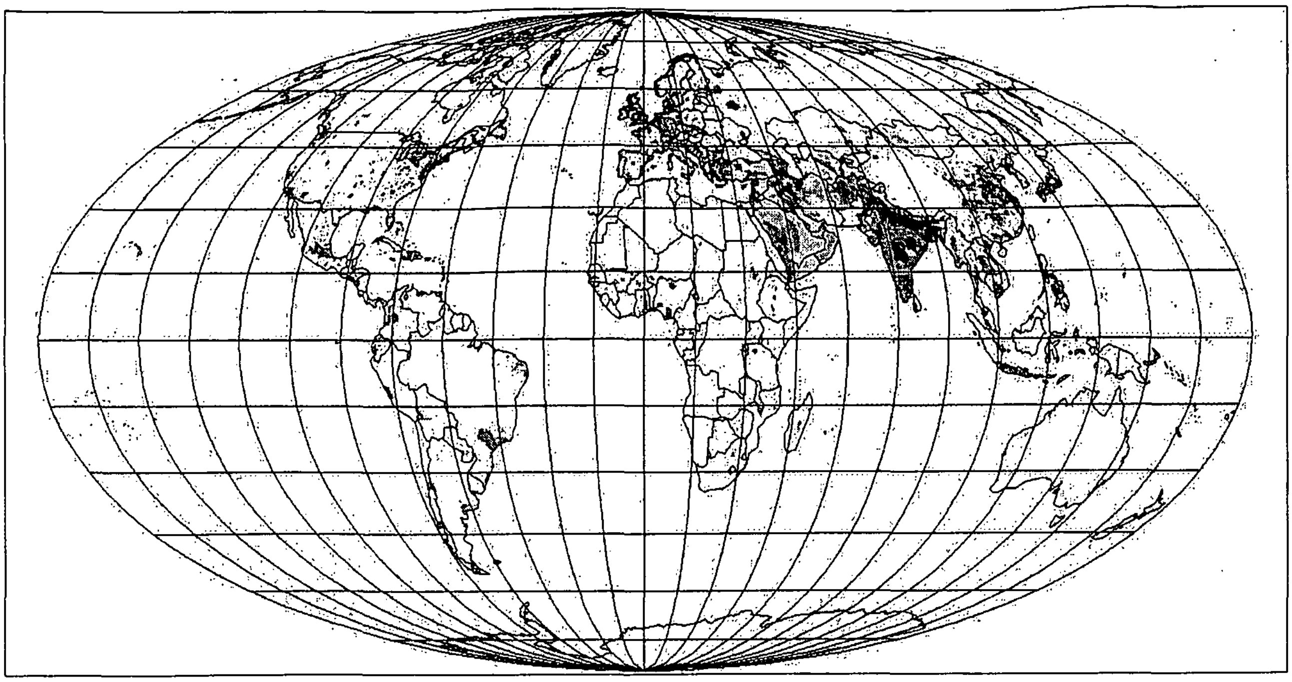


Figure 5.40. October local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

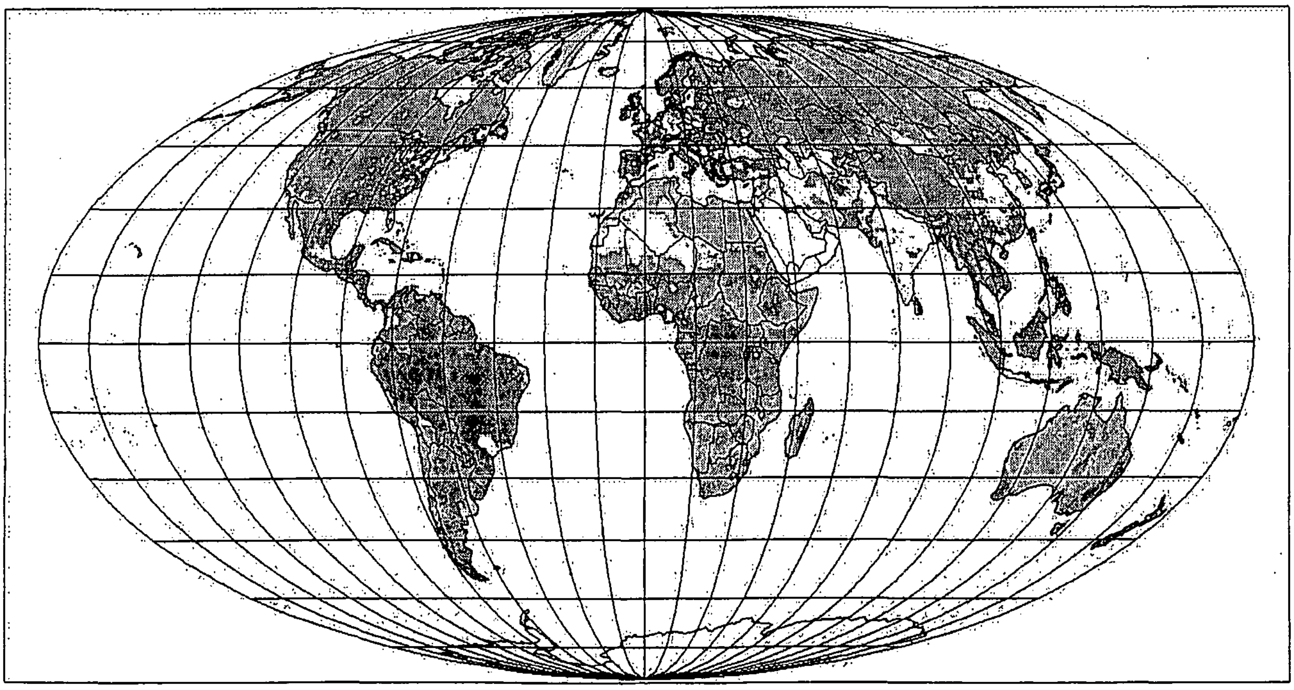


Figure 5.41. Annual average local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

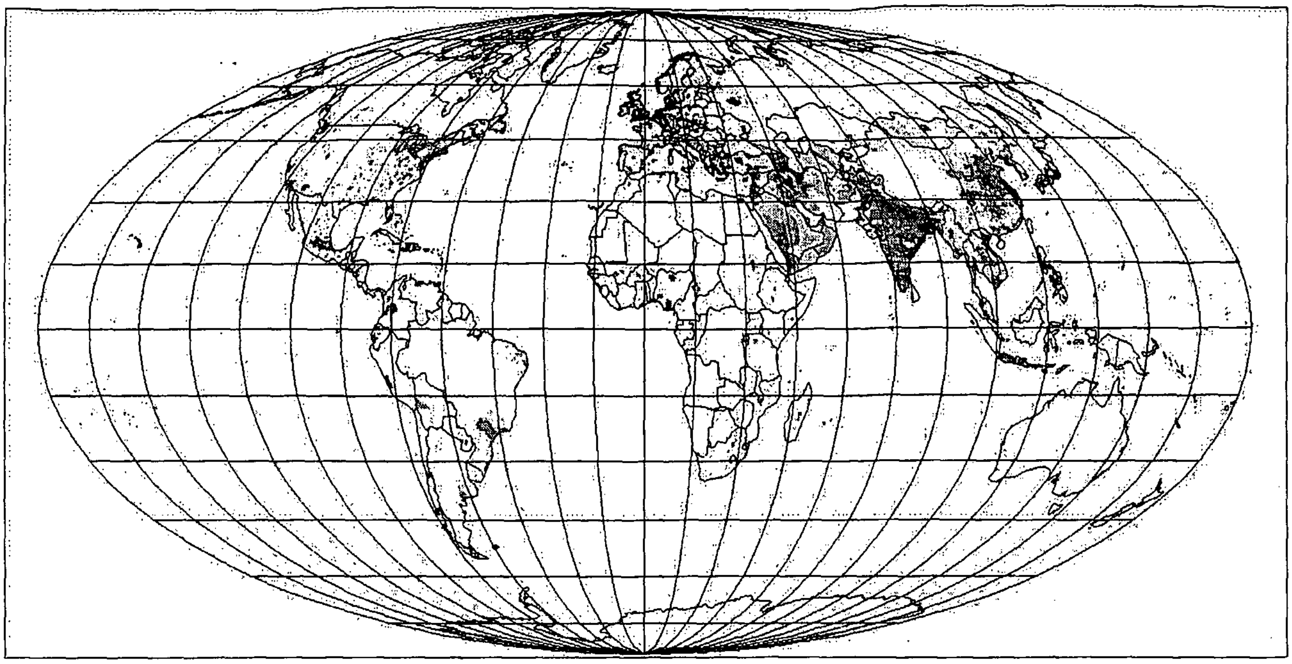


Figure 5.42. Annual average local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the decentralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

The scenario selects the latter option, adding some photovoltaic power production in region 5 not based on building-integrated installations. This is a highly available resource, and there are more than enough areas available to make up for the electricity deficit (see the potential shown in Table 5.2). Still, it does negate the philosophy of all energy being produced locally, but this is probably less unacceptable than the huge imports and exports of fuels, which is necessary in this scenario, and which introduce a dependency on non-local resources difficult to reconcile with the value basis of the decentralised scenario.

Table 5.4. Balance of potential regional supply in decentralised mode, and demand.

Region (cf. Table 2.2)	**1**	**2**	**3**	**4**	**5**	**6**	**Total**	**unit**
Vegetable food	108	113	91	192	40	-140	**402**	GW
Animal food	43	31	16	91	-63	-27	**91**	GW
Transportation (relative to 48.5% of biofuels)	9	-69	-19	202	-230	112	**2**	GW
All other energy, annual av.	123	-14	103	528	-879	201	**72**	GW
All other energy, January	106	-71	297	559	-1000	234	**100**	GW
All other energy, April	101	-3	-16	488	-900	165	**-165**	GW
All other energy, July	155	26	37	577	-750	213	**253**	GW
All other energy, October	129	-8	93	489	-800	191	**98**	GW

"All other" energy supply includes electricity from hydro, solar cells and wind turbines, plus 51.5% of biofuels. "All other" demand comprises electricity for heat pumps supplying heating, cooling and low-temperature heat, medium- and high-temperature energy, stationary mechanical energy, and electricity for appliances and other apparatus, including refrigeration.

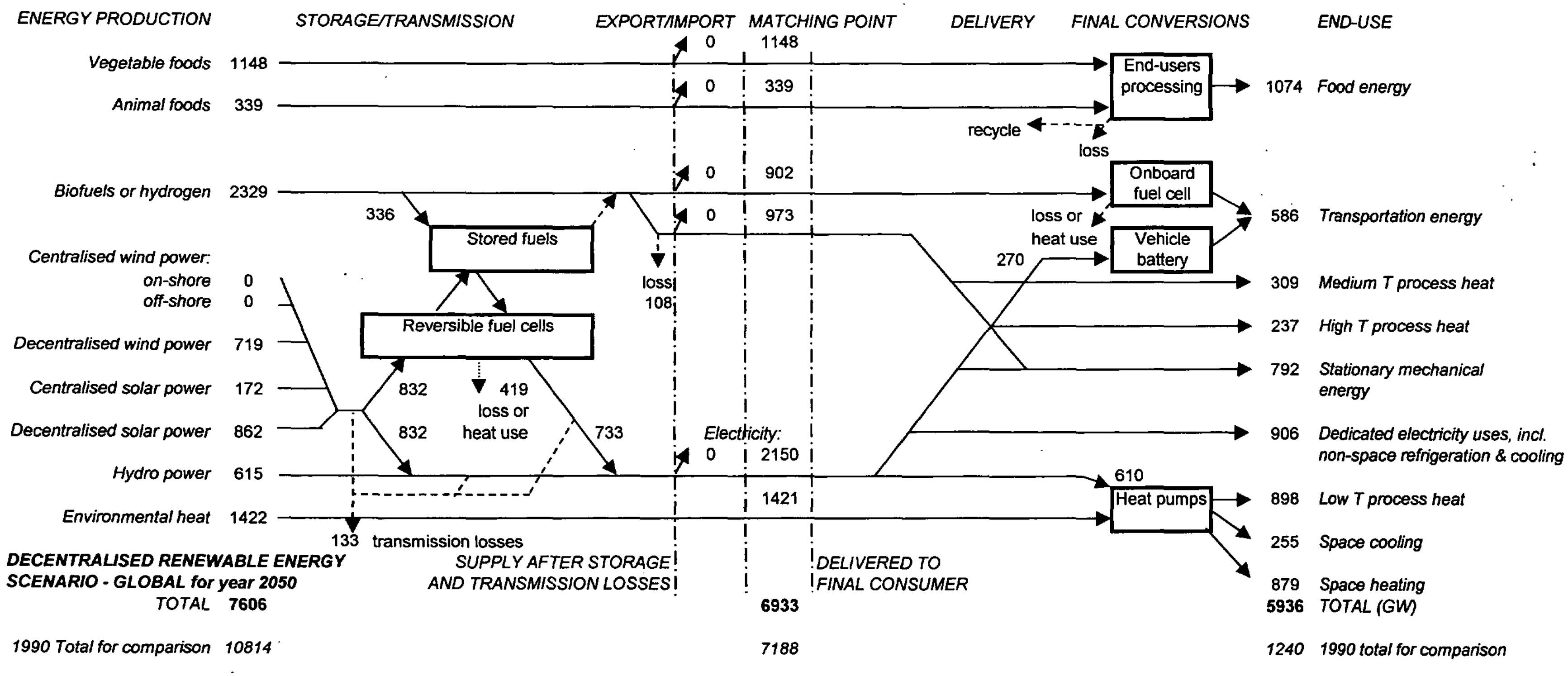


Figure 5.43. Overview of decentralised 2050 scenario (all energy flows in GW or GWy/y).

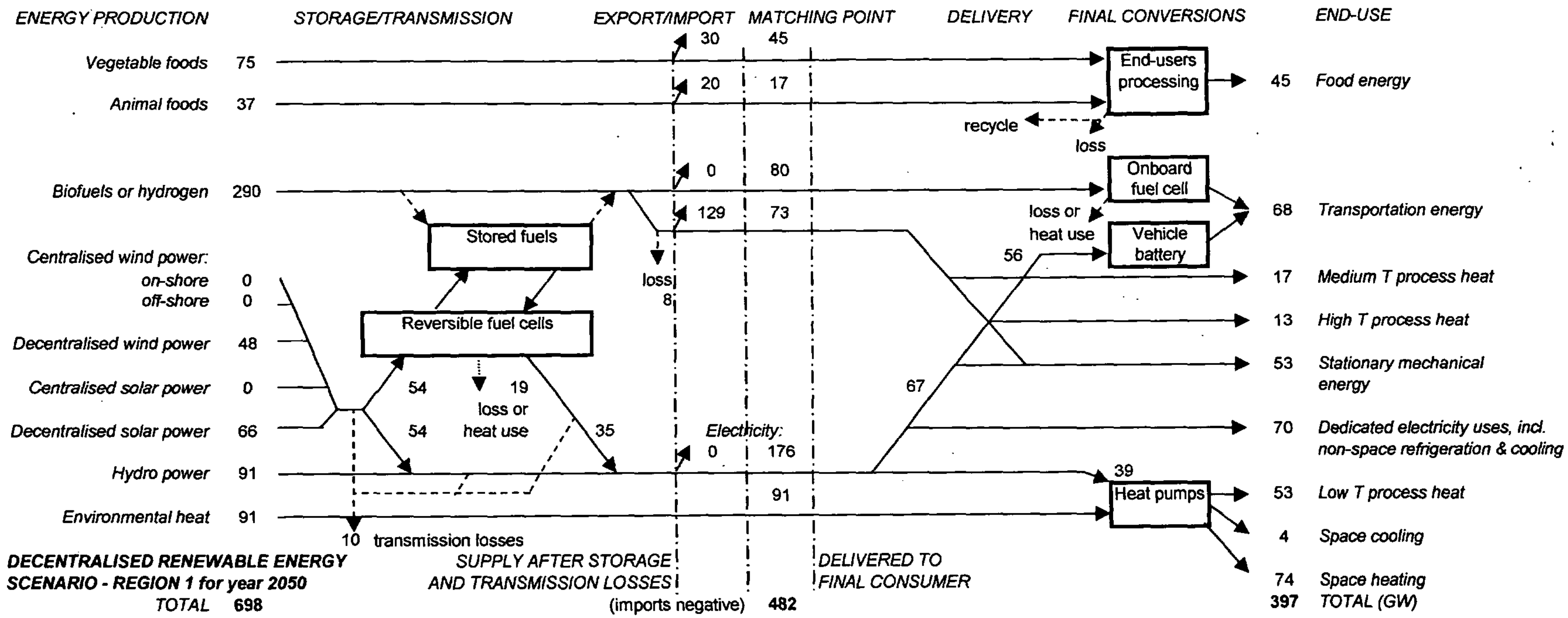


Figure 5.44. Region 1 decentralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

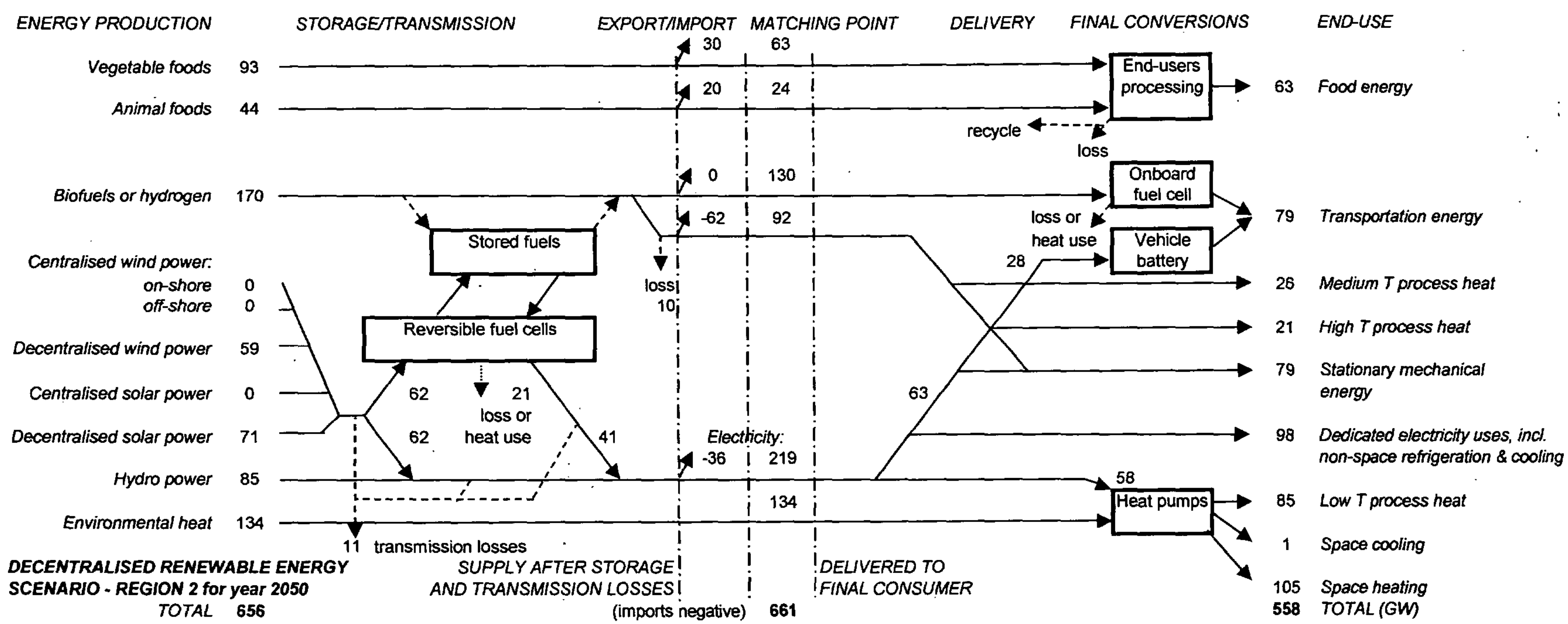


Figure 5.45. Region 2 decentralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

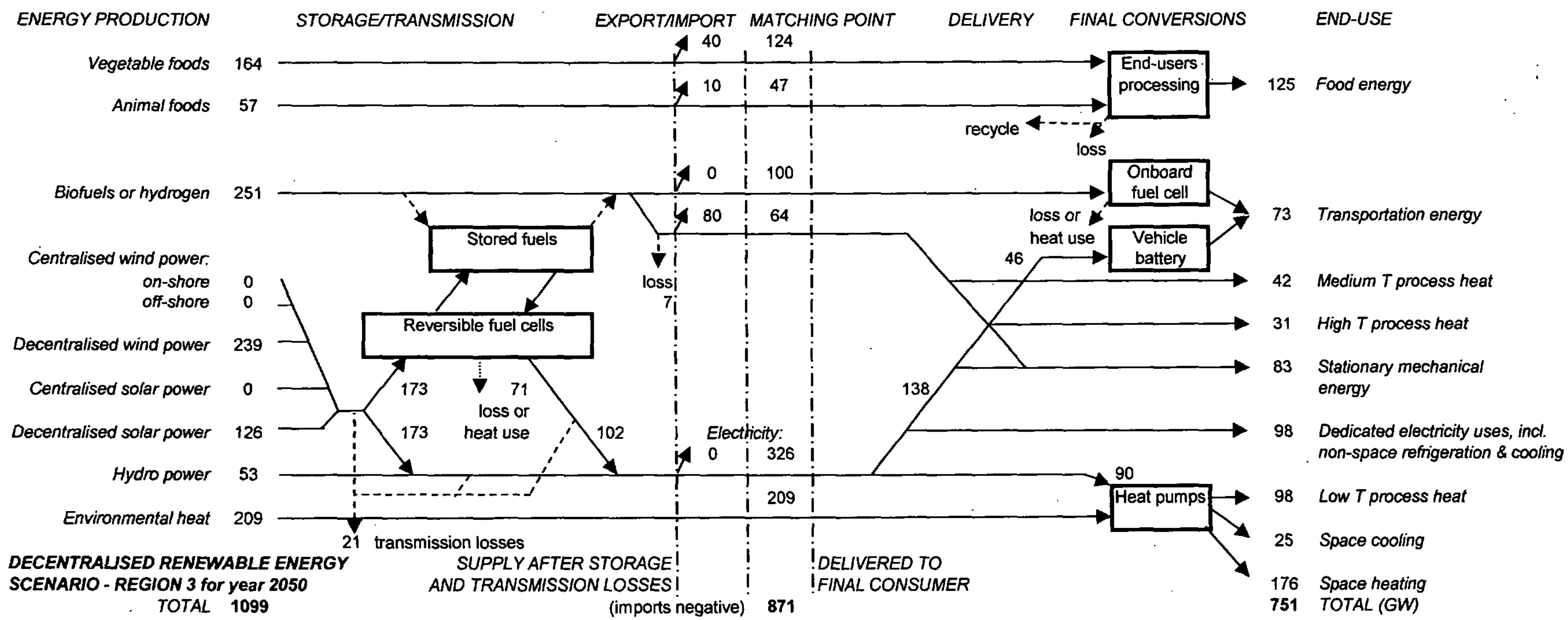


Figure 5.46. Region 3 decentralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

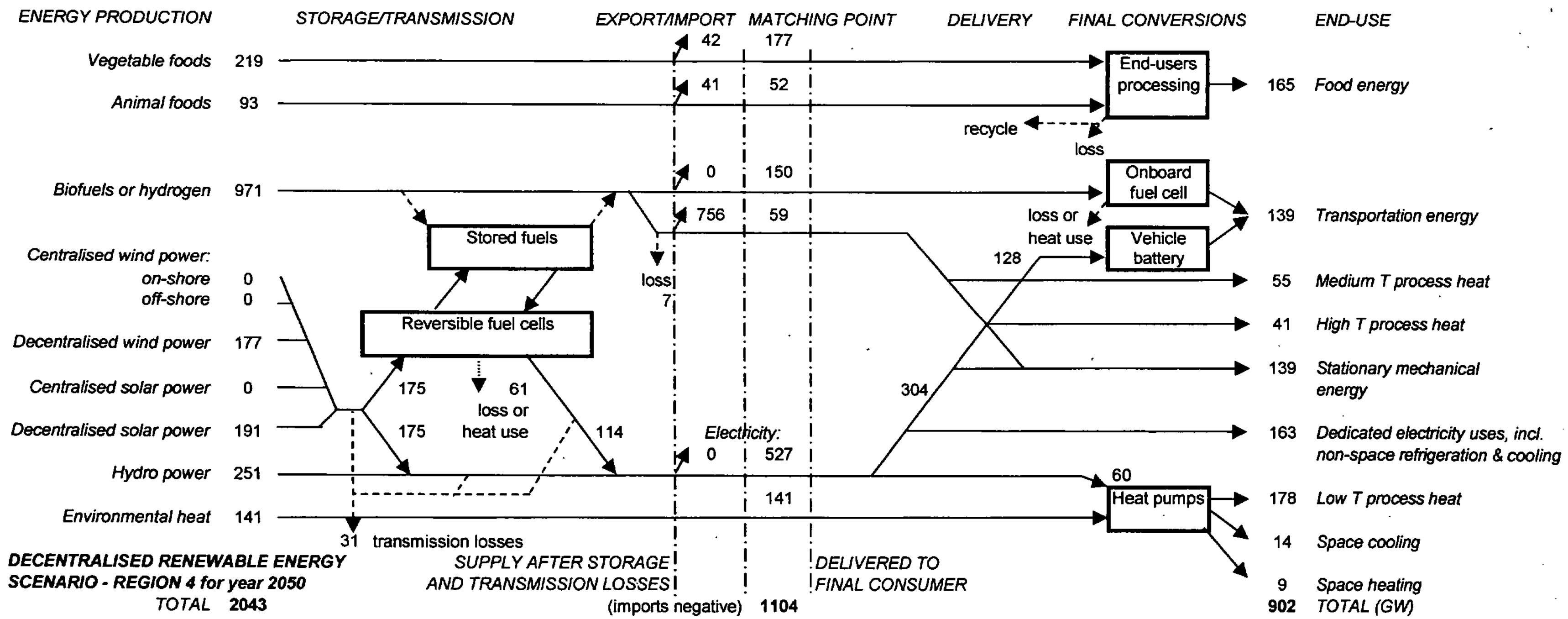


Figure 5.47. Region 4 decentralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

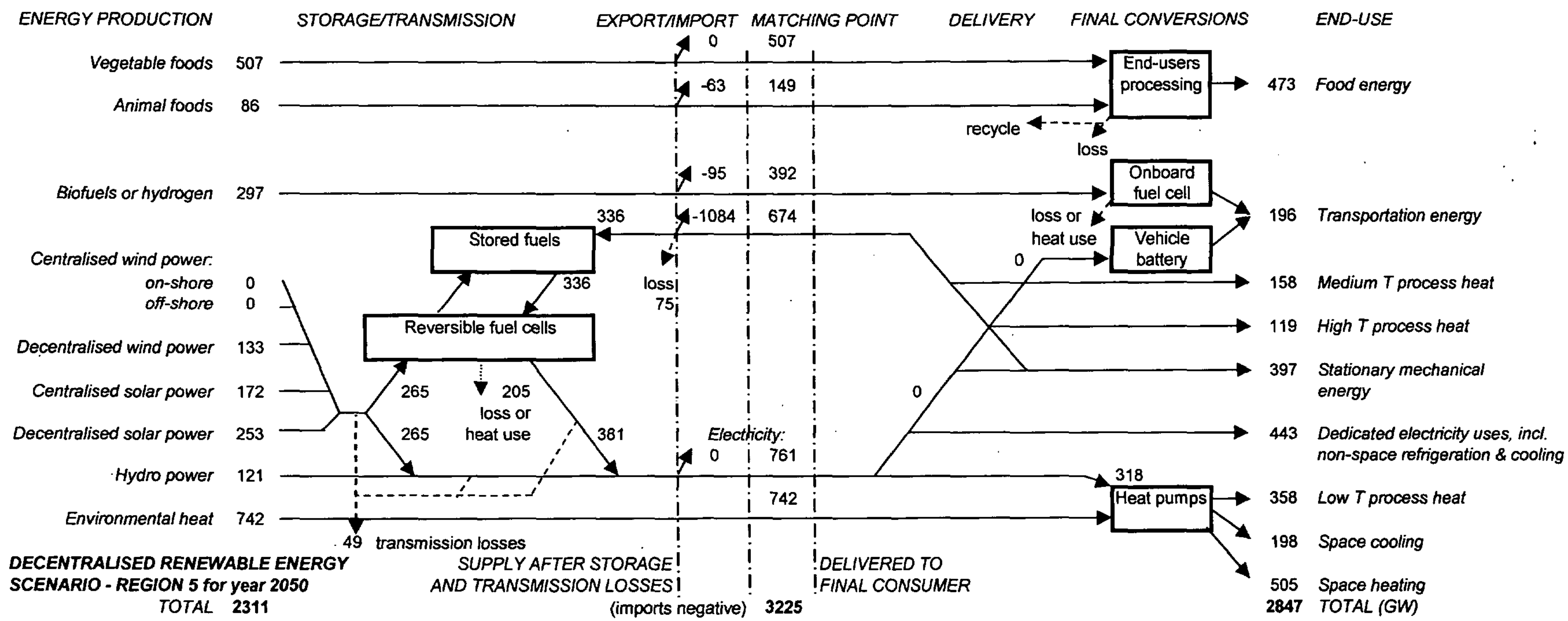


Figure 5.48. Region 5 decentralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

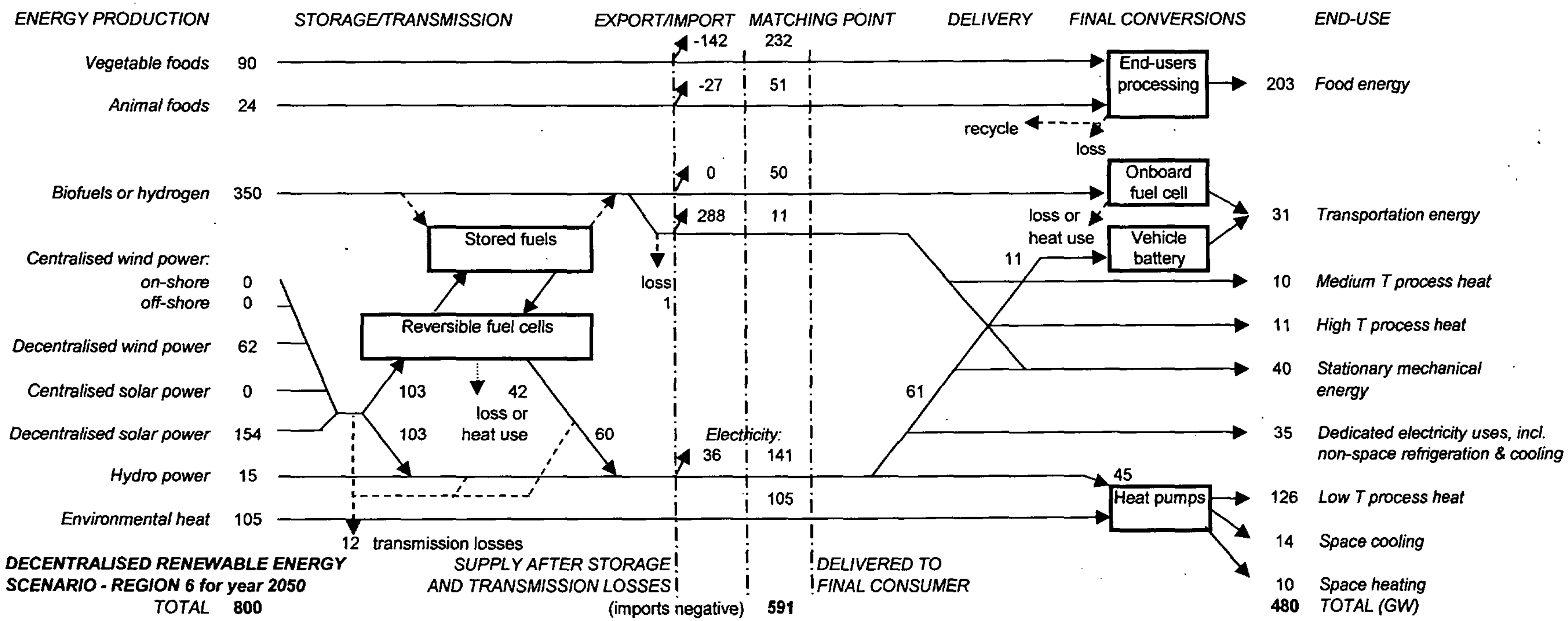


Figure 5.49. Region 6 decentralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

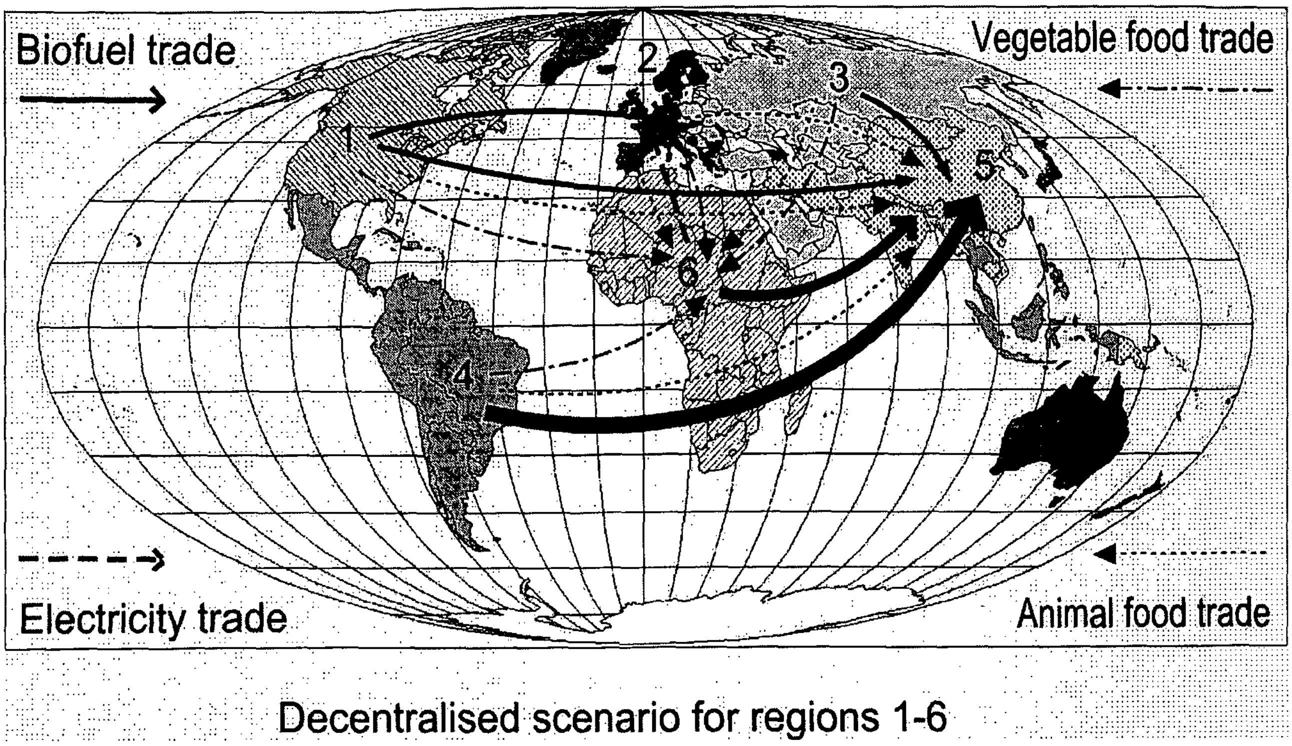


Figure 5.50. Patterns of food and energy trade in the decentralised 2050 scenario. The quantities of import and export are given in Figs. 5.44-5.49. This Figure also shows the locations of the six regions, the individual countries belonging to each being listed in Appendix A.

Figure 5.43 summarises the decentralised scenario and Fig. 5.50 shows the main flows of inter-regional energy trade.

5.3.2 Centralised renewable energy 2050 scenario

By "centralised" scenario is here understood a scenario exploiting central supply installations in addition to the decentralised ones, and with a new attempt to optimise the amounts obtained from each category and the trade between regions. Section 5.2 has provided estimates of the total additionally exploitable resources available in a centralised mode. Their combined magnitude is of the order of ten times the 2050 average demand, and the regional distribution, particularly of the potential photovoltaic power production, is fairly even.

A natural approach to choosing the sources to employ in addition to the decentralised ones is the following: For hydro power, the existing plants and those already under construction are retained, but no additional plants are built, in consideration of the environmental impacts that may be caused. The bulk of the remaining resources shown in Fig. 5.25 are large-reservoir type hydro sites, notably in South America. They are not used in the scenario.

Wind turbines not attached to farm buildings are introduced: In Western Europe, part of the substantial off-shore wind potential should first be put into operation, because this is already economical and installation is in progress. In region 3, there are also additional centralised wind resources, but since the problem for the decentralised scenario was the seasonal variation of continental winds, it will give a more stable system to exploit some of the centralised photovoltaic potential. For region 5, the only realistic proposal is to exploit

substantial amounts of photovoltaic power, plus the smaller additional centralised biomass potential available. A little off-shore wind is exploitable in the South.

Table 5.5 gives the amounts of centralised sources proposed to be exploited in the centralised scenario, and Table 5.6 states the fraction of the potential resources that they constitute. For region 4, we have reduced the use of biomass for fuels, in line with the arguments of forest preservation given in section 5.3.1. Still, region 4 has the option of a very large energy export.

The resulting energy system is much more robust than the decentralised one, and none of the renewable energy sources are utilised to the ceiling. This modesty should actually be considered realistic, due to the variations between seasons and years of renewable energy production (as already discussed for food production). Table 5.5 indicates substantial variations in supply/demand balances between seasons. We believe to have taken this into account by the storage cycle introduced (see Figs. 5.63-5.69). However, a detailed simulation needs to be performed to ensure this, as done for Western Europe in a similar study (Sørensen, 1998). In an economic evaluation, the cost of establishing a surplus generation capacity is to be weighted against the cost of providing more energy storage than envisaged in our reference case (50% of wind and solar cell power passing through storage facilities, as stated in section 5.2). It is in the spirit of the centralised scenario, that imports and exports are used in those cases where they ease the strain on ecosystems. It is therefore a conclusion, that the exploitation of centralised renewable resources allows more environmental concerns to be considered than insisting on producing as much as possible of the energy needed locally.

Table 5.5. Assumed energy supply (after storage conversion cycles and transmission but before interregional imports/exports) in centralised 2050 scenario, and corresponding supply-demand balances.

Region (cf. Table 2)	**1**	**2**	**3**	**4**	**5**	**6**	**Total**	**unit**
Total food balance (as Table 10)	151	144	107	283	-23	-167	**493**	GW
Total biofuels used	250	190	300	640	327	192	**1899**	GW
Of which decentralised biofuels	250	166	236	640	295	192	**1779**	GW
Balance: total biofuels minus use for transportation	136	158	146	277	392	61	**1170**	GW
Hydro power	80	70	50	120	110	10	**440**	GW
Decentralised solar power	27	50	67	109	189	23	**465**	GW
Centralised solar power	40	20	114	19	400	100	**693**	GW
Decentralised wind power	20	37	80	100	100	10	**347**	GW
On-shore wind parks	12	10	20	38	46	0	**126**	GW
Off-shore wind power	0	40	0	0	13	0	**53**	GW
Balance: other energy, ann.av.	100	-63	139	288	-660	217	**22**	GW
Balance: other energy, Jan.	74	-120	169	306	-890	214	**-250**	GW
Balance: other energy, April	87	-51	72	243	-710	200	**-160**	GW
Balance: other energy, July	129	-17	180	352	-410	233	**461**	GW
Balance: other energy, Oct.	110	-64	129	252	-610	220	**35**	GW

Table 5.5 gives the regional balances of supply and demand for the resources exploited in the centralised scenario (before import and export), and Figs. 5.63-5.69 show the overall scenario

and its regional implications. The food balances are identical to those of Figs. 5.27-5.30, and the local surpluses and deficits for biofuels and electricity (before trade of energy) are shown in Figs. 5.51-5.62. The main routes of import/export are depicted in Fig. 5.70. The overall picture is similar to that of the decentralised scenario, except for the higher resilience obtained from the centralised production in wind farm, photovoltaic parks and energy forests or crops. The amount of centralised energy used to cover the scenario demand is still very modest compared to the potential listed in section 5.2, even when it is used to ensure no abuse of new large hydro installations or rainforest conversion. The PV and wind energy export options arising e.g. for desert land give such areas new opportunities for development, and in some cases make up for current oil export revenues lost. Also the large biofuel exports considered for South America give credibility to the assumed substantial economic development of this continent.

Table 5.6. Fraction of potential resources used in centralised 2050 scenario.

Region	1	2	3	4	5	6	average
Decentralised biofuels	0.91	0.98	0.96	0.93	1.00	0.92	0.94
Centralised biofuels	0	0.12	0.64	0	0	0	0.21
Hydro power	0.88	0.82	0.95	0.48	0.90	0.67	0.71
Decentralised solar power	0.54	0.93	0.71	0.76	0.99	0.20	0.72
Centralised solar power	0.013	0.003	0.014	0.004	0.041	0.005	0.013
Decentralised wind power	0.56	0.85	0.45	0.75	1.00	0.21	0.64
On-shore wind parks	0.75	0.068	0.27	0.66	1.00	0	0.21
Off-shore wind power	0	0.52	0	0	0.70	0	0.16

5.4 DISCUSSION OF RENEWABLE ENERGY SCENARIOS

In discussing the robustness of our scenarios against changes in assumptions, it is useful to separate the demand and the supply scenarios. The demand scenario assumes that efficiency measures are performed, that would entail smaller costs than any of the options for additional energy supply. This may appear a very reasonable assumption, but it is a feature of the present system, than in several demand categories, there are efficiency improvements not made, which would be highly economic even with current prices. The reason for this may be sought in the lower prestige seemingly accorded to demand-side measures as compared with new supply. If this element of irrationality can be eliminated in the future is uncertain, and many scenarios of future energy demand estimate substantially higher consumption levels than the one assumed in the present study. In our centralised 2050 scenario, there is a low utilisation of available renewable energy sources, and substantially higher demands could be satisfied, notably with photovoltaic plants not attached to buildings. The centralised scenario is thus highly resilient to changes in demand, whereas the tight matching of demand and supply in the decentralised scenario makes this more vulnerable.

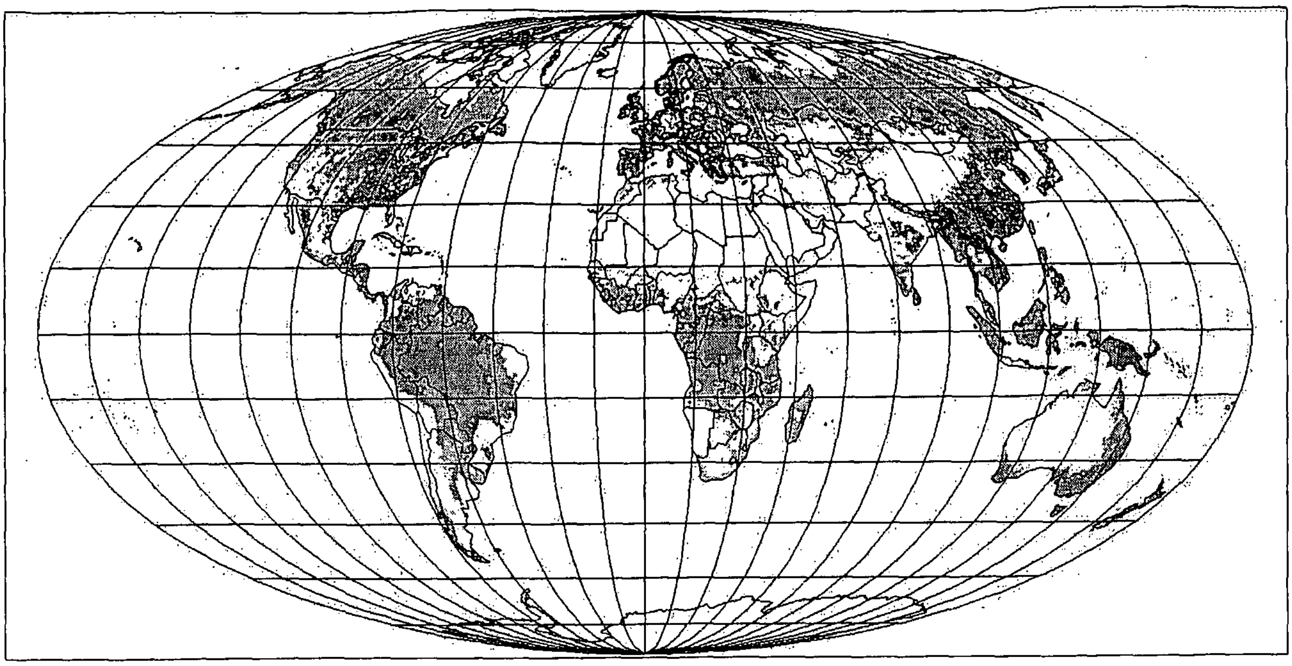


Figure 5.51. Local surplus of biofuel supplies (such as methanol) over demand for transportation fuels on an area basis, according to the centralised 2050 scenario. (annual average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

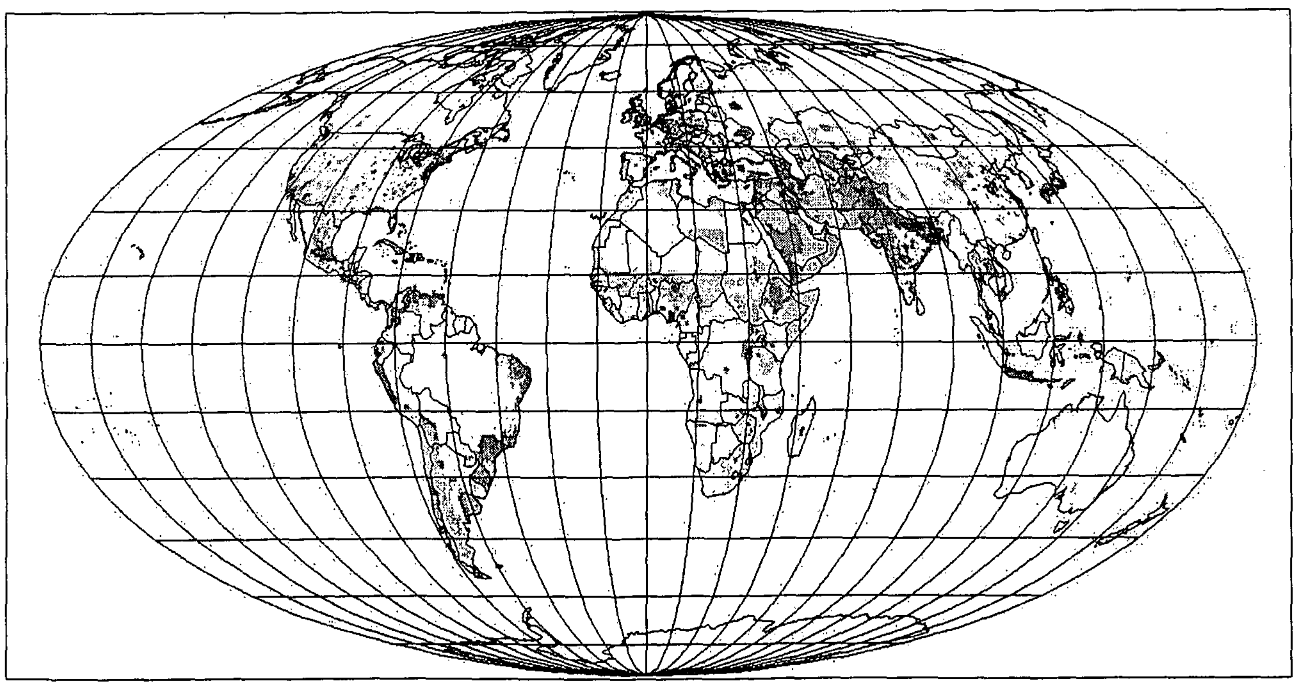


Figure 5.52. Local deficit of biofuel supplies (such as methanol) relative to demand for transportation fuels on an area basis, according to the centralised 2050 scenario. (annual average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

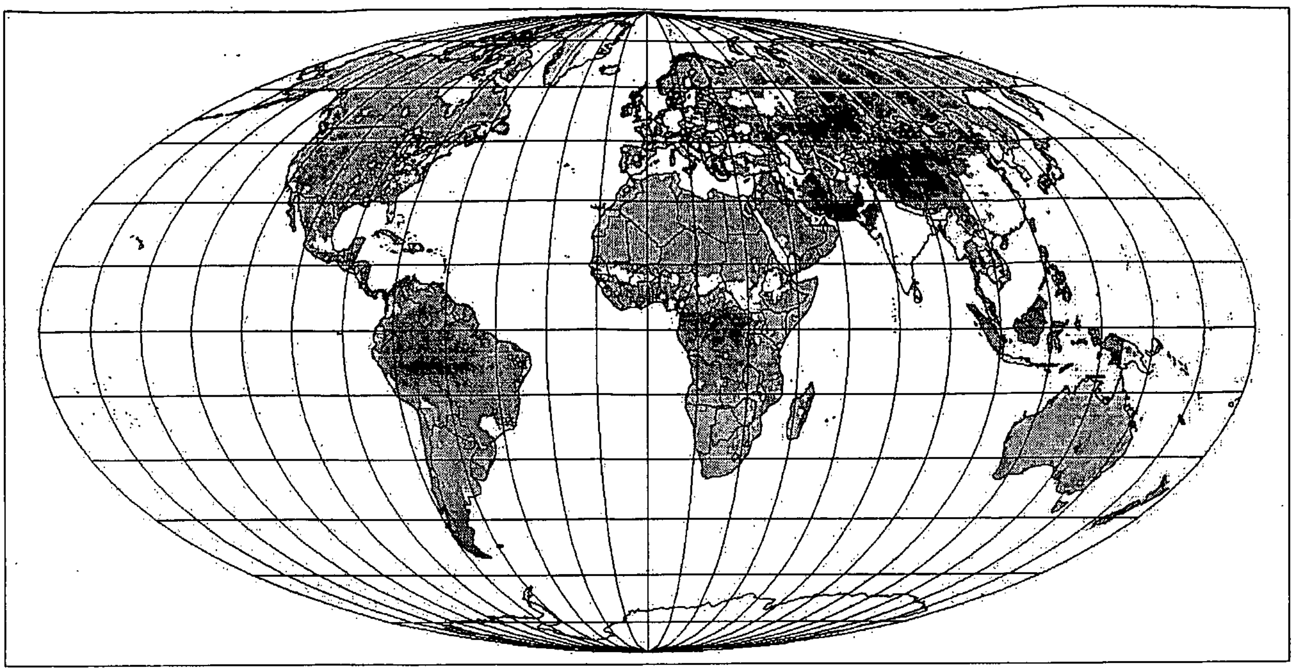


Figure 5.53. January local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

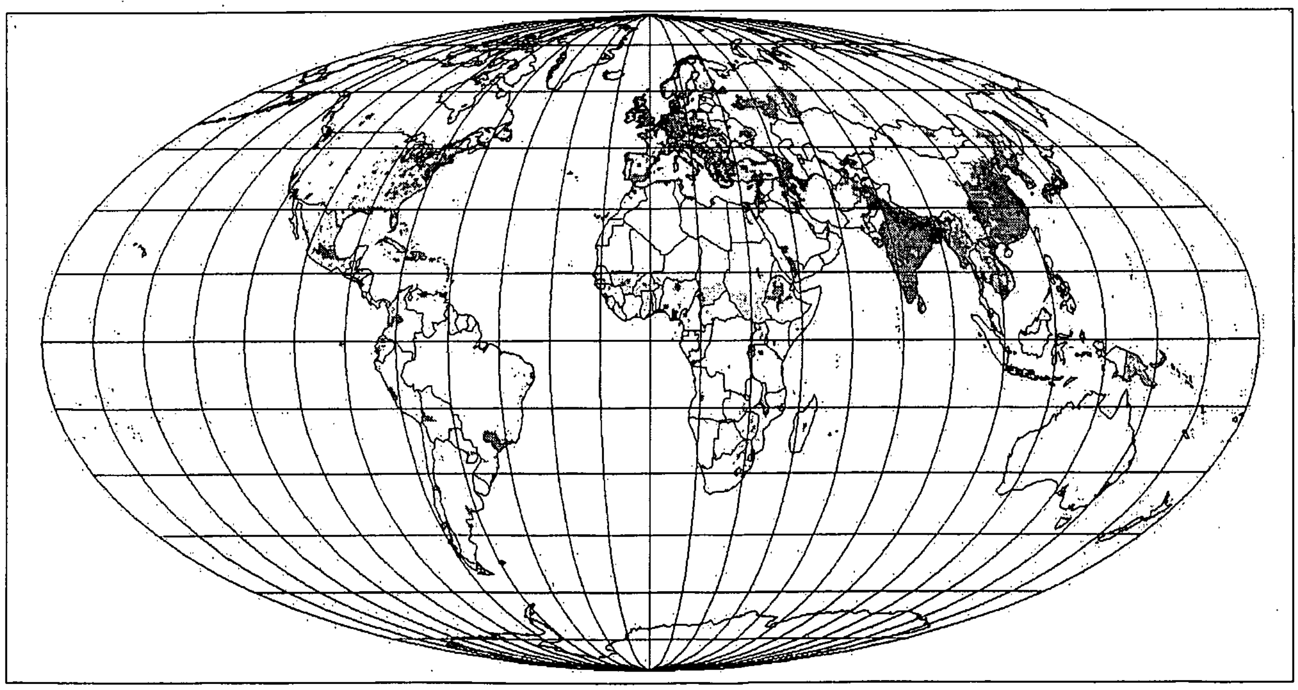


Figure 5.54. January local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

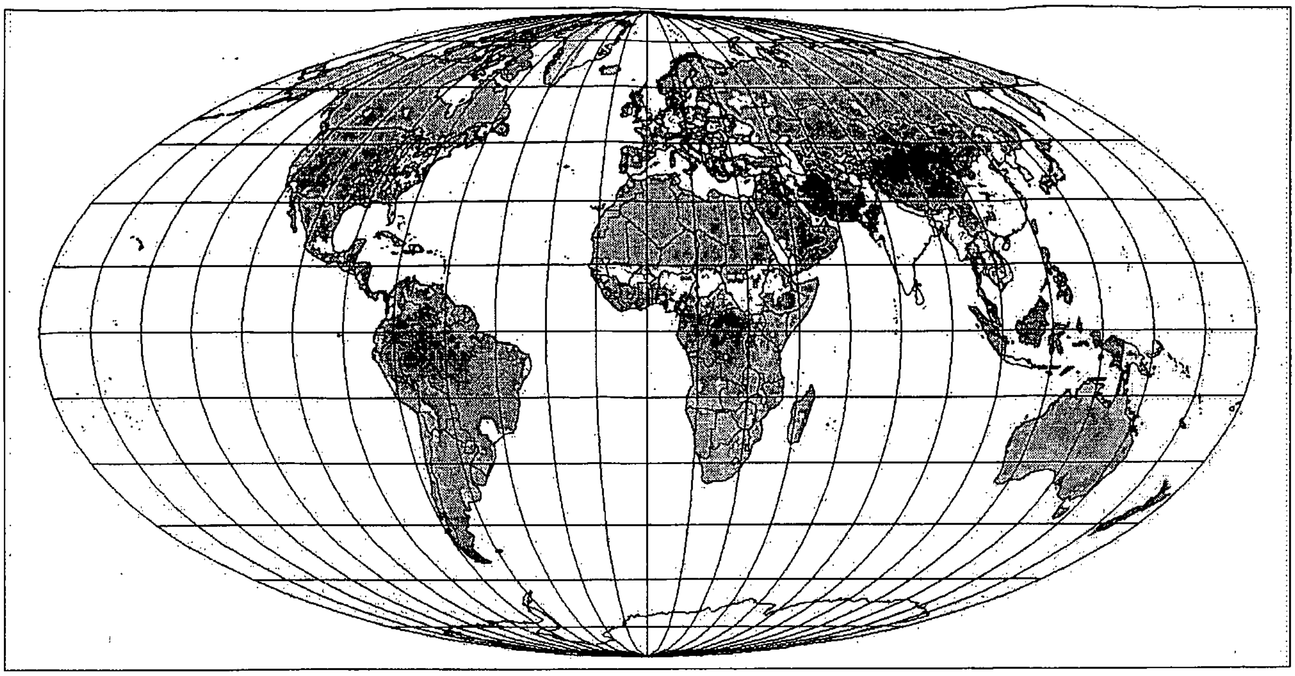


Figure 5.55. April local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

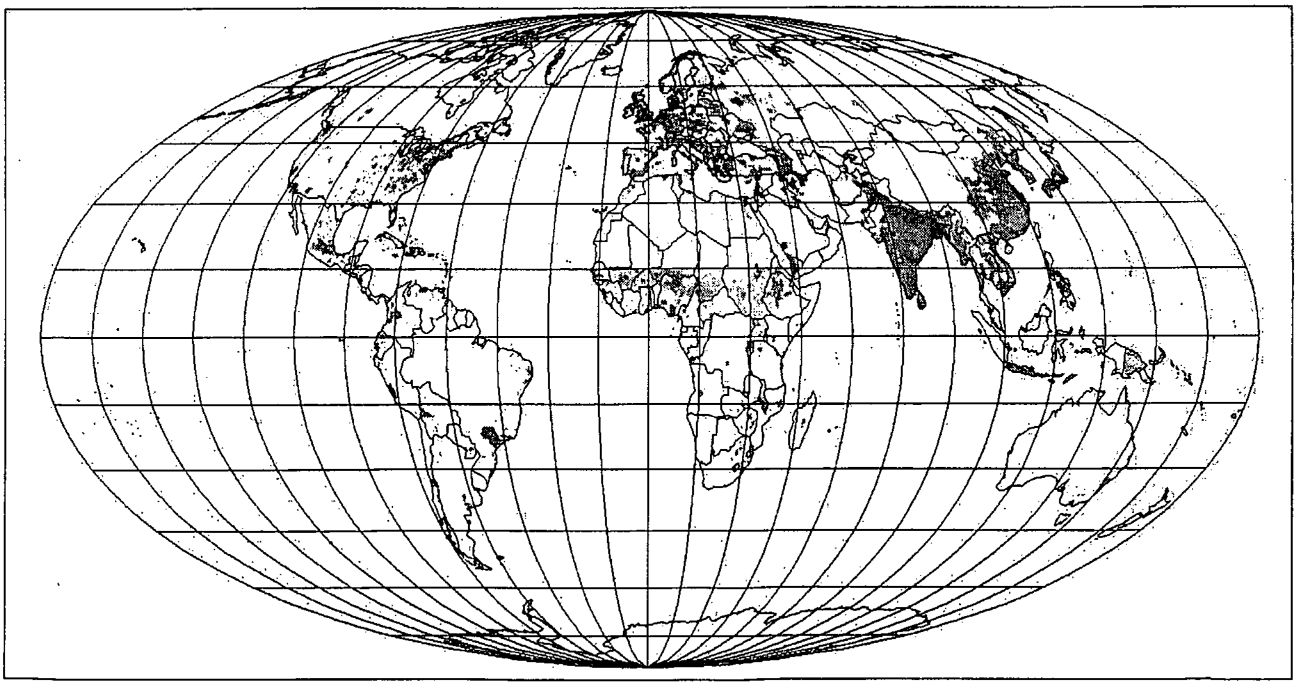


Figure 5.56. April local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

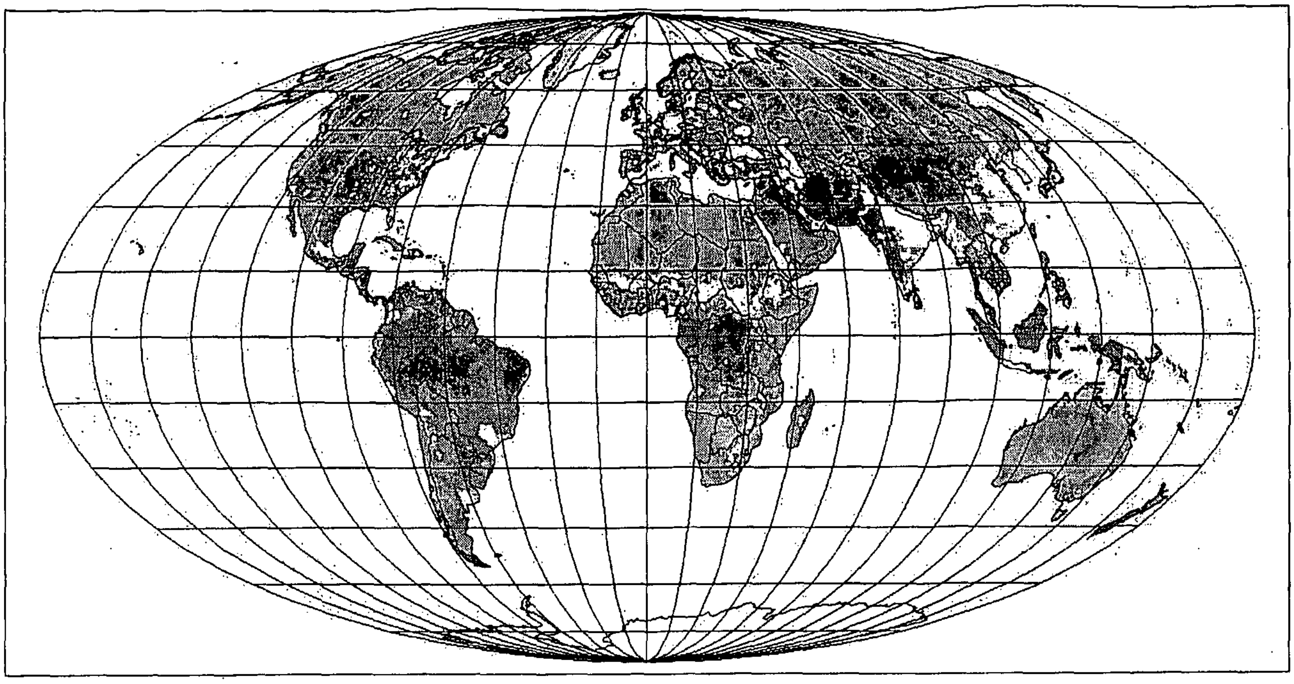


Figure 5.57. July local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

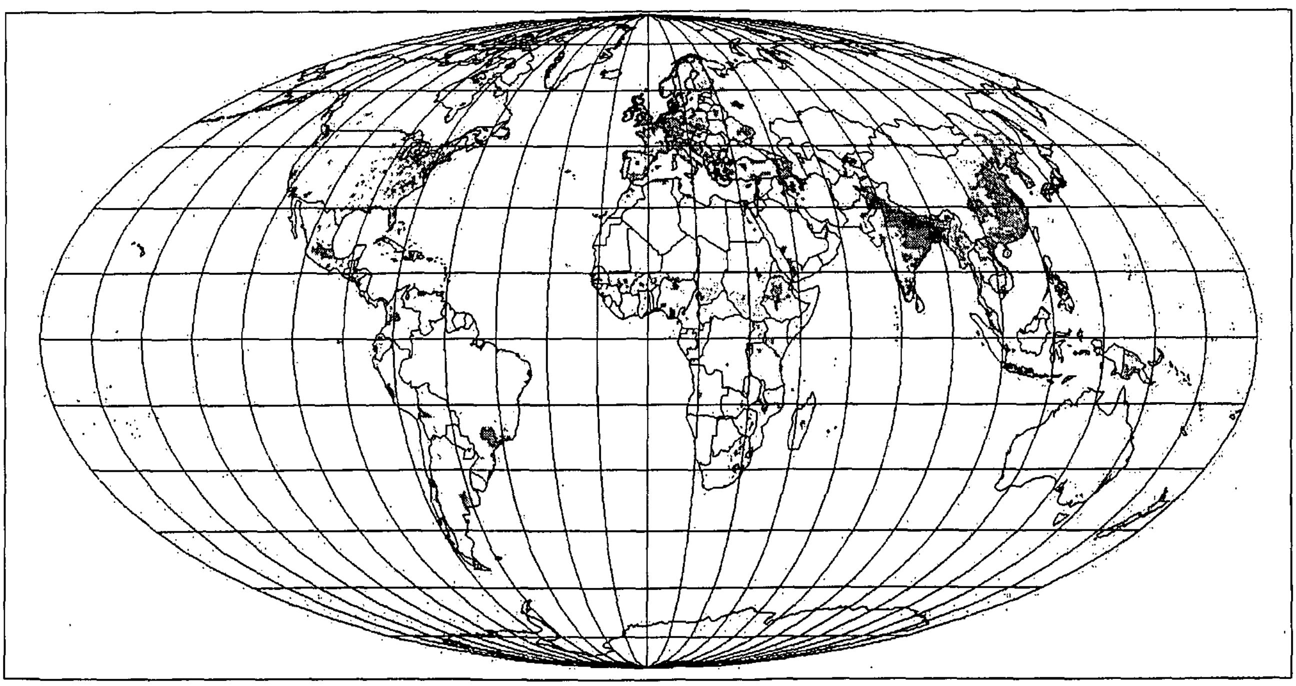


Figure 5.58. July local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

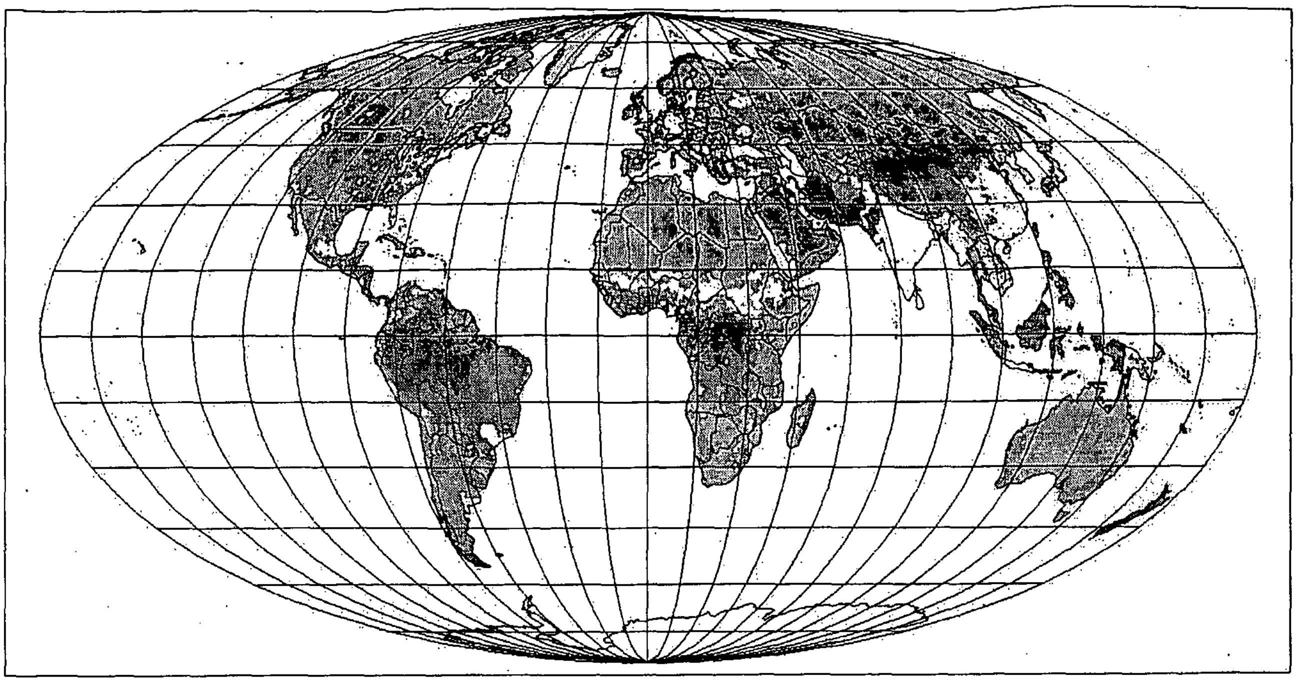


Figure 5.59. October local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

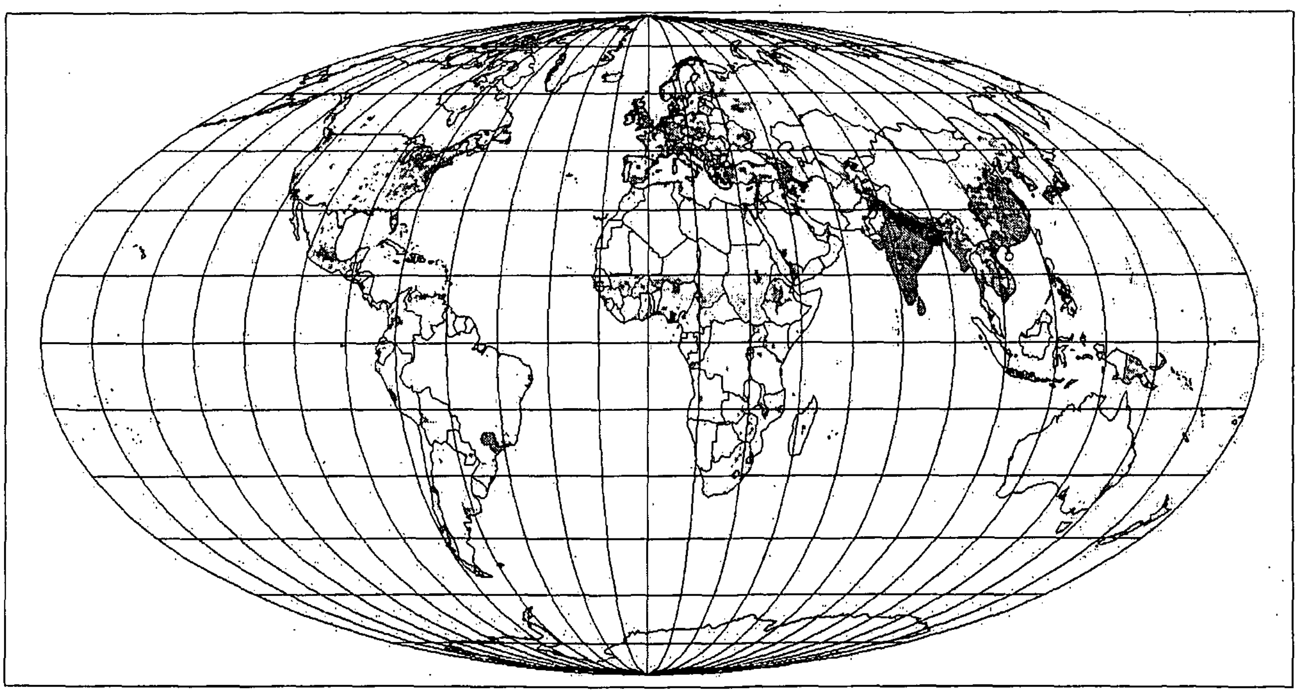


Figure 5.60. October local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

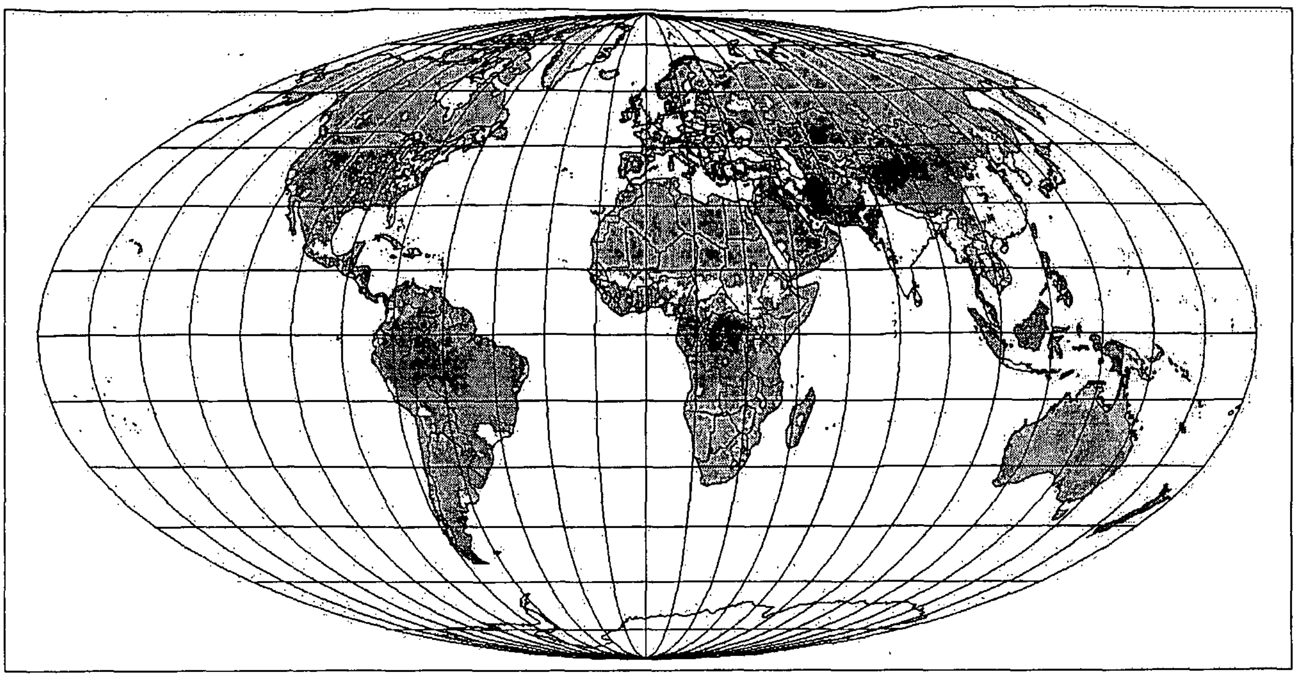


Figure 5.61. Annual average local surplus of supplies of electricity and biofuels (such as biogas or hydrogen) over demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average supply minus demand in W/m^2 is shown if positive; scale given in Figure 5.11d).

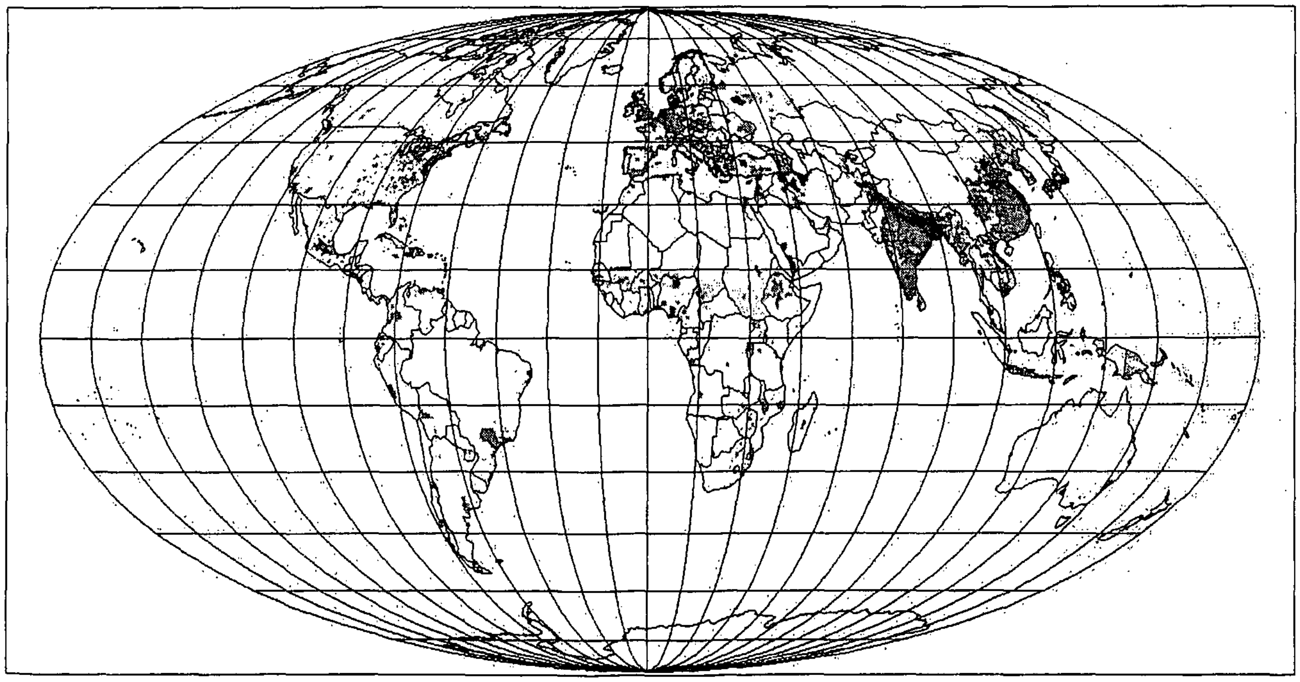


Figure 5.62. Annual average local deficit of the supplies of electricity and biofuels (such as biogas or hydrogen) relative to demand (all demand except food and transportation) on an area basis, according to the centralised 2050 scenario. (average demand minus supply in W/m^2 is shown if positive; scale given in Figure 5.28b).

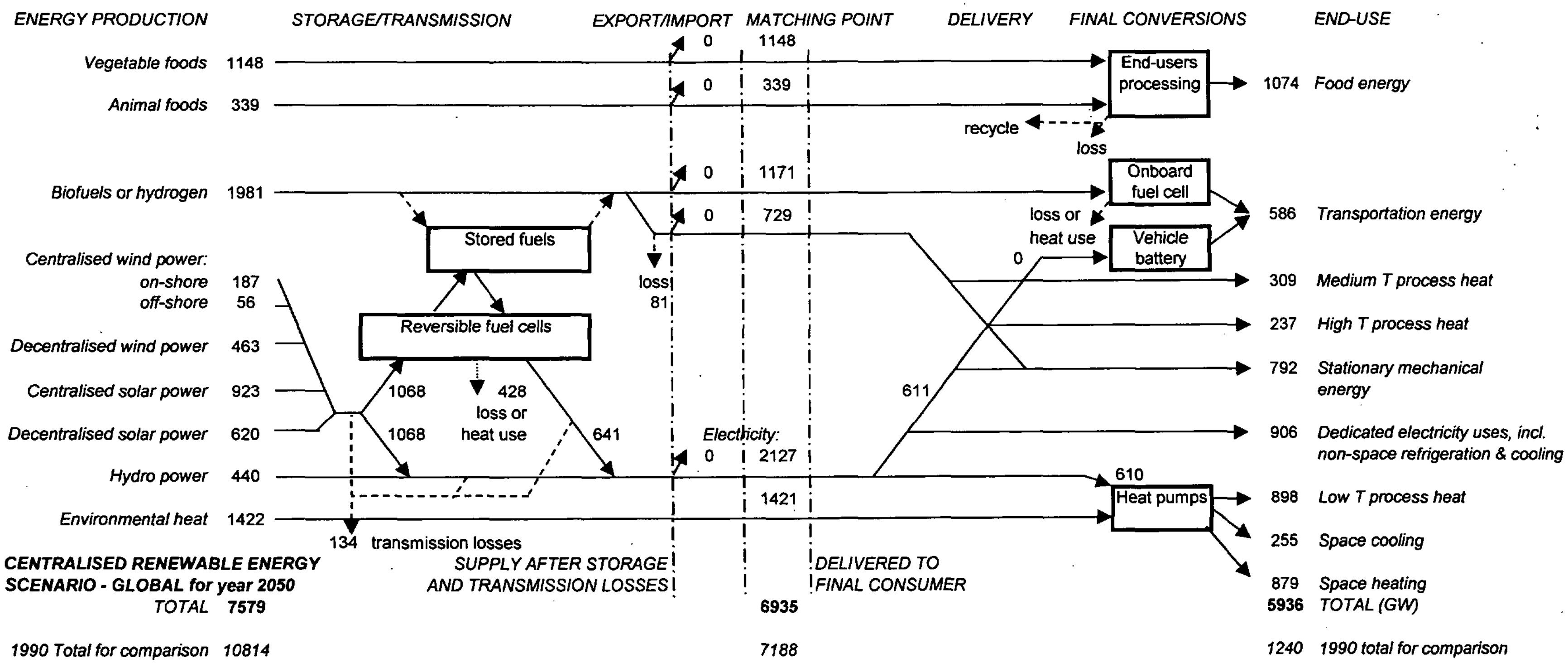


Figure 5.63. Overview of centralised 2050 scenario (all energy flows in GW or GWy/y).

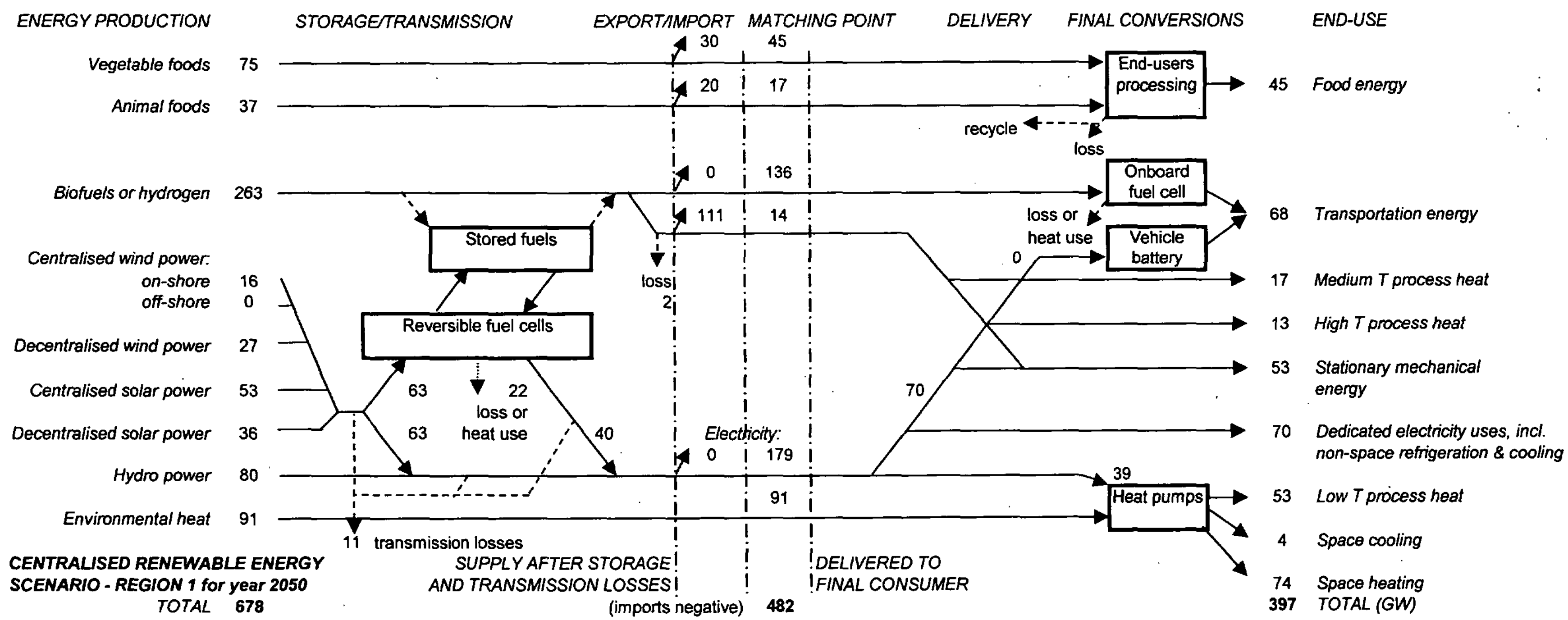


Figure 5.64. Region 1 centralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

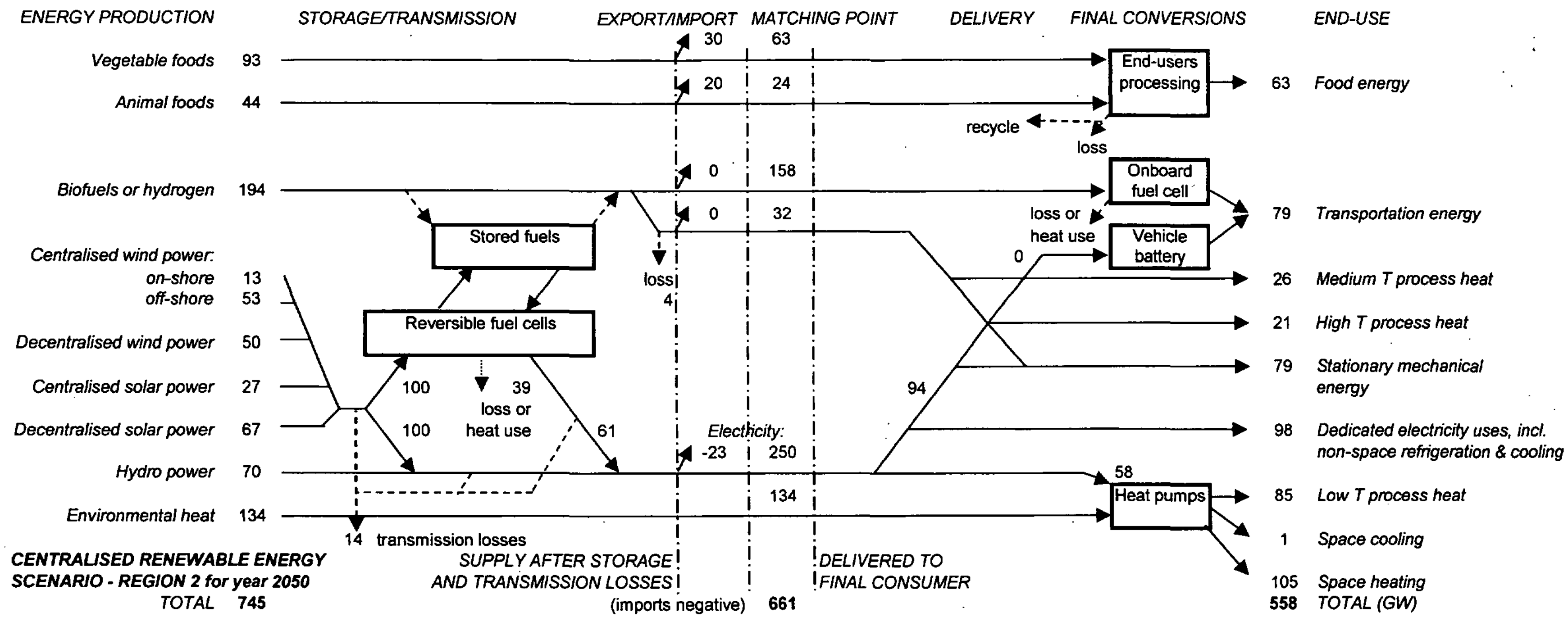


Figure 5.65. Region 2 centralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

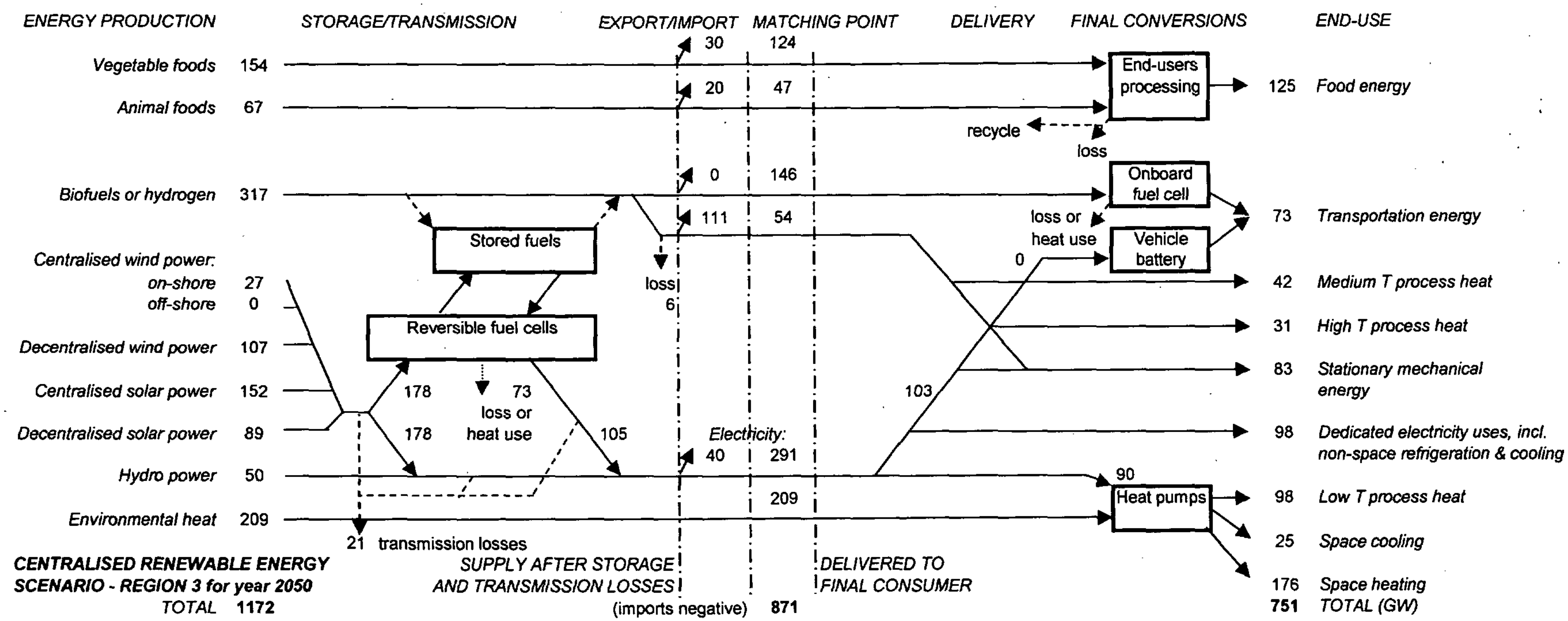


Figure 5.66. Region 3 centralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

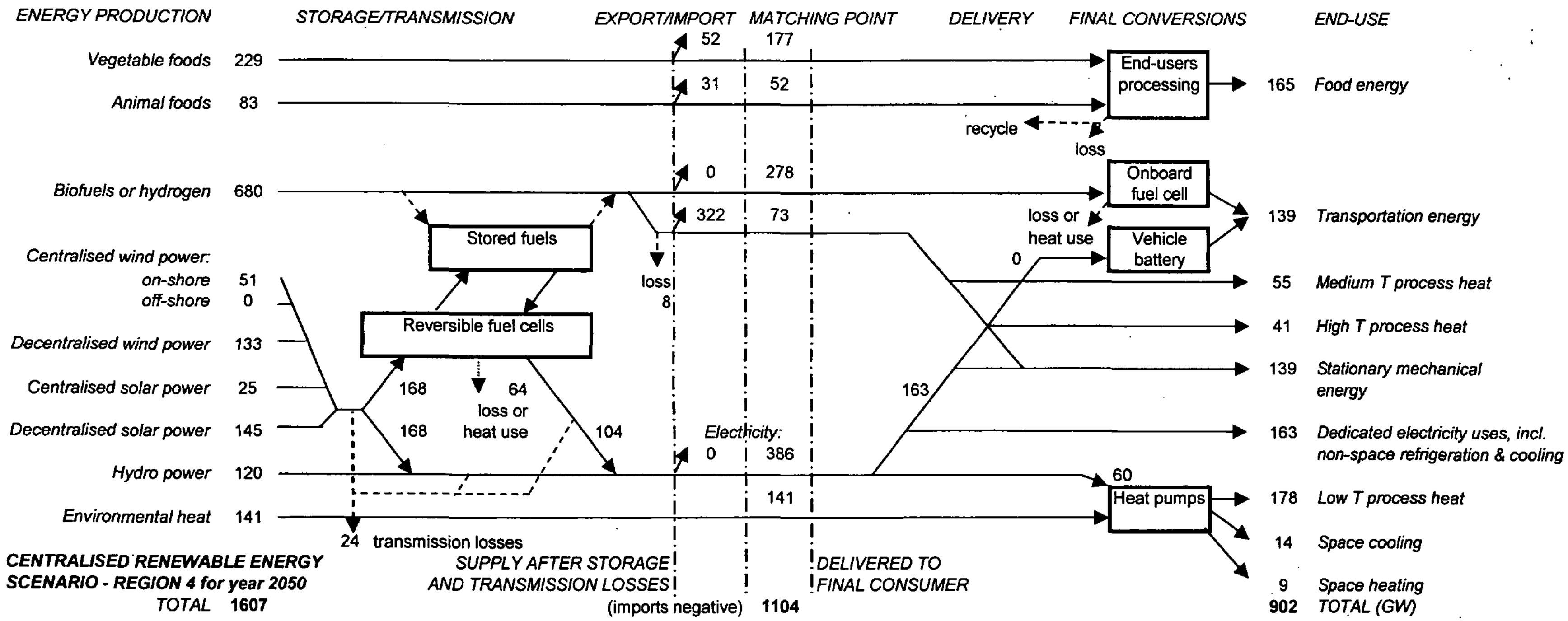


Figure 5.67. Region 4 centralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

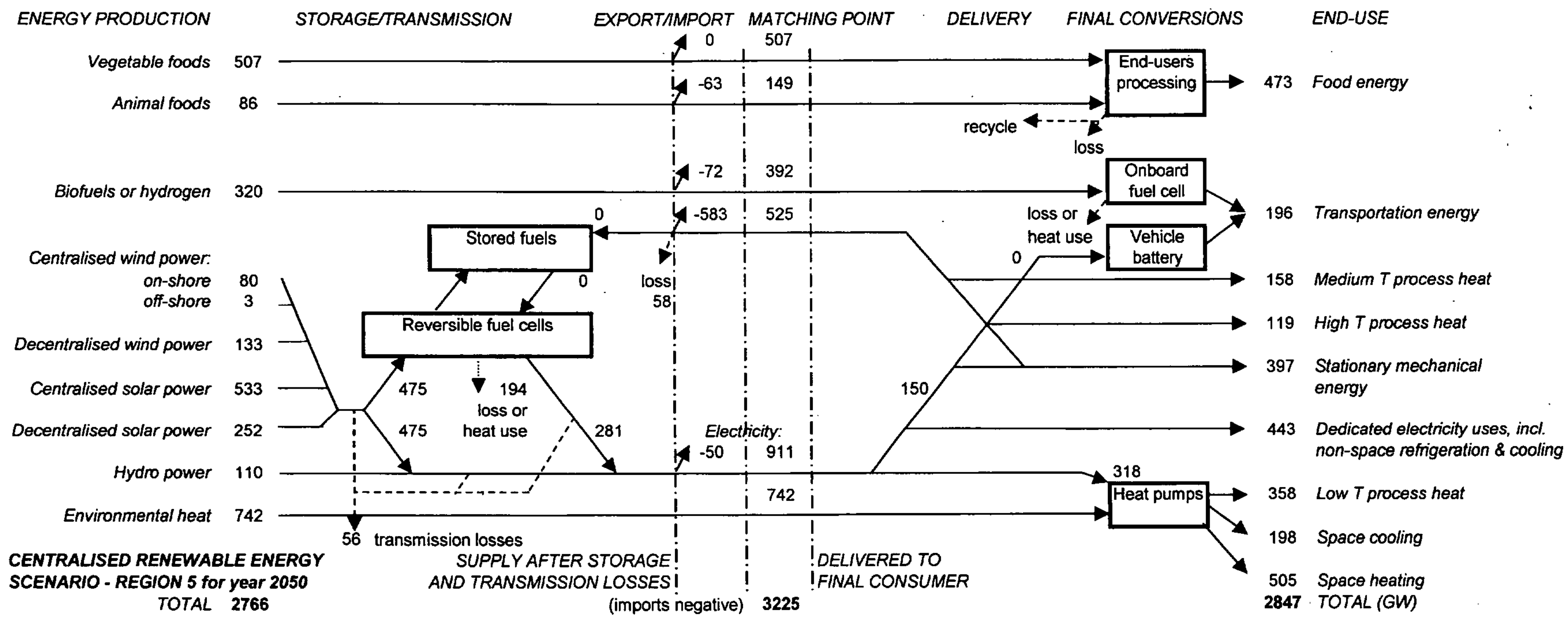


Figure 5.68. Region 5 centralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

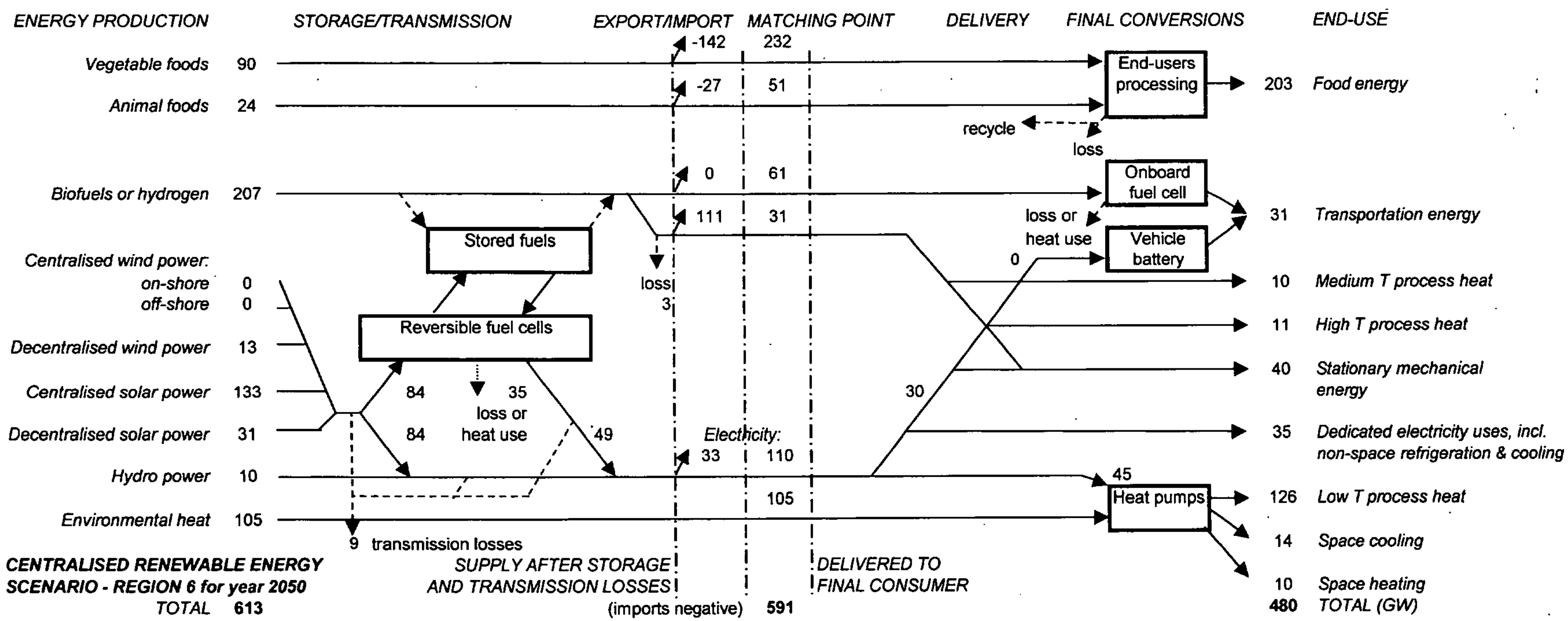


Figure 5.69. Region 6 centralised 2050 scenario with indication of import and export (all energy flows in GW or GWy/y).

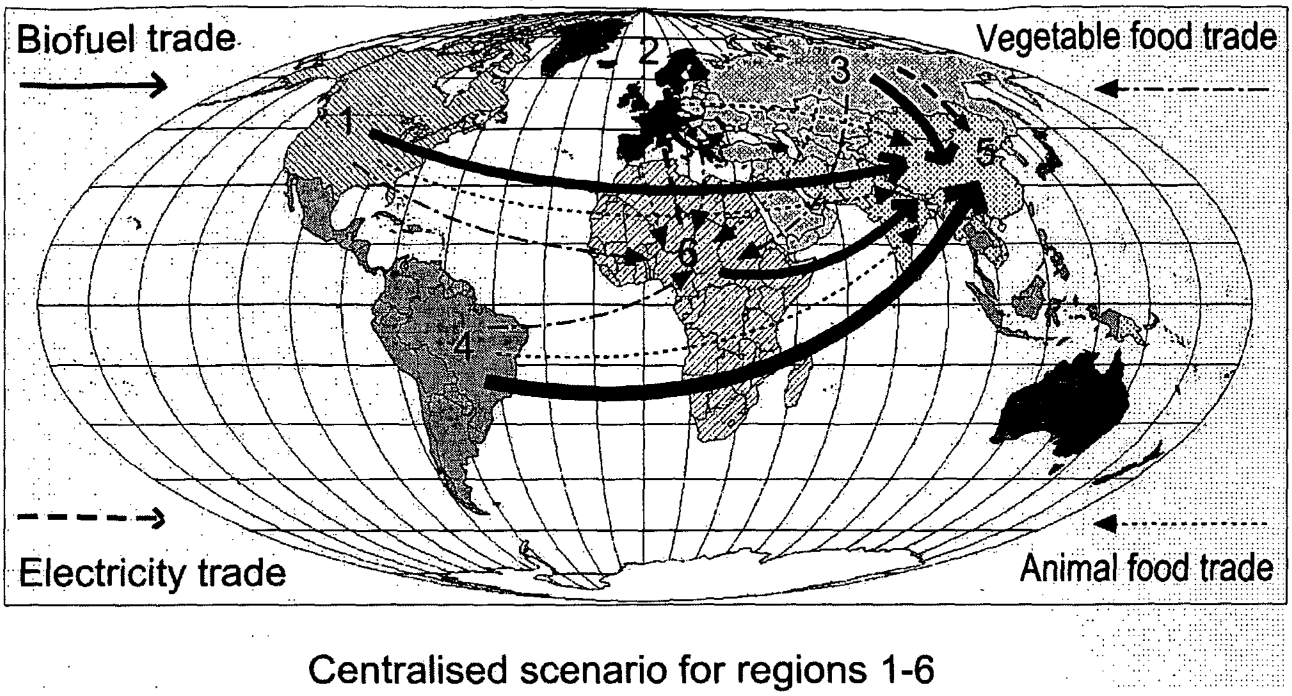


Figure 5.70. Patterns of food and energy trade in the centralised 2050 scenario. The quantities of import and export are given in Figs. 5.64-5.69. This Figure also shows the locations of the six regions, the individual countries belonging to each being listed in Appendix A.

The supply scenarios demonstrate that the decentralised option, defined as using only building-integrated PV and less than one detached wind turbine per farm house, plus existing hydro, leaves little room for increase of supply. For buildings, a higher solar utilisation would require urban planning with orientation of streets and buildings optimised for solar capture. This is unlikely to be feasible, as half the buildings in 2050 already exists, and the other half will be built gradually over the 50 year period, implying the necessity of a very rapid action if urban planning aspects should be significantly altered. For farm-attached wind turbines, we have assumed that not every farm possesses a turbine by year 2050. This is justified both due to resource variations (even on extended lands belonging to a farm, no site with suitable wind conditions may be found, due to nearby forests or other obstructing landscape features), and also because not all farmers may chose to install a turbine. The model we have adopted corresponds to the most dense dispersed wind turbine density found today in Denmark, and our assumption is that current smaller turbines will be replaced by larger ones by year 2050. This is not even happening in Denmark, where the former regulation allowing replacement of turbines with few planning restriction has been replaced by a full planning review being required for each new installation, with the argument that the larger modern wind turbines pose new landscape integration problems. Thus it is also for wind turbines difficult to imagine a substantial increase within the decentralised mode, relative to the scenario proposed.

One area where the proposed decentralised scenario may be conservative, is in coverage of heat demands. There are a number of possibilities for deriving additional heat from the scenario, provided that district heating lines are available for transporting the heat to the sites of demand: The storage cycle, transforming wind and solar power to fuels and later regaining

electricity through reversible fuel cells, gives rise to waste heat that could be lead to demand sites. The same is true of industrial high-temperature heat usage, where waste heat could be cascaded down to users of lower temperature heat. If these methods are adopted, the generation of low-temperature heat through heat pumps could be more or less eliminated, leaving more electricity to high quality uses. In practical terms, these options may allow a demand increase of some 25%.

There are a few features of the "mechanised" scenario building that may be unrealistic: For instance in region 2, there is a high production of solar power in Australia, which could not in a practical way be transmitted to the demand sites in Japan and Europe. The same is true for off-shore wind power produced along the coasts of Greenland and Northern Norway. This affects only the centralised scenario, and since it has many unused, centralised renewable energy resources nearer to the demand centres, there is no serious problem involved.

The centralised renewable energy scenario can easily remedy such local problems, and can sustain much higher levels of demand, while still offering seasonal smoothing of supply through the storage conversion cycles devised. As mentioned above, it also makes it much easier to solve the geographical mismatch between energy generation and demand. Due to the use of wind parks and central solar plants, it has less long-distance transport and transmission of energy than the decentralised scenario, but at the same time it readily accepts such energy trade, that may be considered incompatible with the value basis of a decentralised scenario.

Chapter 6

CONCLUSIONS

6.1 GENERAL ASSESSMENT

The four combinations of a plausible demand scenario for the mid 21^{st} century with supply scenarios based on fossil, nuclear and two versions of renewable energy have all been demonstrated to constitute technically consistent scenarios, provided that the assumed technology development actually takes place.

Estimating the likelihood of the assumed technical advances, the technologies for fossil gasification to hydrogen fuel and subsequent use in fuel cells all exist, but need substantial further development in order to become economically attractive. Particularly for the fuel cell development, the improvement goes far beyond what can be swept under the heading of "including externalities" in the cost appraisal. For the disposal technologies, and particularly the ocean disposal required for a large-scale handling of carbon dioxide, there is little doubt that the CO_2 can be dumped into the ocean (as ice or using suitable pipes) at an affordable cost. However, it needs to be proven by experiment, that this simple procedure do in fact constitute a safe form of disposal, leaving the carbon containing substance away from the biosphere for sufficiently long periods of time.

The safe nuclear scenario is clearly the weakest of the four, as it depends on a technology development that has not even started. On the other hand, the assertion by the nuclear industry that this amounts to starting all over again seems exaggerated, as the expertise for handling both accelerator technology and a new reactor concept is present to an extent that cannot be compared with the level characterising the early reactor development during the 1950ies. Still, the proper reason for questioning this technology development is a very real concern over, whether a practical version of the energy amplifier will indeed get rid of the problems characterising current nuclear technologies. Is there not a risk, that other new developments will bring the proliferation risk back, just as the centrifuge technology changed enrichment from being in the hands of a very exclusive club of huge and expensive laboratories to becoming accessible to poor countries and potentially to determined terrorist organisations? May there not be novel accident routes that will become revealed only when the technology has reached a more concrete form? Because of the time required to transform a scientist's idea to an industrial product, the safe nuclear scenario is likely to have problems reaching a high share in energy supply by the middle of the 21^{st} century. Lessons from renewable energy tells that the transition time required is of the order of 25 years from the day where the technology is ready.

Both the clean fossil and the safe nuclear scenario are transitional solutions based on finite fuel resources. The known reserves are too small to warrant a major transition from today's fossil or nuclear technologies to the new "clean" or "safe" ones, and only the belief that a high proportion of the general resources known to exist can indeed be exploited in practical, economic and environmentally acceptable operations will make any of these two scenarios interesting.

For the two renewable energy scenarios, there is also technology development that has to happen, notably a substantial cost reduction for one or some of the many solar electricity technologies currently identified and developed on a small scale, and like in the other scenarios the development of fuel cell technologies and other parts of the scenario responsible for handling the energy storage requirement of intermittent energy supplies. Generally speaking, the last couple of decades have witnessed a modest success in developing the renewable energy conversion technologies, making these perhaps a little closer to the marketplace than the clean fossil technologies and certainly closer than the safe nuclear technology.

As regards the use of the expression "centralised" to characterise one of the renewable energy scenarios, a qualification may be in order: To some, this expression has a negative value connotation, reminding of centralised economic planning or lack of decision power by the individual citizen. Here, the word is used solely to signal the use of technologies that are not integrated into homes or controlled by individuals, as the rooftop solar panels, individually owned wind turbines and fuel cell plants located in each building in the decentralised scenario. Such community-size installations would appear beneficial for a robust energy system, regardless of the type of ownership structure that may be associated with them.

The analysis has born out, that the decentralised scenario is highly vulnerable to uncertainty in its assumptions, and particularly to increases in demand above what has been assumed. Furthermore, the large inter-continental trade in energy (even larger for the decentralised than for the centralised renewable energy scenario) does appear in contradiction with the local self-sufficiency paradigm underlying the decentralised energy scenario. None of these problems affect the scenario called "centralised", as it has an abundance of additional supply options and actually value the trade as a way to maintain a global interaction having served many countries well in the past.

6.2 ECONOMIC EVALUATION

It may be considered a specific virtue of the present study that it does not make over-optimistic cost estimates for the technologies that are contemplated. In fact, it would not be proper to give three-digit cost figures for a situation 50 years into the future, for technologies of which many are not today even close to their final form. What can be said, however, is that the technologies selected (among a much larger catalogue of options) are those most likely to reach acceptable costs. Nobody envisages this cost to be as low as the present cost of energy, and that would also not be a proper starting point for comparison, as the current supply system has to be changed over the period considered, for reasons of the environment more than for reasons of resource depletion. The only exception is the energy efficiency measures assumed taken in the demand scenario: they all make sense even at current energy cost. For the supply and conversion technologies, the best that can be hoped for is that the cost can be kept within reasonable limits in a frame of reference defined by adding externality costs to all energy-related activities: Each of the options considered here has externality-reducing benefits that should enter into such a comparison.

One could then suggest, that the problem is turned around, so that a "standard price" or "goal" is determined for each technology, i.e. the price that would allow this technology to penetrate the market to precisely the extent assumed in the particular scenario (Nielsen and Sørensen, 1998). Again this assumes a knowledge of the future society, that cannot be taken for granted. Changes in values and paradigms will alter the valuation of externalities, and will add other externalities than those identified today. Therefore is it simply not possible to calculate such standard prices to an accuracy that would render them useful for the discussion. In other words, what can be done is only to point to the plausibility of the selected technologies as likely becoming economic in the eyes of a future society, and to remind of the fact, that all decisions on changes so profound as the ones considered here for the energy system has in the past been made on the basis of normative convictions, visions of determined individuals along with their persistence in pursuing specific goals. No progress was ever based upon economic evaluations, most innovations had to fight claims of defying economic rationality (meaning the rationality of the past, a concept of little use in shaping the future).

6.3 IMPLEMENTATION STRATEGY

Implementation of either of the 2050 scenarios, or a combination of them, involves sketching a path of moving from the current system primarily based on fossil fuels to a very different system, and identifying the conditions that have to be fulfilled to make the transition happen. These could be economic milestones for the new technologies involved, or they could be political decisions needed to be taken. It is here assumed that the social climate, in which the transitions happen is governed by a mixture of free market competition and regulation by society, as it is the case in most regions of the world today. The regulatory part would impose requirements, such as building codes and minimum technical standards for reasons of safety and consumer protection, and maximum energy use for appliances. Another public handle is environmental taxes, that incorporate indirect costs which otherwise would distort the competition between different solutions in the marketplace. A consistent method of estimating the environmental taxes that will make the market a fair one is life-cycle analysis of the entire energy supply chains and the technologies involved. The methodology for doing this, with examples for many of the renewable energy systems considered here, may be found in Kuemmel et al. (1997).

In a fair market, the price that new technologies have to measure up against, is the price of currently used coal, oil, natural gas, hydro and nuclear technologies, all supplemented with the externalities not included in the present market prices and reflecting precisely the negative impacts that the new scenarios propose to remedy. Renewable technologies such as wind power, the cost of which today is only slightly above current fossil fuel-based systems, will clearly be economic if externalities are included (as these are very small for wind power and more than twice the actual price for fossil fuels). Also technologies such as biofuel production, which today involve a cost about twice that of fossil fuels, would in the fair market be able to enter by standard competitive forces. The same is true for coal gasification, again being presently seen as producing hydrogen at an energy cost about a factor two above the price of e.g. natural gas. For photovoltaic power and the new conversion and storage technologies (e.g. fuel cells), present costs are higher than what can be remedied by introducing externalities in the comparison with fossil fuels. Therefore, these have to be assumed to pass through a technical development over the fifty-year transition period, that brings the price down to below the threshold value. Subsidies may be contemplated in order to speed up this process in the initial phase, but already the political readiness to include externalities in prices would constitute a strong motivation for the development of alternative solutions. For the nuclear energy amplifier technologies, very preliminary cost estimates are based on the same kind of over-optimism characterising the early development of nuclear power ("too cheap to meter") (Fernandez et al., 1996). The real cost of the safe nuclear fuel cycle cannot be estimated today, but is likely to be at least 2-3 times the current energy costs.

The assumptions that the future transition will be driven by fair market rules are at variance with the present situation. On one side, there are hidden subsidies in some regions (e.g. to nuclear power), and on the other side, monopolies and generally differences in size and power of the industries involved in different technologies makes the price setting likely not to follow those prescribed by the life-cycle analysis in a fair market philosophy. An obvious solution is to regulate the market not by taxation but by legislation, requiring e.g. power providers to use specific technologies. This makes

it unnecessary to accumulate tax money at the state level (which by some nations is seen as a positive feature), but makes the system rather stiff, as each technical change has to be followed up by possibly altering the legislative regime. The taxation method is more flexible, and once the level of environmental tax is decided by governments, the market functions exactly as before, but should give the manufacturers of the new technologies with smaller environmental impacts a good change to compete, even if they are initially smaller than the established market players. It is also important that externalities are set politically, thereby doing away with the uncertainties of scientific assessment, once the legislation is in place. A problem is the possible differences in tax levels, that different nations may see as fair. International synchronisation is highly desirable, as in all policy aimed at reducing global threats. Depending on the degree of planning tradition in different societies, the energy transition might also benefit from "setting goals" and continually monitoring if they are fulfilled. If for example the market does not respond well enough to the price signals set by the environmental taxes, it is then possible to adjust the size of the imposed externality (which would often not violate the scientific basis for it) or introduce specific legislation to remove the obstacles to a free and fair market.

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APPENDIX A: REGIONAL ASSIGNMENTS OF COUNTRIES

COUNTRY	CONTINENT	RE-GION	POPULATION 1996	POPULATION 2050	Urban % 1992	Urban % 2050
Afghanistan	Asia	III	20883	61373	18.92	55.97
Albania	Europe	II	3401	4747	36.34	72.65
Algeria	Africa	VI	28784	58991	53.34	89.65
Andorra	Europe	II				
Angola	Africa	VI	11185	38897	29.86	75.80
Anguilla	North America	IV	8	13	0.00	0.00
Antarctica	Antarctica	-				
Antigua & Barbuda	North America	IV	66	99	35.56	60.94
Argentina	South America	IV	35219	54522	87.14	90.00
Armenia	Europe	II	3638	4376	67.98	89.11
Aruba (Netherlands)	North America	IV	71	109	0.00	0.00
Australia	Australia	II	18057	25286	84.94	90.00
Austria	Europe	II	8106	7430	55.44	77.52
Azerbaijan	Europe	II	7594	10881	54.96	83.15
Azores (Portuguese)	Europe	II				
Bahamas	North America	I	284	435	84.76	85.18
Bahrain	Asia	III	570	940	88.62	90.00
Bangladesh	Asia	III	120073	218188	16.74	57.62
Barbados	North America	IV	261	306	45.84	53.15
Belarus	Europe	III	10348	8726	68.56	90.00
Belgium	Europe	II	10159	9763	96.70	90.00
Belize	North America	IV	219	480	47.28	69.64
Benin	Africa	VI	5563	18095	29.92	68.73
Bermuda	North America	IV				
Bhutan	Asia	III	1812	5184	6.00	28.85
Bolivia	South America	IV	7593	16966	57.80	90.00
Bosnia and Herzegovina	Europe	II	3628	3789	49.00	84.15
Botswana	Africa	VI	1484	3320	25.10	77.65
Brazil	South America	IV	161087	243259	72.04	90.00
British Virgin Islands	North America	I	19	37	0.00	0.00
Brunei Darussalam	Asia	III	300	512	57.74	79.29
Bulgaria	Europe	II	8468	6690	68.90	90.00
Burkina Faso	Africa	VI	10780	35419	21.62	90.00
Burundi	Africa	VI	6221	16937	6.78	31.77
Cambodia	Asia	V	10273	21394	18.84	63.06
Cameroon	Africa	VI	13560	41951	42.14	85.83
Canada	North America	I	29680	36352	76.64	89.58
Cape Verde	Africa	VI	396	864	48.24	68.91
Cayman Islands	North America	IV	32	67	100.00	100.00
Central African Republic	Africa	VI	3344	8215	39.00	74.15
Chad	Africa	VI	6515	18004	20.86	52.74
Chile	South America	IV	14421	22215	83.54	90.00
China	Asia	V	1232083	1516664	27.84	75.58
Colombia	South America	IV	36444	62284	71.08	90.00
Comoros	Africa	VI	632	1876	28.96	48.36
Congo	Africa	VI	2668	8729	55.62	90.00
Cook Islands	Oceania	IV	19	29	0.00	0.00
Costa Rica	North America	IV	3500	6902	48.14	84.80
Croatia	Europe	III	4501	3991	61.64	90.00

Cuba	North America	IV	11018	11284	74.56	90.00
Cyprus	Europe	III	756	1029	52.48	65.70
Czech Republic	Europe	III	10251	8572	65.10	84.26
Denmark	Europe	II	5237	5234	84.96	90.00
Djibouti	Africa	VI	617	1506	81.54	90.00
Dominica	North America	IV	71	97	0.00	0.00
Dominican Republic	North America	IV	7961	13141	62.08	90.00
Ecuador	South America	IV	11699	21190	56.24	90.00
Egypt	Africa	VI	63271	115480	44.26	75.44
El Salvador	North America	IV	5796	11364	44.38	75.35
Equatorial Guinea	Africa	VI	410	1144	38.30	90.00
Eritrea	Africa	VI	3280	8808	17.00	50.39
Estonia	Europe	III	1471	1084	72.32	90.00
Ethiopia	Africa	VI	58243	212732	12.74	43.08
Falkland Islands	South America	IV				
Fiji	Oceania	IV	797	1393	39.86	75.26
Finland	Europe	II	5126	5172	62.12	86.52
Fmr. Yugosl. Rep. Macedonia	Europe	III	2174	2646	58.64	85.64
France	Europe	II	58333	58370	72.74	89.02
French Guiana	South America	IV	153	353	75.36	83.52
French Polynesia	Oceania	IV	223	403	56.40	80.30
Gabon	Africa	VI	1106	2952	47.42	87.11
Gambia	Africa	VI	1141	2604	23.76	68.12
Georgia	Asia	III	5442	6028	57.00	86.88
Germany	Europe	II	81922	69542	85.78	90.00
Ghana	Africa	VI	17832	51205	34.92	75.48
Gibraltar	Europe	II	28	28	100.00	100.00
Greece	Europe	II	10490	9013	63.64	90.00
Greenland	Europe	II	58	72	78.90	86.11
Grenada	North America	IV	92	134	0.00	0.00
Guadeloupe	North America	IV	431	634	98.86	90.00
Guam	Oceania	IV	153	250	38.08	59.03
Guatemala	North America	IV	10928	29353	40.24	78.48
Guinea	Africa	VI	7518	22914	27.32	72.45
Guinea Bissau	Africa	VI	1091	2674	20.82	63.32
Guyana	South America	IV	838	1239	34.64	77.45
Haiti	North America	IV	7259	17524	29.80	72.33
Honduras	North America	IV	5816	13920	41.98	80.68
Hong Kong	Asia	IV				
Hungary	Europe	III	10049	7715	63.14	90.00
Iceland	Europe	II	271	363	91.00	90.00
India	Asia	V	944580	1532674	26.02	59.38
Indonesia	Asia	IV	200453	318264	32.52	82.58
Iran	Asia	V	69975	170269	57.38	88.35
Iraq	Asia	V	20607	56129	72.92	90.00
Iraq – Saudi Arabia Neutral Zone	Asia	V				
Ireland	Europe	II	3554	3809	57.14	81.50
Israel	Asia	III	5664	9144	90.42	90.00
Italy	Europe	II	57226	42092	66.66	83.08
Ivory Coast	Africa	VI	14015	31706	41.68	80.91
Jamaica	North America	IV	2491	3886	52.38	83.35
Japan	Asia	II	125351	109546	77.36	90.00
Jordan	Asia	III	5581	16671	69.40	90.00
Kazakhstan	Asia	III	16820	22260	58.44	87.55
Kenya	Africa	VI	27799	66054	25.24	70.52

Kiribati	Oceania	IV	80	165	35.04	61.33
Korea Dem. People's Rep.	Asia	V	22466	32873	60.40	86.06
Korea	8.6	Asia	45314	52146	76.80	90.00
Kuwait	Asia	III	1687	3406	96.34	90.00
Kyrgyzstan	Asia	III	4469	7182	38.48	71.03
Laos	Asia	V	5035	13889	22.00	62.42
Latvia	Europe	III	2504	1891	71.84	90.00
Lebanon	Asia	III	3084	5189	85.16	90.00
Lesotho	Africa	VI	2078	5643	20.88	66.79
Liberia	Africa	VI	2245	9955	43.26	81.47
Libya Arab Jamahiriy	Africa	VI	5593	19109	83.84	90.00
Liechtenstein	Europe	II				
Lithuania	Europe	III	3728	3297	70.12	90.00
Luxembourg	Europe	II	412	461	87.42	90.00
Madagascar	Africa	VI	15353	50807	25.12	68.85
Malawi	Africa	VI	9845	29825	12.48	46.79
Malaysia	Asia	IV	20581	38089	51.36	89.39
Maldives	Asia	V				
Mali	Africa	VI	11134	36817	25.08	68.88
Malta	Europe	II	369	442	88.28	90.00
Marshall Islands	Oceania	IV				
Martinique	North America	IV	384	518	91.62	90.00
Mauritania	Africa	VI	2333	6077	49.60	90.00
Mauritius	Africa	VI	1129	1654	40.54	71.23
Mexico	North America	IV	92718	154120	73.68	90.00
Micronesia	Oceania	IV	126	342	27.04	49.82
Moldova	Europe	III	4444	5138	49.36	87.39
Monaco	Europe	II				
Mongolia	Asia	V	2515	4986	59.16	88.76
Morocco	Africa	VI	27021	47276	47.02	80.38
Mozambique	Africa	VI	17796	51774	29.76	84.67
Myanmar	Asia	V	45922	80896	25.36	63.39
Namibia	Africa	VI	1575	4167	34.10	86.65
Nauru	Oceania	IV	11	25	0.00	0.00
Nepal	Asia	V	22021	53621	12.02	50.65
Netherlands	Europe	II	15575	14956	88.82	90.00
New Caledonia	Oceania	IV	184	295	60.78	76.98
New Zealand	Australia	II	3602	5271	85.32	90.00
Nicaragua	North America	IV	4238	9922	61.04	90.00
Niger	Africa	VI	9465	34576	15.92	51.21
Nigeria	Africa	VI	115020	338510	36.84	81.06
Niue	Oceania	IV	2	2	0.00	0.00
Northern Mariana Islands	Oceania	IV	49	92	0.00	0.00
Norway	Europe	II	4348	4694	72.66	89.08
Oman	Asia	III	2302	10930	11.88	49.00
Pakistan	Asia	V	139973	357353	33.08	75.12
Palau Islands	Oceania	IV	17	35	0.00	0.00
Panama	North America	IV	2677	4365	52.34	83.38
Panama Canal Zone		IV				
Papua New Guinea	Asia	V	4400	9637	15.40	44.58
Paraguay	South America	IV	4957	12565	50.42	88.35
Peru	South America	IV	23944	42292	70.76	90.00
Philippines	Asia	IV	69282	130511	50.96	90.00
Poland	Europe	III	38601	39725	63.38	89.08
Portugal	Europe	II	9808	8701	34.34	70.65

Puerto Rico	North America	IV	3736	5119	72.14	77.17
Qatar	Asia	III	558	861	90.50	90.00
Reunion	Africa	VI	664	1033	65.46	82.23
Romania	Europe	III	22655	19009	54.14	83.77
Russian Federation	Asia	III	148126	114318	74.80	90.00
Rwanda	Africa	VI	5397	16937	5.80	21.97
Saint Lucia	North America	IV	144	235	46.84	52.39
San Marino	Europe	II				
Sao Tome & Principe	Africa	VI	135	294	0.00	0.00
Saudi Arabia	Asia	III	18836	59812	78.46	90.00
Senegal	Africa	VI	8532	23442	40.80	78.06
Seychelles	Africa	VI	74	106	51.68	75.09
Sierra Leone	Africa	VI	4297	11368	33.80	78.09
Singapore	Asia	IV	3384	4190	100.00	100.00
Slovakia	Europe	II	5347	5260	57.42	86.56
Slovenia	Europe	III	1924	1471	60.80	90.00
Solomon Islands	Oceania	IV	391	1192	15.60	40.91
Somalia	Africa	VI	9822	36408	24.80	62.06
South Africa	Africa	VI	42393	91466	49.84	83.52
Spain	Europe	II	39674	31755	75.84	90.00
Sri Lanka	Asia	V	18100	26995	21.80	59.06
St.Kitts & Nevis	North America	IV	41	56	40.72	57.03
St.Vincent & Grenadine	North America	IV	113	174	0.00	0.00
Sudan	Africa	VI	27291	59947	23.34	63.17
Suriname	South America	IV	432	711	48.66	86.17
Swaziland	Africa	VI	881	2228	28.32	78.73
Sweden	Europe	II	8819	9574	83.10	90.00
Switzerland	Europe	II	7224	6935	60.02	84.59
Syrian Arab Rep.	Asia	III	14574	34463	51.08	84.33
Taiwan	Asia	IV	2087	2583.706	0.00	0.00
Tajikistan	Asia	III	5935	12366	32.20	63.48
Tanzania	Africa	VI	30799	88963	22.24	67.52
Thailand	Asia	IV	58703	72969	19.22	53.98
Togo	Africa	VI	4201	12655	29.42	69.11
Tonga	Oceania	IV	98	128	37.50	59.47
Trinidad & Tobago	South America	IV	1297	1899	70.18	90.00
Tunisia	Africa	VI	9156	15907	55.82	87.77
Turkey	Europe	III	61797	97911	64.06	90.00
Turkmenistan	Asia	III	4155	7916	44.90	73.20
Turks And Caicos Islands	North America	IV	15	32	0.00	0.00
Tuvalu	Oceania	IV				
US Virgin Islands	North America	I	106	158	0.00	0.00
Uganda	Africa	VI	20256	66305	11.72	42.09
Ukraine	Europe	III	51608	40802	68.62	90.00
United Arab Emirates	Asia	III	2260	3668	82.20	90.00
United Kingdom	Europe	II	58144	58733	89.26	90.00
United States	North America	I	269444	347543	75.60	90.00
Uruguay	South America	IV	3204	4027	89.46	90.00
Uzbekistan	Asia	III	23209	45094	40.88	72.73
Vanuatu	Oceania	IV	174	456	18.82	38.47
Vatican City (Holy See)	Europe	II				
Venezuela	South America	IV	22311	42152	91.36	90.00
Vietnam	Asia	V	75181	129763	20.26	53.20
Western Sahara	Africa	VI	256	558	41.00	56.82
Western Samoa	Oceania	IV	166	319	57.86	79.20

Yemen	Asia	III	15678	61129	30.78	78.62
Yugoslavia (Serbia, Montenegro)	Europe	III	10294	10979	54.46	88.80
Zaire	Africa	VI	46812	164635	28.50	66.29
Zambia	Africa	VI	8275	21965	42.04	73.61
Zimbabwe	Africa	VI	11439	24904	32.00	72.42

The selection of countries/territories and their names is based on the definitions of borders used in common GIS softwaere (MAPINFO, 1997), population data are from UN (1996) and urbanisation percentages from UN (1997).

APPENDIX B: UNITS AND CONVERSION FACTORS

Powers of 10:

Prefix	*Symbol*	*Value*	*Prefix*	*Symbol*	*Value*
atto	a	10^{-18}	kilo	k	10^{3}
femto	f	10^{-15}	mega	M	10^{6}
pico	p	10^{-12}	giga	G	10^{9}
nano	n	10^{-9}	tera	T	10^{12}
micro	μ	10^{-6}	peta	P	10^{15}
milli	m	10^{-3}	exa	E	10^{18}

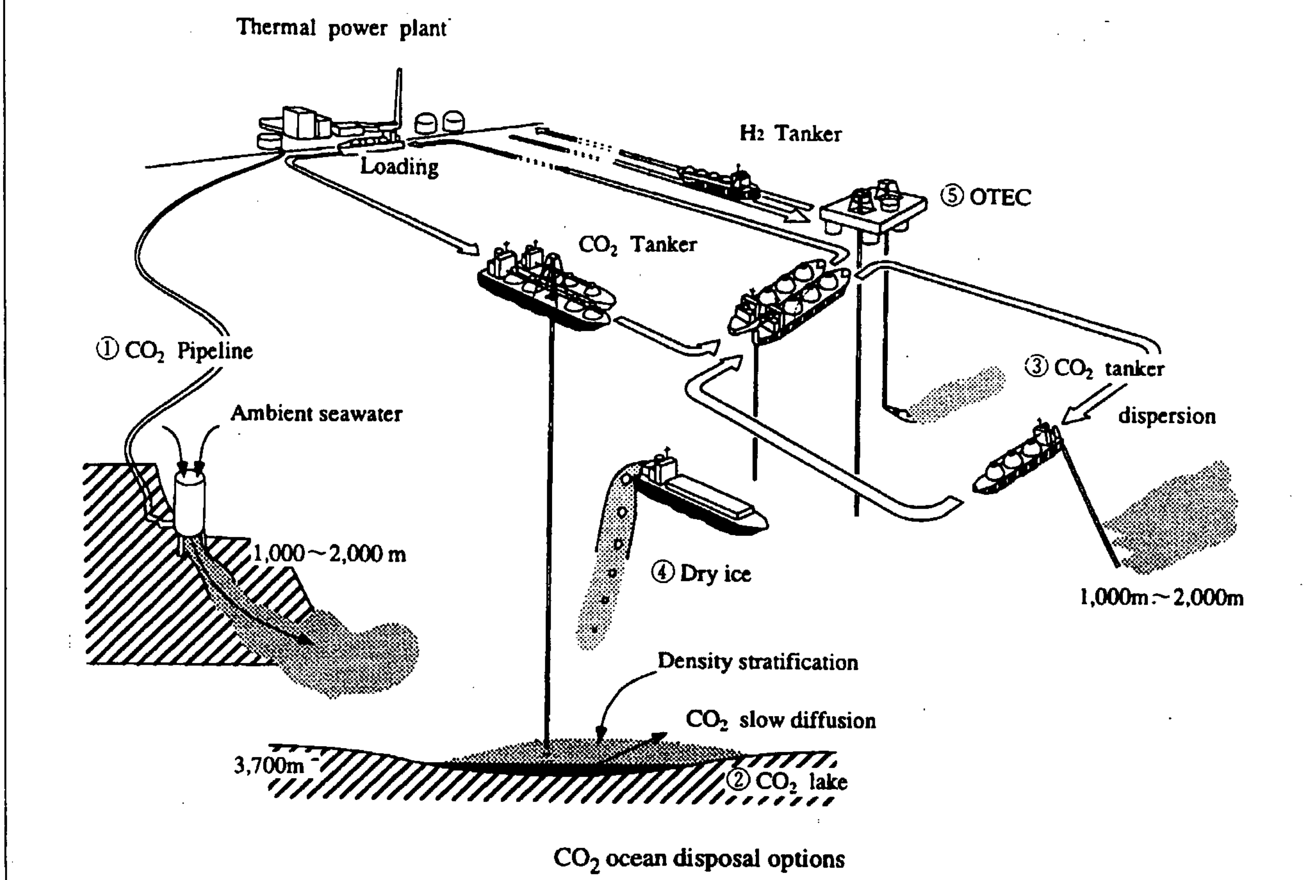
SI units:

Basic unit	*Name*	*Symbol*
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	degree Kelvin	K
luminous intensity	candela	cd
plane angle	radian	rad
solid angle	steradian	sr

Derived unit	*Name*	*Symbol*	*Definition*
energy	joule	J	$kg\ m^{2}\ s^{-2}$
power	watt	W	$J\ s^{-1}$
force	newton	N	$J\ m^{-1}$
pressure	pascal	Pa	$J\ m^{-3}$
electric charge	coulomb	C	A s
potential potential difference	volt	V	$J\ A^{-1}\ s^{-1}$
electric resistance	ohm	Ω	$V\ A^{-1}$
electric capacitance	farad	F	$A\ s\ V^{-1}$
magnetic flux	weber	Wb	V s
inductance	henry	H	$V\ s\ A^{-1}$
magnetic flux density	tesla	T	$V\ s\ m^{-2}$
lunimous flux	lumen	lm	cd sr
illumination	lux	lx	$cd\ sr\ m^{-2}$
frequency	hertz	Hz	$cycle\ s^{-1}$

Conversion factors:

Type	*Name*	*Symbol*	*Approximate value*
energy	electon volt	eV	1.6021 H 10^{-19} J
energy	erg	erg	10^{-7} J (exact)
energy	calorie (thermochemical)	cal	4.184 J
energy	British thermal unit	Btu	1055.06 J
energy	Q	Q	10^{18} Btu (exact)
energy	quad	q	10^{15} Btu (exact)
energy	tons oil equivalent	toe	4.19 H 10^{10} J
energy	barrels oil equivalent	bbl	5.74 H 10^{9} J
energy	tons coal equivalent	tce	2.93 H 10^{10} J
energy	m^3 of natural gas		3.4 H 10^{7} J
energy	litre of gasoline		3.2 H 10^{7} J
energy	kilowatthour	kWh	3.6 H 10^{6} J
power	horsepower	hp	745.7 W
power	kWh per year	kWh/y	0.114 W
radioactivity	curie	Ci	3.7 H 10^{8} s^{-1}
radioactivity	becqerel	Bq	1 s^{-1}
temperature	degree Celsius	°C	K B 273.15
temperature	degree Fahrenheit	°F	9/5 EC+ 32
time	minute	m	60 s (exact)
time	hour	h	3600 s (exact)
time	year	y	8760 h
pressure	atmosphere	atm	1.013 H 10^{5} N m^{-2}
mass	pound	lb	0.4536 kg
length	foot	ft	0.3048 m



(from Fujioka et al., 1997)

APPENDIX C: CLEAN FOSSIL TECHNOLOGIES

(Bernd Kuemmel)

HYDROGEN PRODUCTION

Natural Gas to Hydrogen Plant

From the description of the energy flow given in the introduction it is seen that hydrogen is one important energy carrier. It can be produced from either natural gas, described in the following, or from coal, as will be described later. We have assumed that half the hydrogen will be produced from NG and the other half from coal as described by Sørensen (1996). The basic reaction that one employs, is steam reformation, whereby hot water vapour steam is made to react with natural gas, which mainly consists of methane. The following equation shows the idealised reaction of that step[1]:

$H_2O + CH_4 \rightarrow 3H_2 + CO$

1 As natural gas is purified, *i.e.* contains only very little amounts of *e.g.* H_2S, there will normally not occur catalyst poisoning.

This reaction is endothermic, *i.e.* it requires an energy input, and this is taken from the heat of the water vapour steam, which is cooled down. For that reason the process is called *steam-methane reforming* (SMR). In order to minimise this heat loss, the reaction will in praxis take place over a nickel-based catalyst (Rosen 1996, 1081). The influence of a catalyst allows operation at lower temperatures than otherwise and also gives more control over the product composition (Hauserman 1994, 415). The resultant gas is called *synthesis gas*, or shortly *syn-gas*, the carbon monoxide of which later on is fully oxidised to CO_2 by the so-called *shift reaction*:

$$H_2O + CO \rightarrow H_2 + CO_2$$

The shift reaction is exothermic, *i.e.* it liberates some heat energy, which then again can be used to heat the water to steam for the first reaction.

After those two reactions we have gained a stream of hydrogen and carbon dioxide. The latter has to be removed, which can be done by one of several promising technologies, described later, before we have a stream of hydrogen. According to Rosen (1996, 1083) the product hydrogen purity typically is 97 to 98 per cent[2], and 50 per cent of it stems from the water vapour when using methane as a fuel. This means that there will also be a little amount (about one per cent) of CO_2 in the hydrogen stream. Rosen (1996, 1087) gives an efficiency of 86 per cent compared to the methane feed.

A different method has been described by Poirier and Sapundzhiev (1997): catalytic decomposition of natural gas with fuel stream recycling. In their proposal this would lead to a gas stream rich in hydrogen and some unconverted natural gas, but free of CO or CO_2. Up to a 50 to 60 per cent methane concentration in the stream is not believed to cause problems over a fuel cell stack, and the advantage is that the hydrogen stream would not be diluted with CO_2 as is the case with steam reforming (Poirier and Sapundzhiev 1997, 433).

Their concept is based on having two catalysts, of which one is working and the other is regenerated, whereby the carbon that collects on the catalyst becomes oxidised. The energy liberated so can be used to re-heat the catalysts and would also provide for cogeneration processes. The CO_2 can be recuperated easily. Carbon monoxide that comes from the partial reduction of the catalysts is catalytically transformed to methane, so CO concentrations will be below 5 ppm.

Despite the fact that the authors have not proposed natural gas desulphurisation, as part of the H_2S in the natural gas will be flushed in the form of SO_2 during the catalyst regeneration step, we think that as H_2S today is removed from natural gas to prevent corrosion problems, a similar problem would occur with hydrogen pipelines so that this existing technology should be applied in the future, too.

Such a catalytic technology is maybe another possibility to generate hydrogen from natural gas. This is not what Poirier and Sapundzhiev originally had in mind, but their figure 1 (p. 430) implies that the hydrogen harvest could be surpassing 90 per cent under certain pressure and temperature conditions. This technology might become an alternative to SMR, especially in locations near final consumers, where the heat from the regeneration could be used for steam and power generation, so that the original design would be realised.

Independent of what technology one chooses in the end[3], one important parameter is the cost of the produced hydrogen.

Costs:

We conclude that hydrogen from natural gas will be producible with SMR for about 5.4 Euro per GJ.

Blok *et al.*[4] (1997) propose to use the recovered CO_2 for enhancing natural gas production (NGR) by pumping the recovered CO_2 into almost depleted NG fields. In that way the cost of the hydrogen would only rise about 2 per cent[5] compared to simply venting the CO_2, as is the case today (Blok *et al.* 1997, 166). This gives a cost of the produced hydrogen of about 4 to 5.7 Euro per GJ[6]

Later on Blok *et al.* argue that unless CO_2 sequestration takes place, it would be more cost effective to transport the natural gas, but as we in this scenario have assumed a binding disposal that question is not left open to discuss. Technically it would be difficult to argue for a long range NG transport, if this also implies return transport of CO_2 on a similar

---

2 This means that CO_2 emissions are about 0.6 kg per GJ.

3 Rosen (1996, 1080) summarises a row of hydrogen generating technologies and judges both catalytic decomposition of natural gas or SMR to be mature.

4 Actually Blok *et al.* investigate a SMR method for generating hydrogen, but independent of this their general argument is valid.

5 Although the costs depend very much on the distance between the fields and can rise about 10 per cent if this is increased from 100 to 500 km.

6 Original data \$5.18 to 7.19 per GJ, (for gas prices of: \$3 - \$5/GJ).

scale[7]. This argument is supportive for the assumption that hydrogen generation generally will be taking place near the source of natural gas.

Most of the data on the SMR method shown in Table C.1 were found in Wurster and Zittel (1994, 135), who have collected a series of hydrogen technologies.

Table C.1 Data for SMR of NG, Linde process

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	250	Wurster and Zittel 1994, 135	
annual load, h	8000	Wurster and Zittel 1994, 135	
lifetime, ys	25	Wurster and Zittel 1994, 135	
overall efficiency	81.2 %	Wurster and Zittel 1994, 135	
O&M, in % pa	1		estimate
raw price (Euro / GJ)	3.9	Audus 1996, 840	
product price (Euro / GJ)	5.4		calculated from given data
product price (mEuro / kWh)	19.4		calculated from given data
capacity, MW	387	Wurster and Zittel 1994, 135	
Annual hydrogen output, 10^6 GJ / y	8.6	Wurster and Zittel 1994, 135	
Annual hydrogen output, 10^6 m^3 / y	800	Wurster and Zittel 1994, 135	
Pressure level, Input, MPa	4	Wurster and Zittel 1994, 135	
Pressure level, Output, MPa	3	Wurster and Zittel 1994, 135	
Specific CO_2 emissions, kg/ GJ H_2	16.4	Blok *et al.* 1997, 163	
Specific CO_2 emissions, kg/ m^3 H_2	0.82	Wurster and Zittel 1994, 135	
Specific CO_2 emissions, m^3 CO_2 / m^3 H_2	0.435	Wurster and Zittel 1994, 135	

Source: Wurster and Zittel (1994, 135), data for 2050.

This value should be compared with other literature data: today hydrogen costs about: 12.8 to 16.7 Euro per GJ (CO_2 free, *i.e.* probably the more expensive Kværner process) (Wurster and Zittel 1994, 130)[8]; an internet source gives 3.6 Euro per GJ for steam reformation (IR 10); and a Canadian investigation (Ouellette et al. 1997, 401): 13 (compressed) to 21 - 46 (liquefied) Euro per GJ. The latter source has given market prices for hydrogen for the chemical industry, so that those are probably not relevant for our investigation.

From a figure in Blok *et al.* (1997, 163) we conclude that CO_2 emissions for the EGR option amount to 16.4 kg per GJ H_2.

7 The cost of transmitting the CO_2 100 km would be 0.096 Euro per GJ ($0.12/GJ), which is more than double than that of an equivalent hydrogen transport ($0.05/GJ).

8 Original data: 46-60mEuro/kWh; US¢65/kg; CD$3/kg (compressed) and CD$5-11/kg (liquefied).

Coal Gasification Hydrogen Plant

This section will contain a description of the coal gasification process leading to the generation of process and syngas and the associated hydrogen generation. As a large series of coal gasification processes exists Kristiansen (1996, 16), we will not describe the technologies specifically here. Instead we will present the results of a few investigations on the subject. A part of this description is actually based on descriptions of coal power plants, which are treated below.

In principle the hydrogen production from coal is similar to the production from natural gas, described above, with the exception that there should also be a supply of oxygen for a reaction with the carbon of the coal[9]. In the case of coal gasification we need a stream of water vapour and oxygen led over the coal resulting in the following reactions (Rosen (1996, 1083):

$C_{25}H_{20} + 25\ H_2O \rightarrow 25\ CO + 35\ H_2$; and

$C_{25}H_{20} + 12.5\ O_2 \rightarrow 25\ CO + 10\ H_2$.

83 per cent of the hydrogen from this reaction will, according to Rosen (1996, 1083), derive from the water vapour. The purity of the produced hydrogen should be between 93 and 98 per cent.

Smith and Thambimuthu (1991) mention a technology to produce hydrogen and solid black carbon from the coal, albeit only at a thermal efficiency of 24 per cent. This method does not seem to be very attractive from an energetical point of view.

According to Rosen (1996, 1087) the hydrogen production via coal gasification will result in an energy output of 59 per cent in the form of hydrogen. Another idea of efficiency of the gasification process can be gained from Hauserman (1994, 418), where the product gas[10] is supposed to consist of about 60 % H_2, 2 % CO, 29 % CO_2, and 9 % CH_4. This means that this technology will only be competitive with SMR, if the coal is sufficiently cheap.

In any case, the need to perform product gas cleaning from impurities arises. Jansen *et al.* (1992) propose to use a high temperature gas and fly-slag cleaning system[11]. In their description not the CO_2 itself but actually the hydrogen is removed from the gas stream by ceramic membranes at an efficiency of 88 per cent[12] (Jansen *et al.* 1992, 367, 369). The remaining hydrogen could be burned and so deliver energy for the steam generation.

The coal fuelled hydrogen plants could be installed together with the CO_2 injection sites on platforms at suitable locations on the ocean. Coal would be transported by large vessels[13] to the plant, the CO_2, the ash could be disposed of easily and without extra transport costs, and the hydrogen would be transported to the consumers in ships similar to today's LNG vessels. Part of the hydrogen would be used at the plant for fuelling electrical appliances or pumps via fuel cell solutions.

The fact that swimming production platforms have been developed for the off-shore oil industry should argue for the feasibility of such a technology, too[14]. Such production and deposition platforms might from a safety point of view be situated outside the regions exposed to tropical cyclones[15], *i.e.* within a 5°N to 5°S belt in the tropical oceans. But there slightly more energy will be needed for liquefying the CO_2 and the hydrogen compared to a more temperate location.

Other solutions could be to perform *in situ* or *underground coal gasification* (ICG, UCG, res.) in order to generate a process gas that can be used for hydrogen generation. In principle an oxygen and steam stream are injected in below ground coal reservoirs, where a path of increased permeability has been created by *e.g.* horizontal boreholes or chemical processes (IR 9). The product gas has a heating value of 8 to 11 MJ per Nm^3 (3 to 7 if air is blown instead of oxygen) and contains carbon monoxide, hydrogen and methane. This mixture could be used in some of the technologies that we present. For example the hdyrogen could be separated and sold or the mixture could be fuelled in power stations.

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9 According to Rosen (1996, 1083) coal can be represented as $C_1H_{0.8}$, equivalent to our: $C_{25}H_{20}$.

10 Normally product mixes are given as volume percentages for gases, we assume this is also valid here.

11 In fact this description is also one based on an IGCC method, but we have chosen to present the ideas on the H_2 separation and the cleaning processes proposed by Jansen *et al.* (1992).

12 This might be easier, as hydrogen ions have a very small diameter compared to all other ions. Still those membranes need more development (Audus 1997, 218), but as our scenario looks very much into the future, we think that the use of this technology can be defended.

13 There are obvious economies of scale in very large coal vessels, shown by Huang (1995).

14 As has been described elsewhere, the Mars TLP is one recent example (Spiegel 1996).

15 Those are trivially called hurricanes or typhoons depending on location.

Myasnikov *et al.* and Myasnikov and Lazarenko (1995) have shown that ICG can be realised at some locations in the Kuznetsk basin, Russia, as a means to overcome ecological and logistic problems in the region. This technology would abolish the transport of the coal, minimise other environmental problems, as with slag heaps, and not the least it would make available coal resources that currently cannot be exploited due to large depths and consequential technical problems (Davies 1995, 56).

However, the problem with impurities contained in the ICG gas still has to be solved, and another challenge is to find a way to increase the rate of chemical reactions in the UCG process (Myasnikov *et al.* and Myasnikov and Lazarenko 1995). The deposition of the CO_2 is still a problem, unless it can be disposed of via EOR, res. EGR[16] in nearby depleted oil or gas fields, it will have to be transported to disposal sites.

Hinman (1991, 121) bemoans the lack of interest in R&D on UCG, but his argument on potential ground water contamination by the resumes of UCG seems to be invalid, if this method was used with coal resources at great depth. Only when steeply sloping surface near seams are exploited by this technology, such problems might occur. We may assume that this will not be the case, and that those resources would normally be exploited conventionally or left untouched.

Costs:

The hydrogen from coal gasification would cost about 3.6 Euro per GJ to produce, Table C.2. If UCG was exploited, costs might possibly be somewhat lower.

Table C.2 Data for hydrogen from coal (Linde Prices, partial oxidation)

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	500	Wurster and Zittel 1994, 137	
annual load, h	8000	Wurster and Zittel 1994, 137	
lifetime, ys	30		estimate
overall efficiency	60 %	Rosen 1996, 1087	
O&M, in % pa	1		estimate
raw price (Euro / GJ)	1.6	Kjær 1996, 900	
product price (Euro / GJ)	3.7		calculated from given data
product price (mEuro / kWh)	13.4		calculated from given data
capacity, MW	387	Wurster and Zittel 1994, 137	
Specific CO_2 emissions, kg/ m^3 H_2	2	Wurster and Zittel 1994, 137	
Specific CO_2 emissions, m^3 CO_2 / m^3 H_2	0.807	Wurster and Zittel 1994, 137	

Source: data for 2050 from Wurster and Zittel (1994, 137); Data for partial oxidation of coal, Linde process.

The data in Wurster and Zittel (1994, 137) seem to indicate that CO_2 emissions are about 14 kg per GJ (50 g per kWh).

Hydrogen Storage and Transport

Some of the technologies that currently are being used for NG storage will also be feasible , albeit modified, in a hydrogen energy system. On a large scale, hydrogen storage may take place in the form of empty caverns, in the same way

16 *Enhanced Oil Recovery*, res. *Enhanced Gas Recovery*.

that natural gas is stored today. But opposite to natural gas at the present time[17], the need may arise to store the hydrogen decentralised, *i.e.* in smaller units. For example the use of decentralised fuel cells will cause the need to address decentralised hydrogen storage.

Following Taylor (1994, 369) we conclude that hydrogen stores should not pose much larger risks than refineries or ammonia plants where the substance that may escape is poisonous. Hydrogen is very volatile, so that rapid dilution would reduce explosion danger. Data on the risks related to natural gas storage plants would probably also be representative for hydrogen storage, and be similar to interpret as indicated by Taylor (1994, 386). As with town gas, odorants may be added to the hydrogen for easier leak detection. If a sulphur containing odorant is chosen, it will have to be removed before use to avoid fuel cell poisoning.

Morthorst *et al.* (1993, 22) mention hydrogen's wide range of inflammability, a low ignition energy and a large range of mixture area for explosivity as important factors for a risk assessment. Another problem is that hydrogen can cause brittleness in various metals, so that different alloys will have to be employed for pipes and compressors and new materials for seals and valves compared to today's natural gas technologies (IR 10).

So far hydrogen has not been used on a very large scale as an energy carrier, so that storage technology for this fuel still are developing. Apart from storing it in gaseous form, as described above, attempts have been made to investigate other forms of storage (Zittel and Wurster 1994, 118 f.): in the form of metal hydrides, within sponge iron, as a liquid, by cryo-adsorption or in the form of liquid hydrides. All of these technologies have some relevance to the transport of the hydrogen, too. We will not present data on the storage systems separately, as they will implicitly be covered in the hydrogen transport.

If we look at the storage as such, then its efficiency is crucial. For example to compress hydrogen at a "petrol" station will need about a fifth of the energy in the hydrogen (IR 10). The efficiency of this process therefore is only about 80 %. It looks even worse for cryogenic storage, where the parasitic energy for the pumping is about 40 % (IR 10). This might be defensible for a high-cost application as in the transport sector – it might be unobtainable in other sectors, where fuel efficiency is of vital importance.

What these problems imply is that storage will have to be done in a pressurised form for decentralised and mobile applications. For maritime transport from remote sources of hydrogen, cryogenic methods deem to be reasonable, while for long-range terrestrial transport, pipeline solutions will be the technology of choice.

As has been presented elsewhere in this text, it might be realistic to introduce the full hydrogen energy system stepwise, *i.e.* by starting distributing natural gas and hydrogen mixtures by pipelines. In that respect it might prove less expensive to transport hydrogen rich mixtures at elevated pressures compared to natural gas at low pressures (Öney *et al.* 1994, 818).

This is not obvious from the start, as hydrogen actually has a lower energy content per volume than natural gas, which consists nearly exclusively of methane. To transport the same energy amount a larger volume has to be moved with hydrogen than for methane. This increases the power demand and numbers of compressors. As a balance between the costs for those and the pipe, whose diameter can be increased to enable easier flow, needs to be established, the pressure, at which the hydrogen is provided, has an important influence.

Already if one compares transport of coal, natural gas and electricity by rail, pipeline or by overhead cables for comparable distances, it has been shown that electricity transport generally is unfavourable. The costs for natural gas and coal transport by (slurry) pipeline are generally the lowest (Davies 1995, 65)[18].

If the transport distances to the markets are comparatively short then the advantage of using the CO_2 from SMR could be used for EGR has to be considered. However Blok *et al.* (1997, 167) also stress that the situation is complicated in that for distant hydrogen markets it would be less costly to transmit the natural gas to the hydrogen plant near the market, where pressure levels for distribution would be lower. In those cases the transport of the CO_2 becomes the economically limiting factor.

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[17] This comparison is not quite fair, as compressed natural gas (CNG) is being used in some cases, like for cars in New Zealand. Also other light hydrocarbons, like propane, are being stored in pressurised or liquid forms. However, those contribute not overwhelmingly to the global energy supply today.

[18] For natural gas Jensen (1994, 248) shows a graph from which we conclude that transporting NG 3200 km (2000 miles) would cost about 1.3 Euro per GJ onshore and about 2.3 Euro per GJ offshore. For longer distances LNG transports cost about from 1.9 to 2.6 Euro per GJ (6400, res. 11300 km; 4000 res. 7000 miles).

We also have to take into consideration that in the future due to the growing awareness of the limitation of the fossil resources the primary energy supply will have to be economised with. In this situation one would give emphasis to exploiting natural gas sources using EGR as compared to transporting the natural gas to the customers at the expense of not being able to exploit the whole resource. This can then be somewhat compensated for by gasifying an extra amount of coal to produce more hydrogen, but this will in reality very much be directed by the economics of each solution.

As a first idea it might be allowable to calculate with an overall efficiency of the hydrogen store and pipeline system of about 86 per cent, as proposed in Sørensen (1996). The actual distribution of the losses will then have to be gained from a deeper analysis.

One question arises from the transport of cryogenic hydrogen: where shall the energy come from to heat it up so that it can be sent out as a gas in the distribution pipelines? In some places this can be done at the land-based power stations, where the cold can be used to chill the CO_2 separated from the flue gas stream. This of course will dictate the location of most of the power stations, *i.e.* they have to be placed near the landing sites of the hydrogen tankers.

At other places this synergy might not be able to exploit, so the heat would have to come from the environment. In the winter period this would not be favoured. But in the summer period for example this can be a prominent solution, when the cold could be used for chilling purposes. This would in many instances save extra energy for air conditioning equipment. One could also imagine using the heat difference between the liquid hydrogen and the environment in a rankine kind of engine.

Table C.3 Data for hydrogen pipeline transport

parameter	value	source	remarks
Technical data	**per unit**		
spec. investment, Euro/kW	400	Wurster and Zittel 1994, 144	
annual load, h	8000	Wurster and Zittel 1994, 144	
lifetime, ys	30	Wurster and Zittel 1994, 144	
overall efficiency	86.2 %	Wurster and Zittel 1994, 144	
O&M, in % pa	2		estimate
product price (Euro / GJ)	0.6	Wurster and Zittel 1994, 144	calculated from given data
product price (mEuro / kWh)	2.2	Wurster and Zittel 1994, 144	calculated from given data
Inlet Pressure, MPa	10	Wurster and Zittel 1994, 144	
Outlet Pressure, MPa	5.9	Wurster and Zittel 1994, 144	
Capacity, GW	72	Wurster and Zittel 1994, 144	
Annual Delivery, GWh	774000	Wurster and Zittel 1994, 144	

Costs:

As explained above hydrogen storage costs will be implicitly included in the transport costs. We think the hydrogen transported to the customers generally would cost about 6 Euro per GJ. This value includes the intra-continental maritime and on-shore transport and storage.

The total cost of hydrogen from production to the distribution channels will then be about 9.6 to 11.4 GJ per Euro, depending on whether it has been produced from coal or natural gas. An average value might be 10 Euro per GJ.

The costs of pipeline hydrogen transport has been given by Öney *et al.* (1995, 819 f.) of about 0.3 to 1.0 Euro per GJ for a 200 km transport length (depending on the inlet pressure) and of 1.6 Euro per GJ for 500 km[19]. For a distance double that, we estimate that costs would be about 3 Euro per GJ, perhaps slightly lower[20]. Taking the value from Blok *et al.* (1997, 167) would result in a cost of only 0.04 Euro per GJ and 100 km pipeline transport, or 0.2 Euro per GJ for 500 km[21]. Values from Wurster and Zittel (1994) give a cost figure of about 0.6 Euro per GJ, Table C.3.

In this respect it might be interesting to note that a majority of the global population is currently living within 60 km of a coast, and that this share will increase to at least about 75 per cent[22]. This means that transport distances on land would be small, if hydrogen was shipped from off-shore installations to the coasts.

As with the case of *liquefied natural gas* (LNG), where transport is currently taking place in special vessels, this can also be realised with liquefied hydrogen (LH_2). Problems arise from: extremely low density, very low boiling point and the safety aspects (Giacomazzi 1989, 603). In order to prevent boiling losses it is essential to have fast vessels (16 to 19 knots[23]), and the insulation of the containers has to be optimised (ibid., 605, 613). Another challenge is making the vessels stable against rolling[24] to protect the ship's structures, the liquid gas containers, and make cruising less of a nuisance for the crew.

Opposite to Giacomazzi (1989, 614) we believe that the boil-off will be used for propulsion, as fuel cell electrical units will be applied in maritime transport, as described in Wurster and Zittel (1994, 150).

Giacomazzi (1989, 615) gives an overview of the costs of the LH_2 transport by the vessels. Actually those values need to be recalculated in order to take into account the substitution of the bunker with boiled-off hydrogen and fuel cell solutions. For a ride of 3000 nm costs could be as low as about 2 Euro per GJ[25]. For a similar solution another source results in a value of lower than about 5.6 Euro per GJ (Wurster and Zittel 1994, 146)[26].

On the other hand maritime and land-based transcontinental transport of LH_2 in containers could be realised gradually, by starting with standardised commercial vacuum super-insulated ISO 40 ft containers (40 m^3 LH_2) (Wurster and Zittel 1994, 119, 145) with boil-off losses of about 5 per cent for a holding period of 30 days (=0.01 % / d). Investments costs would be about 900 Euro per kW, which would result in fuel cost adders of about 3 Euro per GJ[27].

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19 about \$.4-1.2/GJ; about 2.3 $\$_{1994}$.

20 Costs would still about double at this distance, as compressor and pipeline costs develop almost linearly with the distance, and any economies of scale, for larger power transport, will have limited importance (Öney *et al.* 1995, 820).

21 Original data: $\$_{1991}$0.05/GJ (100 km) at a pressure drop of 2.5 bar per 100 km.

22 Today two-thirds, expected to rise to 75 % by the year 2010 (Scott *et al.* 1996, 404).

23 One knot is one nautical mile, nm, per hour.

24 This is related to the metacentric height, which results from the difference between the metacentric radius and the height of the centre of gravity (Giacomazzi 1989, 605).

25 Original value: about 25 mEuro per normal cubic metre of hydrogen at about 12.7 MJ / Nm^3. With reference to the values for LNG tankers given in footnote 61: If we take into consideration that costs for hydrogen transport will be higher than for LNG, as the required storage temperatures are lower so insulation demands higher, then assuming about a tripling in costs will only mean about 1.5 Euro per GJ. Technological developments could mean lower realised costs than assumed here.

26 Original value: <2 cEuro per kWh. If one uses the data given in Wurster and Zittel (1994, 119) to compute the average cost of LH_2 transporting, then a value of 2.6 to 3.2 Euro per GJ results. It has been assumed that the cost of the barge carrier will only appear with a weight of one tenth, as it would be shuttling between consumers and production sites and be able to carry five barges at a time. Using the same cost values for a larger so-called SWATH-ship design, transportation costs come down to: 0.3 to 0.4 Euro per GJ!

27 The energy needed for this transport should be deducted from the end-use energy in the transport sector to make the analysis fair.

Hydrogen CHP Stations

Centralised IGCC power stations with CO_2 recovery will be presented later on, but there will have to be CHP power stations elsewhere in the energy system. They will be hydrogen fuelled, as this fuel is the *energy currency*[28] of the energy system. Therefore we investigate hydrogen fuelled fuel cell power stations or CC plants with *gas turbines* (GT). The reason that also GT solutions arise is that those can provide electricity at a very high efficiency, which in places will be a large advantage. We start with the presentation of the fuel cell technology.

In a flaming article Rogner (1994) boasts of *fuel cells* (FC) being the only technology in the power sector with a clear future perspective, as it can exploit several kinds of fuels and therefore opens up for new solutions. This all sounds very nice. But what is the FC technology actually?

A fuel cell is an electrochemical device to generate electricity from a stream of energy carriers like hydrogen or natural gas. The most prominent FC technology for utility application is probably the *solid oxide fuel cell* (SOFC) technology, which can be used reversibly, too (Morthorst *et al.* 1993). But a series of other FC technologies exists: MCFC, PAFC, etc.[29]. Common for all of them is that they convert the chemical energy of a fuel directly into an electrical voltage, which then can be fed into the electricity grid, after having been reformed to AC voltage[30], unless DC systems are being employed on a local scale.

When Lobachev and Richter (1996) present an investigation of a power station employing the SOFC technology, they also treat aspects as the influence of the FC voltage: an increase from 0.6 to 0.7 Volts is equivalent to an increase in the FC efficiency by about 4 per cent. Higher voltage during production leads to lower current intensities for the same power output[31] and this minimises ohmic losses[32]. On the other hand one then has to install more fuel cell clusters to achieve the same overall efficiency, so that an economic balance will have to be found.

The coupling of fuel cells with steam turbines (CC) is possible, but shall not be presented here. However, Kobayashi *et al.* (1997, 190) have presented a new and innovative hydrogen fuelled "chemical" gas-turbine system with an efficiency of 64 per cent. This is about 10 per cent higher than today's NG fuelled GT CC.

If we consider that electricity will have to be produced at a very high efficiency due to the relative increase in demand for this energy carrier, then we will have to choose such a technology as standard for the future energy system. The assumption of an electrical efficiency of 60 per cent (1300/2200 GWy) in the original scenario sketch (Sørensen 1996) therefore seems to be reasonable.

In decentralised installations FCs will provide space heating. In the later section on the scenario results and their interpretation it will be assumed that the transmission of this heat will take place with the same efficiency as in larger district heatign systems: *e.g.* 80 %. To indicate potentials to integrate FCs with other technology, one could use absorption cooling integrated in PAFC or MCFC systems to meet cooling or air conditioning requirements (Troost 1994, 190). Such integration will be a more natural feature in the energy systems of the future, but unfortunately we cannot take those into consideration to a high degree of detail.

Costs:

Electricity generation costs from hydrogen fuelled CHP would be around 18 Euro per GJ. This value needs to be corrected for the cogenerated heat, which will in places lead to cost reductions, see the section on cogenerated heat and electricity costs below.

Ippommatsu *et al.* (1996, 134, 135) have analysed the production steps in fuel cell manufacturing and considered six different designs of SOFC. They conclude that it should be possible to manufacture fuel cells at a cell cost of between 360 and 624 Euro per kW, so that system costs for a power station would be around 1600 Euro per kW[33]. In fact FC

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[28] Scott (1995, 90).

[29] Besides SOFC there are also several other types of fuel cells that are currently being investigated: *AFC* (Alkaline Fuel Cell), *PAFC* (Phosphoric Acid Fuel Cell), *PEMFC* (Proton-Exchange Membrane Fuel Cell), *MCFC* (Molten Carbonate Fuel Cell), or *SPEFC* (Solid Polymer Electrolyte Fuel Cell), *SPFC* (Solid Proton exchange Fuel Cell), *DMFC* (Direct Methanol Fuel Cell), (Stimming *et al.*, 1992).

[30] Losses for this process should be about 3 % (Lobachev and Richter 1996, 288).

[31] The electrical power is equal to the voltage times the current: $W = U \cdot I$.

[32] This means that the electricity flow through the FC will be reduced less by the normal electrical resistance of the material, so that more power is made available to the electricity generation.

[33] Original data: \$450.780/kW (FC); \$2000/kW (system cost); \$200/kW (cell cost future).

costs should become even lower: If one assumes a higher power density (in W per m^2) for coming commercial fuel cells, then cell costs should be in the 160 Euro per kW class.

If we, just for fun, combine information on the balance of plant costs of a total plant with a range of 65 to 85 per cent (Penner *et al.* 1995, 413) with expected costs of PEMFC fuel cells from the transport sector, where prices have to be very low: 24 to 32 Euro per kW[34] (ibid., p. 424), then we end up with estimates of: 28 to 49 Euro per kW, which might be far too optimistic, but probably may be realised in the end. The transport sector is not the least competitive sector in the World!

Penner *et al.* (1995, 380) state that the system costs of hydrogen fuelled FC CC power stations would reach about 800 Euro per kW[35] around 2010. A Danish source, DEA (995a, 83) estimates about 600 Euro per kW[36] for 2015. Judging from the necessary development in the transport sector economics for fuel cells should become much more favourable, so that even lower costs than those will be applicable. However, energy costs are not very sensitive to a change in the installation costs, 500 Euro per kW instead of the chosen 600 will only lead to a reduction by 2 per cent!

Data for hydrogen CHP

parameter	**value**	**source**	**remarks**
Technical data	**per unit**		
spec. investment, Euro/kW	600	DEA 1995a, 83	
annual load, h	7500		estimate
lifetime, ys	30	DEA 1995a, 83	
overall efficiency	64 %	Kobayashi *et al.* 1997, 190	
O&M, in % pa	5	DEA 1995a, 83	
raw price (Euro / GJ)	10		calculated from given data
product price (Euro / GJ)	17.9		calculated from given data
product price (mEuro / kWh)	64.3		calculated from given data
capacity, MW	100		estimate

Note: This technology would be modular, *i.e.* capacities could range from some kW to several hundred MW. **Overall efficiency:** here means only of electricity generation. Depending on local conditions it will be possible to co-generat heat, this will mean an extra of about 30 per cent, but at a reduction of the produced electricity amount!

CO_2 RECOVERY

In this study we assume that the *power plants with CO_2 recovery* (PPCR) are fuelled with coal[37], as this is the largest fossil energy source known today. The power stations are of the combined cycle type; where heat from a first combus-

34 \$30-40/kW.

35 \$1000/kW.

36 5-6 Mkr_{1994}/MW for a NG fuelled CHP power station, *i.e.* the investment includes the heat generation part!

37 When we write “coal”, we actually think of coal that will be useful for gasification. This will change, for example the specifications with respect to the ash fusion point temperature compared to specifications for current power stations (Scott and Carpenter 1996, 63). With respect to lignite (sometimes called brown coal, in German: Braunkohle) Haupt (1996, 107) describes an IGCC project with an efficiency estimated to lie between 45 and 46 per cent. This is impressively high for lignite, so this might open up the use of this kind of lower quality coal for power purposes.

tion step is recovered to produce steam for a conventional turbine; and equipped with a CO_2 recovery technology. These power stations thus are different from most current ones[38].

One technology we cannot describe properly, as we were not able to find appropriate data for it. It may, however, be one option in the future: the *magnetohydrodynamic* (MHD) energy conversion, whereby heat can be converted directly into electricity. It is currently only in an investigative phase and will not be treated in the following, although it is expected to reach efficiencies of between 50 and 55 per cent for a second generation, triple cycle[39] configuration (IR 9) and might have the potential to become the large scale power technology of choice in some decades. Its main advantage, from an exergy point of view, is that it exploits the high temperature of the flame better than gas turbines (Sens *et al.* 1994, 275).

The combined cycle technology has been chosen, as only this will ensure high thermal efficiency, which is a vital fact when we recall that the CO_2 recovery itself will need some energy. Furthermore the *combined heat and power* (CHP) technology will be considered, its success in the Netherlands have been described by Blok and Farla (1996), and its energetical advantages are obvious.

In principle there are three basic technologies to make power stations with CO_2 capture: burning the fuel with air and separating the CO_2 from the flue gas, burning the fuel with pure oxygen and recycling the CO_2, or reforming the fuel to a product gas, removing the CO_2 and fuelling with the hydrogen instead (Akai 1995, 801). The latter technology will here be treated as a modified version, and with respect to the first two we will argue for the second, *i.e.* the CO_2 recycling, as this most probably will lead to the lowest costs.

We have used following sources for information on this technology: Hendriks *et al.* (1989), Nakabayashi *et al.* (1995), Peters (1989) and several other texts[40]; and we argue for the use of an *integrated coal gasification combined cycle* (IGCC) power station technology with subsequent CO_2 recovery. In the first place this might seem to be proposing a completely new concept, but an IGCC PP can be realised in several phases, as explained in Haupt (1996), so in principle one could already today prepare possible IGCC sites.

If we start with the gasification part, then Peters (1989) describes several technologies leading to the production of a CO and H_2 mix, the raw or product gas, which afterwards is cleaned to remove dust and pollutants like H_2S, NO_x or SO_2. The coal gasification technology offers the advantage of pre-scrubbing of the raw gas – opposed to end of pipe *i.e.* after the end of the combustion process. This makes possible very low emissions of SO_2, and NO_x emissions can be abated easily too. It might not be essential to realise a hot gas cleanup, as the improvements will only be about one per cent in the total power station efficiency (Haupt 1996, 108).

Opposite to PF power stations low ash fusion temperature coal are preferred for gasification (Kobayasi 1994, 313). This will enable exploitation of coals not now favoured with the utilities, but the mixing of different coal types to reach the specifications most favourable for a specific plant is already today a well-established technology.

There may or may not occur the necessity to provide pure oxygen for coal gasification. At the time of Peters (1989, 682) no relief from this open question could be offered, and Peters referred to the need of more experimental work to infer, whether the need of pure oxygen becomes necessary. The disadvantage is that it is expensive to produce this gas by *air separation* (AS), the advantage is that the volume of the flue gas produced is reduced and that other gases like argon or nitrogen may be sold (Shao *et al.* 1995, 1117).

If we assume coal combustion with recycling of CO_2 to keep *e.g.* turbine entrance temperatures low enough or flame temperatures from smelting the boilers, the liquid oxygen from the AS can be easier compressed than gaseous oxygen by the gas turbine's compressor and it can furthermore be used to condense part of the CO_2. This integrated process saves significant energy amounts for this activity and should theoretically increase the efficiency of the gas turbine[41] (Shao *et al.* 1995, 1117 f., 1120).

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[38] Today's state of the art coal fired power stations are using a *pulverised coal* (PF) burning technology. The low CO_2 concentration in the flue gas makes CO_2 recovery difficult and costly. For various reasons pulverised coal fired power stations with CO_2 recovery will result in about doubled electricity costs and are suffering from other problems, for example a doubled space demand from the CO_2 recovery plant (Herzog 1996, 224 ff.).

[39] Triple cycle refers to a combined MHD, gas turbine, steam turbine PP.

[40] Some overview may be gained from MIT (1996), but the one-sided abstracts collected there give a sketchy picture only.

[41] In the case of Shao *et al.*'s example of a NG PP by about 3 to 5 per cent. For IGCC a similar amount might be achievable, if the power station is based on gas turbines.

Also the O_2/CO_2 technology almost reduces CO_2 emissions. The CO_2 can be separated easily, *i.e.* without the need of CO_2 separation from flue gases diluted by *e.g.* nitrogen, as occurs in today's airblown power stations. Another advantage of the CO_2 recycling is the reduction in NO_x creation. Okazaki and Ando (1997, 214) have shown that the reduction of recycled NO in the furnace is dominant and amounts to 50-80 % of the total observed NO_x reduction.

For an IGCC without CO_2 recovery Peters (1989, 689) gives a range from 47 to 49 gross and from 43 to 45 net electrical efficiency[42], depending on the gasifier types. This is higher than the 41 to 42 per cent mentioned by Nakabayashi *et al.* (1995, 17). A somewhat higher value is cited by Akai *et al.* (1995, 802) for an oxygen blown IGCC: 43.0 per cent, while the US Department of energy expects 52 per cent net by the year 2010 (IR 8).

The gas turbine solution is currently a very attractive option, and further development has been be noted[43]. On the other hand Hauserman (1994, 416) and Pruschek (1996, 443) declare that an IGCC plant with advanced fuel cells might exceed efficiencies of 60 per cent. And in fact Lobachev and Richter (1996, 289) have presented data that indicate an efficiency of 62 per cent for an IGCC SOFC power station.

If we then consider CO_2 recovery, the net efficiency, *i.e.* the power output relative to the energy input of the coal, will decline. This is a natural consequence of the energy demand necessary to separate the CO_2 from the flue stream, the compression and cooling of the gas for transport and disposal. However, the 38.1 per cent efficiency given by Hendriks *et al.* (1989, 136) seems to be too low, if one compares with later texts on the topic.

Prutkovsky and Chavchanidze (1995, 217) describe CO_2 recovery by "freezing out" and argue that more than 100 per cent LHV efficiency can be achieved via an increase of the dew point temperature and the use of the latent heat of vaporisation. It is a little bit doubtful, whether this is correct; their text is not easy to understand, so we disregard their argument.

Haupt (1996, 107) considers an IGCC with gas turbines and mentions an efficiency of 40.5 per cent with a CO_2 recovery of 88 %. Jansen *et al.* (1992, 369) give a value of only 34.5 per cent for a gas turbine IGCC with about 97 % CO_2 recovery, but 47.5 per cent for an IGCC power station based on the MCFC[44] fuel cell technology. The CO_2 would be compressed to 110 bar. The advantage of the fuel cell technology is that the power drop due to the CO_2 separation is much smaller than for the gas turbine system. Another feature with the fuel cell system is that high-temperature flue gas cleaning CO_2 removal are easier (Jansen *et al.* 1992).

Altogether, *i.e.* after taking into account the CO_2 recovery (see a description of it in the special section later on), the electrical efficiency of such a power station would then be still at least 45 per cent. Some heat will also be available, we guess between 10 and 40 per cent, the exploitation of it depends very much on the local and climatic conditions. There should not be any objections to also have such power stations running in a cogerating mode.

So from an energetical point of view alone we would probably choose the fuel cell solution. We will therefore also have to look at the economical situation.

The correct location of power stations with CO_2 recovery depends very much on the transport costs of the various materials. Seifritz (1996) illustrates an example[45], where the correct location of a PP w/CR also depends on whether the coal is transported cheaply by barge, or more expensive by rail. Therefore we cannot answer the location question with confidence.

Costs:

With respect to electricity generation the IGCC w/CR power would cost about 11 Euro per GJ. This price has to be corrected for any cogenerated heat, see the section on cogenerated heat and electricity costs below.

As said before we have chosen to concentrate on the combined cycle technology for the electricity generation. Pruschek *et al.* (1996, 442) explain that conventional coal power stations have reached their technological and economical limits. Rising the steam temperatures above today's values[46] can only be achieved with the help of special Nickel-based alloys. Presently those are so expensive that the increase in efficiency will no longer outweigh the extra construction costs.

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42 = after own consumption and transformer losses have been discounted

43 For example Haupt (1996, 104) on the Siemens 3A gas turbine efficiency jump and achieved NO_x reduction.

44 MCFC = Molten Carbonate Fuel Cell

45 The mathematics of this is not trivial and necessitates solving a polynomial of 8th degree.

46 This would lead to *ultra super-critical steam cycles* (USC).

For the industrialised world today, with conventional *pressurised fluid bed* (PFB) *pulverised coal* (PF) fired power stations with *flue gas desulphurisation* (FGD), the standard solution would be to use a physical or chemical absorbent to capture the CO_2 (Riemer and Ormerod 1995; who have given an overview of CO_2 capture and sequestration studies of the IEA). This is probably not very effective, as the CO_2 concentration in the flue is diluted by the stream of nitrogen from the air, and the efficiency of those power stations is below 50 per cent[47]. Therefore electricity generation costs would almost double, if one wants to retrofit them with CO_2 removal.

Even the most optimistic case of a natural gas *combined cycle* (CC) with a chemical scrubbing agent (MEA) would cause a rise in generation costs, and also CO_2 recycling would, according to Riemer and Ormerod (1995), still mean almost a doubling of generation costs. Some other quotations are given in the next paragraph.

Peters (1989, 692) mentioned specific investment costs of 1350 $Euro_{1990}$ per kW for a natural gas fuelled 500 MW CC and 1130 $Euro_{1990}$ per kW for a conventional coal power station. Costs would decline below 830 $Euro_{1990}$ per kW, only if ISTIG gas turbines were applied. Hendriks *et al.* (1989, 131) gave a value of 1610 $Euro_{1990}$ per kW for a coal fuelled single cycle power station with CO_2 recovery.

Data for coal fuelled IGMCFC w/CR

parameter	**value**	**source**	**remarks**
Technical data	**per unit**		
spec. investment, Euro/kW	2000		estimate
annual load, h	8000		estimate
lifetime, ys	25	Jansen *et al.* 1992, 370	estimate
overall efficiency	47.5 %	Jansen *et al.* 1992, 369	
O&M, in % pa	5	DEA 1995, 84	
raw price (Euro / GJ)	1.6	Kjær 1996, 900	
product price (Euro / GJ)	10.8		calculated from given data
product price (mEuro / kWh)	39.0		calculated from given data
capacity, MW	800		estimate
collected CO_2, g / kWh	710		calculated from given data
specific CO_2 emissions, g CO_2 / kWh	25	Jansen *et al.* 1992, 370	

Notes:

Overall efficiency: here means only of electricity generation. There will also be possible to exploit cogenerated heat, which depending on local conditions, will mean an extra of up to about 40 per cent. **O&M:** contains membranes and fuel cells with life spans of only 5-10 years (Jansen *et al.* 1992, 370). The **annual load** of 8000 hours is due to the fact that load evening probably will be better achieved with the hydrogen system than with using the coal fired power stations as reserves.

And price expectations have continued to plunge. For a 500-600 MW IGCC power station the specific investment might go down to about 800 Euro per kW (Pruschek *et al.* 1996, 447; IR 8). This argument is followed by Haupt (1996, 105),

47 Even though Kjær (1996, 897) boasts of the PF Esbjergværket with a world record of 45 % rated efficiency, this technology will not be applicable for the mid-21 century treated by this scenario. One reason is that the higher value of electricity will make it essential to provide as much of this energy form as possible.

who expects the same investment costs for IGCC as for conventional PF power stations at the end of the 1990s[48]. From the discussion given before we therefore conclude that estimated capacity costs will be about 2000 Euro per kW for an IGCC or IGMCFC with CO_2 recovery.

With respect to the costs of the produced electricity Jansen *et al.* (1992, 370) give a comparison relative to the IGCC system without CO_2 recovery at an efficiency of 43.6 per cent. Compared to this base line the IGMCFC, with 88 % H_2 recycling, would have generation costs about 40 to 60 per cent higher, and with 95 % H_2 recovery 30 to 50 per cent higher. If CO_2 removal was "optimised" the costs were only 20 to 40 per cent higher[49]. Thus, Jansen *et al.* conclude that CO_2 emissions can be reduced at only a modest increase in production costs.

Akai *et al.* (1995, 802) support the argument by Jansen *et al.*, in that they also only assume power generation costs rising by 20 to 50 per cent due to the CO_2 recovery. They also mention that the efficiency of each technology varies on the carbon content of the fuel, the temperature and pressure situation in the power station and the concentration of SO_2 in the flue gas. This has not so much influence for our analysis as we have assumed that coal will be the main medium used in central power stations, the only free parameter thus is the sulphur content of the fuel, which may vary.

The table that Akai *et al.* (1995, 804) give on PP technologies with CR, gives an overview of the generation costs compared to the reference case, *i.e.* without CR. There values are not directly comparable with the ones mentioned before, as they give values for a complete system and also take into consideration the actual sequestration. For the examples that fit best with our ideas, generation costs would rise by about 40 to 50 per cent.

Also Audus (1997, 219) argues for a rise of generation costs by about 40 per cent above current levels. This is, opposed to Akai *et al.*, not yet covering the transport and disposal of the generated CO_2.

The low investment cost of such a plant might be surprising. However, if we follow the arguments by Haupt (1996) and Pruschek *et al.* (1996) then we have to acknowledge the rapid cost developments that are taking place in the IGCC technology. Probably the same, or slightly lower, costs are applicable, if the coal is to be gasified *in situ* (ICG).

CO_2 emissions would be 7 kg per GJ (25 g per kWh).

CO_2 RECOVERY AND DEPOSITION

We deem it rewarding to investigate the CO_2 recovery and deposition technologies that are being investigated today, and so have included this descriptive section.

Costs:

Costs for electricity, cogenerated heat, and hydrogen should be only increasing by less than about 1 Euro per GJ from the CO_2 sequestration chains described in the following.

CO2 Recovery

Although we already have treated some of the CO_2 recovery methods when the different power station technologies were described, we want to give a collective picture of this technology.

There are a range of CO_2 absorption technologies ranging from dry to wet chemical or physical, membrane or cryogenic processes – as described by Audus (1997, 218) – which could be applied to current power station technologies. Generally the energetics of power stations with CO_2 recovery are worse than for normal power stations, though.

In Hendriks *et al.* (1989, 127 ff.) a chemical process is described, as it seems to be the best one applicable. It is argued for that the CO_2 concentration in the exhaust gases generally is low[50] so that chemical absorption is most suitable. A MEA-based[51] process is being proposed for the first absorption, thereafter it is desorbed at a higher temperature, compressed, dried and cooled.

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48 The original prices were quoted as such: Peters (1989): \$1630/kW for a 500 MW CC; \$1360/kW conventional PP, <\$1000/kW if ISTIG gas turbines. Hendriks *et al.* (1989): Dfl3640/kW coal single cycle w/CO_2 recovery. 1000 \$/kW (Pruschek *et al.* 1996; Haupt 1996). 1050\$/kW (IR8).

49 The efficiencies would be 42.1, 45.4 and 47.5 %, respectively. Relative CO_2 emissions per kWh compared to IGCC (100 %): 3.1, 2.9, and 2.7, respectively.

50 It could be enhanced by using a pure oxygen scheme

51 MEA = Mono Ethanol Amine

The efficiency of this process with respect to CO_2 removal is 90 percent, and the total energy demand for those processes amounts to 5 (4.2 to 5.3) gigajoule for the absorption step and 90 (77 plus 13 kWh) for the compression and pumping. The technology, that Feron and Jansen (1995, 414) have proposed, today uses 140 to 200 kJ per mole CO_2 recovered; in the future 70 to 150 kJ could be feasible.

As with other aspects also in the case of CO_2 recovery new developments have arisen, and the technology palette has become wider. For example IGCC power station design with CO_2 recycling makes possible the extraction of CO_2 without any chemical absorbents at all, and the recovery rates for this process are generally approaching 100 per cent[52]. At the other hand of the spectrum gasification and shift reaction make possible the extraction of the hydrogen from a stream of CO_2 and H_2 by membrane technologies (Jansen *et al.* 1992, 369).

As we have argued for before in the technology descriptions of power stations and SMR, the membrane separation might be the most practical way to go, although there are a couple of challenges left: costs have to be brought down (Audus 1997, 218), and membranes reach saturation at high partial pressures so that Chakma (1995a, 410) argues that this technology would be better for lower concentrations[53], at least currently it does not have any cost benefits.

Depending on the disposal process the CO_2 might even be liquefied, which would cost somewhat more energy, but would make more easy the CO_2 transportation by pipeline (Audus 1997, 218).

Another method might be to treat the CO_2 in flue gas in a wet system using water as an absorbent and soil as a cation-exchanger Chohji *et al.* (1997, 151). Somewhat similar from a chemical point of view is a method described by Hirano *et al.* (1995), where a potassium solution under moist conditions allows for CO_2 recovery. It seems this kind of technology could be best applied at current power stations.

It might prove advantageous to remove SO_2 and CO_2 together (Chakma 1995a, 405). The sulphur generated so could be marketed. On the other hand, it might be necessary to dispose of the sulphur, if transport to possible customers turns out to be uneconomical.

While it has been estimated that costs of CO_2 disposal might decrease by 1 % per year between now and the middle of the next century (Kaya 1995, 376), a 40 % decrease in 50 years, the costs of CO_2 recovery will only have a minor importance for the total costs. Chakma (1995a, 405) has estimated that a 20 % reduction in CO_2 recovery costs will only mean a 10 % reduction in total costs.

CO2 Deposition Capacities

Between the CO_2 recovery and the final deposition one step has been left out so far. It is the establishment of the CO_2 storage capacities of various potential sequestration solutions. In principle there are the land-based solutions and the maritime disposal option. The former can be divided into exploiting aquifers, depleted oil and gas reservoirs and reforestation measures. All of these have varying capacities, as presented by Audus (1997, 668), C.4.

Other options have also been proposed in the literature, like using CO_2 as chemicals feedstock, sequestering it in the form of insoluble carbonates, or storing blocks of frozen, solid CO_2 in polar regions. We will describe some of those, but most can not contribute to CO_2 sequestration to the degree necessary by the large amounts that will have to be disposed of[54]. Another challenge is to realise an adequate retention period.

If we compare the storage capacities with current fossil CO_2 emissions[55], currently about 6 GtC or 22 billion tonnes of CO_2, it can be seen that, except for ocean solutions, most sequestration options do not have the potential to provide a lasting contribution. For example saline aquifers and depleted reservoirs will only be able to absorb about 45 years of current emissions. As we can expect the potential CO_2 emissions to rise from the increased primary energy input in the scenario compared to today[56], we therefore have to acknowledge that ocean disposal will have to contribute the largest share to the sequestration.

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52 We can not exclude some losses from imperfect pipes or accidental releases.

53 This would imply that membranes of the type Chakra proposes would be better for CO_2 absorption from SMR, but not for O_2/CO_2 power stations.

54 For example (IR 22) gives some values for indirect biofixation (1.2 Gt C/y), direct biofixation (0.15 Gt C/y), and in chemicals (0.09 Gt C/y).

55 Emissions from land-use changes can technically not be sequestered, as those sources are too wide-spread.

56 From currently 20 billion tonnes CO_2 to more than 37 billion tonnes CO_2 (c. 10 GtC) with the primary energy assumptions given by Sørensen (1996).

It also appears as if deep ocean disposal has a cost advantage over terrestrial solutions, which would furthermore argue for this option. On the other hand technological questions still remain open with respect to maritime CO_2 transport and final deposition, and this also applies to the terrestrial solutions, although some experience already has been collected with EGR and EOR, and CO_2 has been collected for this solution from a conventional coal-fuelled power station in the United States.

Table C.4. Estimated CO_2 storage capacities and costs (incl. transport costs)

Storage option	Capacity (GtC)	Capacity ($GtCO_2$)	Costs ($/tC)	Costs (Euro/tC)	Costs (Euro/t CO_2)
Deep ocean	>1000	>3600	4.1	3.3	0.9
Saline aquifers	>100	>360	4.7	3.8	1.0
Depleted gas reservoirs	>140	>500	8.2	6.6	1.8
Depleted oil reservoirs	>40	>140	8.2	6.6	1.8
Reforestation	c. 75	c. 270	12.5	10.0	2.7
Enhanced Oil Recovery	65	c. 240	??		
Dry ice in polar caps	??	??	??		

Source: Audus (1997, 668), for EOR Riemer (1996).
Notes: **$:** assumed to be base year 1990.
Reforestation: Capacity interval 50-100; Costs interval 5-20.

Only if residence times of CO_2 storage options are sufficiently long, can CO_2 sequestration offer a contribution to mitigating climate change from the enhancement of the natural greenhouse effect. This increase has been fuelled by anthropogenic emissions that have disturbed the natural balance between carbon sources and sinks.

As has been explained before, if CO_2 concentrations shall be stabilised at some pre-defined value, then CO_2 emissions to the atmosphere have to be reduced compared to current values. This can either be achieved by changing to renewable energy sources that do not cause greenhouse gas emissions, or it can be achieved by collecting the CO_2 and sequestering it in secure reservoirs. This section therefore treats the collection technologies, the CO_2 transport, and the final sequestration options.

CO2 Transport

We have to distinguish between land-based and maritime CO_2 transport. The former will be covered by a description of pipeline installations[57] (also submerged ones), the latter by ship based solutions.

Pipelines are certainly the most viable solutions for the large quantities involved, but today one would be anxious about the high costs that they would cause. Therefore it will be essential to investigate large solutions with very large diameters (Skovholt 1993) to harvest economies of scale.

CO_2 can be converted into a so-called *dense phase*, where its density is much higher than if it is a gas at lower pressures (Skovholt 1993, 1097). This also means that given a certain energy amount one can transport about four times more CO_2 by pumping it in this state as compared to the gas state. However, this state is not very stable, and orography can cause the appearance of both gas and liquid states in the pipeline, which is unfortunate.

The best solution is therefore to transport CO_2 in the supercritical condition, *i.e.* above a pressure of 73.8 bars (Skovholt 1993, 1098). For later deep sea sequestration the advantage is that with further increasing pressure the CO_2 liquid will become denser than seawater at a pressure equivalent to about 3 kilometres water depth.

[57] Road or rail based solutions are unthinkable due to the sheer amount that has to be sequestered (Skovholt 1993, 1096).

For economic reasons the pipelines will have to be very large in diameter, about 1600 mm (Skovholt 1993, 1100). The unsolved problem today, therefore, is how one should treat laying the pipeline in the dimension and at the water depths that are demanded. That current technology is approaching the demands for on-shore pipelines of sufficient dimension might be seen in that the Soviet Union had established a total of 54000 km with 1.5 diameter.

Skovholt (1993, 1102) concludes that the costs of CO_2 deposition by via a 250 km off-shore pipeline solution will be about 0.4 Euro per tonne[58] for the largest diameters (1600 mm) but already about double that amount for slightly smaller diameters (<1000 mm). Also costs tend to be c. double for on-shore compared to off-shore pipelines.

While Skovholt (1993, 1102) already mentions some measures to prevent accidents, or in case one happens worse damages[59], Kruse and Tekiela (1996, 1013) have explicitly examined the consequences of a CO_2-Pipeline rupture, where they have distinguished between gaseous and liquid CO_2 transport. Their conclusion is that it is more advantageous to transport CO_2 as a liquid as compared to a gas. For the parameters they have chosen, a six-doubling of the number of check valves will reduce the maximum distance where threshold values[60] are surpassed by a factor four.

Applying the large value proposed by Skovholt (1993) for the cross sectional area of the pipeline would still mean that the maximum distance will be 1800 meters, as the outflow scales linearly with the cross sectional area (Kruse and Tekiela 1996, 1016)! This means that for large on-shore CO_2 pipelines a 3.6 km wide stripe will have to be reserved to avoid possible fatalities! This will generally support arguments to place the power stations, and other CO_2 collecting units, in remote or near-shore locations to minimise such potential exposure.

One could then also look at ship based transcontinental CO_2 transport. For transport by barges on rivers the same security argument as for the on-shore pipeline applies. But maritime transport of liquid CO_2 to the right deposition locations will also be constrained by economics. To quote Adams *et al.* (1995, 450): "LNG carriers are among the most expensive types of commercial vessels to build."[61], and we may conclude that this will also apply to CO_2 transporting vessels. Also the large amount of CO_2 produced from the power stations means that many roundtrips are necessary – for a 1000 MW coal fired PP about 400 to 533 with a 15000 m^3 vessel. No cost figures were given.

Nevertheless, if the necessity of this kind of transport will occur, then a similar solution to the one presented for the LH_2 transport seems to become feasible: barges to carry the LH_2 tanks, a barge carrier to transport the barges to the sequestration platform. There the barges with full tanks are being exchanged with the emptied ones, which are then recycled. This in a way is a more rational approach than the one presented by *e.g.* Ozaki *et al.* (1997, 230).

Marine CO2 Deposition

With respect to oceanic CO_2 deposition the basic difference is whether the CO_2 should be reaching the deep ocean via a shallow injection, that is possible near the coast, or directly into the deep sea by a vertical pipe carried by a floating vessel or platform. From a legal point of view neither the Global London Convention nor the Oslo convention currently prohibit or restrict the dumping of CO_2 (Adams *et al.* 1995, 451), but in the light of the Brent Spar episode one would have to be prepared to accept some stir of public attention[62].

Orr (1992), in a review article on Haugan and Drange (1992), mention the obvious advantages of shallow injection: natural conditions necessary for shallow injection are more easily met than those for deep injection, power station clus-

[58] Original data: about 0.5 $\$_{1993}$ / tonne.

[59] Like having safety zones on both sides of the pipelines; increase the wall thickness near populated areas; section the pipelines with valves to minimise possible leakages, in populated areas the distances between the valves would be shorter; proper marking of the pipeline premises; proper surveillance and maintenance. Furthermore the pipeline would be routed through more wind-exposed regions so that a leakage would not lead to excessively high concentrations.

[60] Chosen so as to minimise adverse human effects.

[61] IEA (1994b, 50) gives price examples for new LNG tankers between 125,000 and 136,000 cubic metres: average about 200 million Euro ($250 million) with a 140 to 224 million Euro ($180-280 million) range. This translates into a capital cost of about 9 Euro per liquid m^3 (=0.34 Euro per GJ), at 20 roundtrips per year and 3% p.a.. To this should be added O&M costs of about 4-6.4 million Euro ($5-8 million) per tanker-year (=0.08 Euro per GJ).

[62] On the other hand the public also argues that climate change should be mitigated, but this seemingly has not had a large influence on peoples' behaviour with respect to *e.g.* substituing incandescent light bulbs with CFLs on a larger scale. But exactly energy efficiency measures solutions have a much larger impact on the total efficiency of an energy system than upstream activities like more effective power stations.

ters could share the costs related to the necessary pipelines, the sea water density would increase near the point of CO_2 injection which would facilitate local sinking, and the sinking CO_2 rich water plume could reach calcite ($CaCO_3$) rich sediments (Stegen *et al.* 1995, 497), which by reacting to bicarbonate (HCO_3) would further enhance oceanic uptake. He also does mention the possible problems: appropriate injection sites have to be identified, there are substantial local, but supposedly minor global or regional environmental side effects, and power stations' effective rating would diminish[63].

Haugan and Drange (1992) themselves are cautious: "one should not recommend injection of CO_2 in the (upper)[64] ocean to slow down the increase in greenhouse warming unless the theoretical predictions are confirmed by experimental investigations and further analyses, and the environmental impact downstream of the injection point is judged acceptable. But the chemical carrying capacity of the ocean is formidable compared to the expected anthropogenic emissions. If shallow injection is working as indicated by these preliminary investigations, at least in some locations, it may contribute to obtaining the required reduction in net emissions to the atmosphere in the future".

Depsite their warnings some locations could prove to be feasible for CO_2 deposition by shallow injection. Adams *et al.* (1995, 450) narrow the range of locations to ones, where the "continental precipice reaches form 400-500 m to 1000 m in a few kilometres over a smooth bottom" and mention a series of appropriate locations[65]. The shallow injection technology might prove to be a first relief for implementing CO_2 disposal schemes on a larger scale. It will have to be realised within the next two decades, if more experience with CO_2 disposal should be made.

Adams *et al.* (1995, 450) estimate that for a 1 GW power station electricity costs would rise by about 1.8 Euro per GJ[66] for an offshore disposal at a depth of 1000 m and a pipeline distance of 100 km. The total costs of this technology are lower than the ones of the deep-sea injection technology, which will be described now.

Deep sea CO_2 storage has seemingly attracted most attention in Japan (Ohsumi 1995)[67]. The basic idea with deep sea injection of the liquefied CO_2 is that the long residence time of the deep sea water[68] (of the order of magnitude of a millennium, Seifritz 1994, 926) ensures lower atmospheric CO_2 spikes than if the CO_2 was emitted directly into the atmosphere[69]. The CO_2 that directly diffuses from the deeper waters into the upper layers that are in equilibrium with the atmosphere will not play a large role for deep sea injection, and can typically be neglected.

In order to reach the deep sea water masses the CO_2 has to be deposited at a depth of at least 3 kilometres. At this depth the liquid CO_2 would reach a density equivalent to the one of the sea water[70] and so would not tend to rise again due to buoyancy effects (Teng *et al.* 1997, 765).

For industrial application of the deep sea injection a carrier, a ship or a semi-floating platform, would be equipped with a vertical, long steel pipe, and the liquefied CO_2 would be pumped down. Ozaki *et al.* (1997) have explicitly analysed the geometry of the pipe, taking into account the steel's ductility and strength, the pipe size[71], and the sea state with

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63 His argument that most power stations are located inland so that the CO_2 would have to be transported a long way will probably not be valid in the future, as already today power stations would tend to be located near the coast to ensure easy coal proliferation (Porter and Schmitz 1995). Nevertheless such a strategy has also been recommended by Skovholt (1993, 1103).

64 My comment

65 With respect to electricity generation the locations proposed by Adams *et al.* (1995) for shallow injection would imply a change in EU energy trade patterns, as coal fired power stations would have to be located in now remote locations like Portugal, Gibraltar or Norway. The Biscaya bay has also been mentioned (Skovholt 1993).

66 Original data: 0.8¢ / kWh @ 15% interest p.a..

67 Who also gives a short and concise overview of the research activities that have been undertaken to investigate the subject.

68 The deep sea water is slowly following the so-called *conveyor belt* circulation (Broecker 1991) from the subsidence regions in the Arctic Ocean, near Newfoundland and off Antarctica to the upwelling regions west of the American and African continents.

69 Although this also depends on the consumption of the fossil fuel reserves. Nihous *et al.* (1994, 232) remarked that a fast consumption pattern with a major share of deep sea discharge can result in higher atmospheric CO_2 concentrations than a slow exhaustion of the reserves!

70 This exploits that fact that liquid CO_2 is much more compressible than seawater.

71 Which is related to the amount of CO_2 that can be disposed.

respect to the stresses stemming from the movements of the vessels caused by the surface waves, when the significant wave height is smaller than 6 metres. They conclude that such a system was feasible for pipe lengths of up to 4000 metres with ship type carriers, and somewhat longer for semi-submersible types. Even longer pipes rely on the introduction of new pipe materials.

We can here not investigate the possibility of finding locations fulfilling the significant wave height criteria, that we deem is the most determining one, but we very much assume that those can be found, although in places this criteria might only be fulfilled part of the year. In any way the delivery of the CO_2 to the diffusion platforms would be a ship based concept so that mobility of the injection sites could be ensured in principle[72].

It seems to be advantageous to fully automate the CO_2 disposal in order to minimise personal risk exposure. As CO_2 in large concentrations can impair human health, and accidents can not be excluded, the technology probably will be designed to not require manual assistance constantly. Experience has been gained with a similar technology: the production of petroleum by automated platforms in the North Sea.

Unfortunately Ozaki *et al.* (1997) have not given any cost overview of such platforms. To get some preliminary figures for the deposition platforms we therefore apply some of cost values for oil and production platforms. In the German Der Spiegel (Spiegel 1996 & 1997d) two concepts have been described: a floating TLP „Mars" costing about 800 million Euro and a GBS „Hibernia" costing about 5 billion Euro[73].

Now a disposal platform will be cheaper than the Mars platform, as the technology used will be less advanced and complicated, maybe 400 MEuro. Its only purpose will be to float freely and to submerse the liquid CO_2 that is delivered to it by LNG-like vessels. For a lifetime of 50 years and a yearly capacity of about 500 million tonnes of CO_2 capital costs from the platform alone would run to about 0.1 Euro per tonne of CO_2. An IGCC would still produce about 200 kg CO_2 per GJ, so that this would mean a cost of about 0.02 Euro per GJ (0.07 mEuro per kWh). This estimation has not taken care of the cost of the LCO_2 tankers, yet, but it seems to support estimates by Riemer (1996) on the ocean disposal costs[74].

Another possibility, as already indicated, is to combine the CO_2 disposal with the hydrogen generation plant in one common platform. This combination would have the advantage of providing easy access for coal vessels and the shipping of the produced hydrogen. It would also enable an easy CO_2 disposal, as the long ranch transport, necessary for land-based solutions, would not arise. No reference of such an idea has yet been found in the literature, but it seems as if it was the logical thing to do, if one has to use coal for hydrogen generation, as it is doubtful whether land-based CO_2 disposal facilities could be found nearby coal reservoirs[75].

Such a scheme could offer a combination of CO_2 disposal and ocean heat exploitation[76].

Marine Environment Impact

With respect to the question of what happens to the disposed CO_2, Teng *et al.* (1997, 773) think that the liquid CO_2 will neither lead to the creation of solid hydrates nor form a continuous liquid phase. Due to the hydrodynamic instability of liquid CO_2 and the rapid hydrate formation CO_2 droplets will form that will not coalesce to form a continuous phase but rather slowly diffuse. In deeper water the buoyancy of the CO_2 is large so that CO_2 will be surely captured, however at intermediate depths, that we do not consider here, the droplet size will have to be controlled carefully to ensure a long

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72 Such pipe concepts could probably be coupled to a scheme exploiting the heat difference between upper and deeper parts of the ocean, although this extension is not within the scope of this study. In any case the mobility of the injection platforms will be limited, as frequent removal and installation of the pipe would interrupt the disposal process (Ozaki *et al.* 1997, 230).

73 Original data: $1 billion, CD$8.5 billion. The Mars platform should produce 100,000 barrels a day, which is equivalent to about 16 million tons of CO_2 yearly!

74 Although Riemer apparently has calculated with near-coast pipeline solutions.

75 Opposite to oil or gas reservoirs, the CO_2 generated could be applied in EGR or EOR schemes!

76 *Ocean heat technology* (OHT) exploits the heat difference between the upper, warmer layers of the oceans and the lower, colder water masses. They need as large heat difference between the water masses as possible, so they will have to be placed in tropical oceans. Yet physical efficiencies are very low, and the total capacity might not become large. Such platforms in principle are similar to the CO_2 disposal platforms, but generally not as sturdily dimensioned. The locations of these OHT is the same as the combined H_2 producing-CO_2 dispersing platfarms.

lasting stay in the ocean. Adams *et al.* (1995, 451) stress the need for a demonstration project to show environmental benignity of ocean disposal.

Carbonate Disposal

One of the most prominent features with texts dealing with CO_2 disposal by carbonate generation is that they stress its safe and environmentally friendly quality. Another that the raw materials to form stable carbonates should be abundant, which implies that this method could cope with the large amounts that necessarily will have to be disposed of. The basic idea is to make CO_2 react with other minerals in either a dry or an aqueous milieu. Insoluble carbonates are created that will not weather for a sufficiently long period and that therefore should be disposed of, *e.g.* as raw material for preparing street pavements[77].

Lackner *et al.* (1995) give a description of the kinds of rocks that can be used for this purpose. First of all some rocks, like limestone, dolomite and magnesite, have to be excluded, as they already are carbonated. So igneous rocks remain the rocks of choice. Examples are peridotites, serpentinite, gabbro and basalt, and those should be found in sufficient amounts over the World so that CO_2 absorption should be feasible on a large scale.

A variant of the industrial carbonate generation is to pump the CO_2 directly into underground caverns of porous magnesium or calcium bearing rocks (Lackner *et al.* 1995, 1166). The chemical reactions described before will then proceed slowly over several years, but it is not ensured that suitable and sufficient deposits can be found. They need to be mechanically stable and have to be sealed to the outside. It also has to be ensured that the injection well will not be cemented in and sealed by the carbonates.

Opposite to the creation of insoluble carbonates described before, Chohji *et al.* (1997) present a process that would create a solution, which may be comparatively easily discharged, as it should prove harmless to the natural environment (Chohji *et al.* 1997, 158). As they also rely on minerals found in soil, their process might be qualified for utilising the overburden from open coal mines. The basic idea is to saturate the soil solution with CO_2, to aerate it, whereby insoluble carbonates would be formed, and then to release the soil and insoluble carbonate into the environment. This process is technologically simple, but it requires large amounts of water, and so cannot be performed where water demand is high for other purposes. Chohji *et al.* (1997) therefore propose to use it near large dams.

If we assume surface mines, then the large amount of overburden, about twenty times the coal's weight, would seem to guarantee the extraction of a sufficient amount of minerals to perform the carbonate production. As it would be difficult to find large enough markets for the end products, even though their price should be low despitve the transport costs, the deposition of the carbonate will therefore occur at the location of the coal extraction (Lackner *et al.* 1995, 1167 f.). Alternatively the CO_2 has to be returned for EGR.

This method seems to be hampered by the same reasons that Lackner *et al.* (1995) have brought forward: the amount of the produced carbonates would be staggering. Therefore this method would only be employed in a few places, where environmental or agricultural concerns about the changed quality of the soil burden would not object.

Costs:

From an investigation of the typical economics of minerals and building materials, Lackner *et al.* (1995, 1165) conclude that the allowable cost of the CO_2 recovery will be the dominating factor for establishing the viability of the carbonate disposal method. For a cost of about \$30 per tonne of CO_2 this translates into processing and mining costs that per tonne are \$15 for the case of peridotite. For a comparison: cement sells at about \$60 per tonne, but this material needs to be grounded twice and heated, which is not the case for the carbonate method. From their analysis Lackner *et al.* conclude that the CO_2 fixation budget is likely to be marginal for direct carbonates. The cost figure should look more optimistic for the direct injection, though.

Injection into Oil (EOR) or Natural Gas Reservoirs (EGR)

As we have stated before, separation of the CO_2 from SMR installations will offer the advantage of EOR and EGR solutions. One example for the feasibility of EGR is a study by Tontiwachwuthikul *et al.* (1996) for a Canadian location. That this method is economically sound has also been proven elsewhere (Blok *et al.* 1997), see the section on hydrogen production starting on page 167, so that we have chosen to assume that this technology will be used with all natural gas production, as we also assume sufficiently close sites to be identified for EOR.

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77 Where a gravel layer is used to stabilise the road construction.

CO2 Disposal in Antarctic Ice Shield

Antarctica is the most hostile of the seven continents: its eternal ice shield[78] prevents easy access; its climatic conditions do neither welcome visitors nor economic activity. Besides some research projects in the austral summer or military bases durign the whole year, Antarctica is a remote ice-desert. In other words: ideal conditions for storing CO_2 as a solid[79].

This is the basic argument behind the idea of Honjou and Sano (1995) for using Antarctica as a kind of gigantic deep-freezer for frozen dry CO_2. Although average temperatures generally are not lower than the dry-ice point of CO_2, -78 °C[80], Honjou and Sanon argue that so low temperatures can be ensured by having artificial downward caves, with dimensions of about 100 m height and several kilometres length, resulting from excavating the ice. Basic convection would guarantee that the temperature of a block of dry-ice can be kept comfortably below the critical -78 °C, where it sublimates.

The low temperatures would ensure long solid residence times, before the CO_2 gets liberated to atmosphere. Hanjou and Sano (1995, 503) estimate annual sublimation rates of as low as 0.01 % yearly, a value supported by Seifritz (1994, 927), who mentions about 800 years by which half of a dry-ice dome with 200 m diameter will have sublimated.

The major mischief with the Antarctica solution is that this continent is very unapproachable for such kind of industrial activity. The cost question and reality of this solution therefore has not yet been treated in full. Furthermore current international regulations might exclude the region from the catalogue of feasible methods.

78 At least for the periods relevant to human experience.

79 This exploits that frozen CO_2 becomes so-called dry-ice.

80 For example in the austral summer the average temperature is -51 °C at the South Pole; although temperatures at the ice-core drilling site *Vostock* are even lower: -57 °C (Schwander and Stouffer 1984, 46).

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APPENDIX D:

ALTERNATIVE CALCULATION OF THE BIOMASS POTENTIAL

(Peter Meibom)

To estimate the biomass available for energy purposes is a complicated task. The size of the areas available for growing agricultural and energy crops has to be estimated, and the yield on these areas must be determined. The biomass needed to cover the food demand of the human population must be calculated, and also the feed demands of animals producing meat and milk.

In section 5.2.4 the model for doing this was explained and the numerical assumptions made in the calculation were given. The result of the calculation was the energy content of the production of vegetable and animal food deliveries, and the energy content of biofuels produced from forestry waste, crop residues, animal manure and dedicated energy crops. These results were summarised in Table 5.2.

In the course of the project another calculation of the potential biomass production was made based on more or less the same model but with different numerical assumptions made. We have chosen to present this calculation also and compare the results from the two different calculations, with the purpose of showing the uncertainties involved in estimating the global potential biomass production in the year 2050.

First the alternative calculation is given, and then the results are compared.

D.1 Areas available for growing agricultural and energy crops

We have used the "Global land cover characteristics data base ver. 1.2." [1] to estimate the areas available as agricultural or grazing. This data set gives the geographical distribution on a global basis of the different land uses and vegetation types of today. We have taken the land belonging to the groups; "dryland cropland and pasture, irrigated cropland and pasture, cropland/woodland mosaic, cropland/grassland mosaic, grassland" as potentially usable. The last group "grassland" only as grazing lands. By only considering the areas belonging to these groups as available for farming, we implicitly assume that the forests of today will keep there present size until 2050, thereby assuring that no forest will be cleared, because of the need of biomass for energy purposes. The residues from the forest that are cut to produce industrial roundwood and paper will be used to produce energy. In **Table D.1** the areas of the different land types in the regions[1] are given.

D.2 Calculation of biomass yields

The biomass yield at a particular place is determined by a multitude of things including climate, soil and terrain conditions, the properties of the crops grown at the place, and finally management practices. We have chosen to use the results from an already existing model together with our own assumptions instead of making a full model of crop growth.

D.2.1 Terrestrial ecosystem model (TEM)

The starting point for the estimation of biomass yield on a 0.5°×0.5° grid covering the terrestrial surface of the earth is net primary production (NPP) data calculated by the TEM (see [2 & 3] and references within for a description of the TEM). The TEM is a processed-based ecosystem simulation model that uses spatially referenced information on climate, elevation, soils, vegetation and water availability to make monthly estimates of among other things NPP. The NPP data we are using comes from a TEM simulation covering the terrestrial surface of the globe at 0.5° resolution for the atmospheric CO_2 concentration of today of 340 parts per million by volume (ppmv) [1]. Jerry M. Melillo and John Helfrich have kindly put these data at our disposal.

[1] The division into regions is more detailed in this appendix than in the rest of the report. A list over the countries belonging to each region is given in

Table D.10.

Region		I Dryland cropland and pasture	II Irrigated cropland and pasture	III Crop-land/grassland mosaic	IV Crop-land/woodland mosaic	V grassland
sub-Saharan Africa	Area km^2	504064	3288	226865	1377279	1782548
	Average NPP (gC/m^2)	517	195	356	521	241
China+	Area km^2	865366	1147707	667014	426649	2609577
	Average NPP (gC/m^2)	619	742	623	716	208
Eastern Europe	Area km^2	489545	1816	211717	367510	2716
	Average NPP (gC/m^2)	459	444	442	462	373
FSU	Area km^2	2409332	212251	811199	1434959	1917850
	Average NPP (gC/m^2)	314	177	255	282	153
Latin America	Area km^2	1391587	29227	967111	2988386	1967359
	Average NPP (gC/m^2)	657	472	638	703	419
Middle East	Area km^2	220514	56476	22594	243106	427757
	Average NPP (gC/m^2)	276	200	243	284	219
North America	Area km^2	1317083	104913	912692	515787	1326943
	Average NPP (gC/m^2)	477	228	390	516	283
OECD Pacific	Area km^2	616830	34586	11593	57873	488382
	Average NPP (gC/m^2)	443	580	570	600	300
S&SE Asia	Area km^2	1701844	1474724	368922	513014	163466
	Average NPP (gC/m^2)	492	635	475	881	778
Western Europe	Area km^2	920292	32303	319382	1016498	195469
	Average NPP (gC/m^2)	499	396	497	485	259

Table D.1 Areas and average NPP calculated from TEM for the regions.

The NPP estimates are done for undisturbed, mature vegetation where 18 different vegetation types each one described by a set of vegetation-specific parameters are used to characterise the potential, global, natural vegetation. As before mentioned the estimation includes climate, soils, water availability and furthermore also nitrogen availability is included. In **Table D.1** the average NPP for each land type and region is given.

crops. These rather crude assumptions have nothing to do with the TEM and should not be connected with the model, but are done entirely by us.

D.2.2 Translating from yearly NPP data to biomass yield of agricultural and energy crops

The NPP data from TEM are expressed in grams of carbon per square meter per year. These NPP data can be translated into units of grams of dry matter per square meter per year by multiplying with a factor of 2.05[2], and into units of watt-years per year per square meter by multiplying with a factor of 0.00133.

The main assumption behind our use of the NPP data from TEM is that the NPP data gives the geographical distribution of the total yearly biomass production, irrespective of whether the vegetation consists of undisturbed, natural vegetation or a mix of energy and agricultural crops. This assumption is partly justified by investigations showing, that between C_3 agricultural crops, various other herbaceous plants, and trees (all of which are of the C_3 type) there is little difference in the total biomass yield per unit of light intercepted by the leaves during the growing season for plants grown with nutrients and water supplies adequate for good growth [3].

When the geographical distribution of the total yearly biomass production is determined from TEM, we still have to estimate the ratio between the NPP data from TEM calculated for mature, undisturbed vegetation and the yields of agricultural crops and energy crops. This is done by comparing TEM's NPP data for Denmark with actual yields obtained in the Danish agriculture today. For trees used as energy crops only the branch and steam are usable to fuel production. Likewise for agricultural crops only part of the plant will be edible by humans. To estimate the biomass yield of agricultural and energy crops, we need assumptions saying how much of the total biomass yield that goes into the different parts of the plant. These assumptions are given in **Table D.3**.

The Danish agriculture is very intensive with full use of fertilisers and pesticides, therefore these yields are not expected to increase from now to 2050, because we assume a so called sustainable agriculture in 2050 with much less use of fertilisers and no pesticides. Also the Danish yields are seen as maximum yields obtainable for a rich society using a lot of technology that have a long tradition for research and development in the agricultural sector. For those regions that haven't reached the same income level in 2050, and have very low yields today, the yields will be reduced by an agricultural intensity factor given in **Table D.2**.

Region	sub-Saharan Africa	China +	Eastern Europe	FSU	Latin America	Middle East	North America	OECD Pacific	S&SE Asia	Western Europe
Agricu. intensity	0.4	0.7	0.7	0.7	0.7	0.7	D.0	D.0	0.7	D.0

Table D.2 Agricultural intensity factors in 2050 giving the difference in yields obtained in the different regions compared to a fully optimised and highly technological agriculture.

The NPP data for Denmark gives an average biomass yield of 10 t/ha of dry matter. By using the factors in **Table D.3** the edible yield of food crops is 4 Dt/ha. (Dt is "tons dry weight"). The average yield of cereals in Denmark in the years 1994-1996 is 6.0 t/ha [4], which with a moisture content of 16 % {4] gives a dry matter yield of 5.0 Dt/ha. Therefore the NPP data is scaled with a factor of 1.25 to give the yield of food crops in a sustainable but still highly intensive and technological agriculture in 2050.

As there is little experience with energy crops in Denmark today, we have taken our assumptions about future yields from Hall et al. [5]. They estimate that in large plantations operated in a sustainable manner average yields of 10 to 15 Dt/ha per year of wood usable for energy purposes may be expected during the first quarter of the next century in temperate regions and 15 to 20 Dt/ha per year in the second quarter, and even higher yields in tropical regions. Compared to this our assumption about an average yield of 10 Dt/ha per year of wood usable for energy purposes in Denmark in 2050 seems very modest, and gives an scaling factor of 1.6[3] for converting from NPP data to yields of energy crops.

The scaling factor for converting from NPP data to the yields of the vegetation growing in the land type grassland is put to 1, because this vegetation is unmanaged by humans.

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[2] Neglecting minor chemical constituents and moisture content, a typical biomass feedstock can be represented chemically as $CH_{D.45}O_{0.7}$ [3]. Taking the atomic weight of the constituents into account the weight fraction between the dry matter of the biomass and the carbon content is 2.05.

[3] 10/(10×0.6) = D.6

	Scaling factor NPP-> yield	Edible yield	Residue available for fodder or energy purposes	Residues left on the field or burned or eaten by wild animals	Root
food crops	1.25	0.4[4]	0.2	0.2	0.2
energy crops[5]	1.6		0.6	0.3	0.1
grazing land	1.0		0.4	0.4	0.2

Table D.3 Factors saying how much of the total yield, which are usable as food, feed or to energy production, and the scaling factors used to translate from NPP to crop yield.

The NPP values and the derived yields for agricultural and energy crops for the land type "irrigated cropland and pasture" are calculated for rainfed vegetation. It could therefore be argued that these yields should be higher, when irrigation was applied. From the size of these areas obtained from the global land cover data base, it can be seen that the irrigated areas only have real importance in China+ and S&SE Asia, where the NPP values already are quite high and higher than the land type "Dryland cropland and pasture" in these regions. For this reason and out fear of overestimating the yields, we have chosen not to raise the yields in the irrigated areas.

D.3 Calculation of food demand

The assumptions behind the calculation of the food demand are given in **Table D.4**. The biomass production needed to cover the food demand is calculated as follows:

$$B(i) = BV(i) + BA(i)$$

$$BV(i) = \frac{FI(i)\cdot(1-AF(i))}{(1-LR(i))\cdot(1-LH)\cdot(1-SU)}$$

$$BA(i) = \frac{FI(i)\cdot AF(i)\cdot FR(i)}{(1-LR(i))\cdot(1-LH)\cdot(1-SU)}$$

Here *B(i)* is the biomass production per capita in the region *i* needed to cover the food demand. *BV* is the biomass production per capita needed to cover the vegetable part of the food demand. *BA* is the biomass production per capita needed to cover the animal part of the food demand. *FI* is the food intake per capita in the region *i*, *AF* the fraction of the food energy covered by food from animals. *LR* is the loss fraction in the retail level, which includes wastage from food storage, kitchen preparation and cooking, and plate waste. This waste can be used both as feed to animals and utilised to produce biogas. *LH* is the loss fraction between the harvest of the crops and delivery at the retail level and consists of distribution and processing losses. This biomass loss is not considered recoverable for other purposes. *SU* is the fraction of the crops used as seeds. *FR* is the feed ratio, which is the ratio between the energy content in the feed eaten by the animals and the energy content in the food products produced by the animals.

As it can be seen from **Table D.4** the food intake per capita is the same in all regions except Africa. The 120 Wy/y per capita are considered as full covering of all food requirements. Africa is the poorest region in 2050 and therefore this region hasn't achieved full goal satisfaction of the food demand. The values of *AF, LH* and *SU* are largely taken from the analysis made by Leach and others in the Polestar studies [6,7].

[4] The value 0.4 fits well with different cereals species like wheat and rice, which are the most important food crops in the world.

[5] Energy trees, two coppice rotations for each planting. All growth taking place above ground after the first cut, which explaines that only 0.1 of the NPP goes to the root.

Region	Energy content in food intake Wy/y/cap **FI**	loss fraction in retail level **LR**	fraction of food energy from animals **AF**	feed ratio **FR**	losses from harvest to retail level **LH**	seed use **SU**
sub-Saharan Africa	100	0.20	0.10	6.3	0.1	0.05
China+	120	0.25	0.20	6	0.1	0.05
Eastern Europe	120	0.25	0.30	5	0.1	0.05
FSU	120	0.25	0.30	4.8	0.1	0.05
Latin America	120	0.25	0.20	6.9	0.1	0.05
Middle East	120	0.25	0.20	5.1	0.1	0.05
North America	120	0.25	0.30	6.3	0.1	0.05
OECD Pacific	120	0.25	0.30	5.4	0.1	0.05
S&SE Asia	120	0.25	0.20	4.5	0.1	0.05
Western Europe	120	0.25	0.30	5.3	0.1	0.05

Table D.4 The assumptions lying behind the calculation of the necessary food production per capita.

The feed ratio for the different animal products[6] is calculated using data from the Danish agriculture [4] and summarised in **Table D.5**. To obtain the average feed ratios in the regions, FAO data from 1995 [8] giving the size of the production of each animal product in each region have determined how much each animal product contributes to the animal part of the human diet in 2050 (see **Table D.6**).

animal products	Milk	Beef and veal etc.[7]	Mutton, lamp, goat meat	Pigmeat	Poultry meat and eggs etc.[8]	Fish
feed ratio	3.3	14.3	8.3	6.3	5	-

Table D.5 Feed ratio for the different animal products.

Region	Beef and veal etc.	Pigmeat	Mutton, lamp, goat meat	Poultry meat and eggs etc.	Milk	Fish
Sub-Saharan Africa	0.19	0.04	0.09	0.21	0.43	0.04
China+	0.05	0.48	0.02	0.37	0.05	0.02
Eastern Europe	0.07	0.25	0.01	0.15	0.49	0.03
FSU	0.11	0.06	0.02	0.08	0.66	0.07
Latin America	0.26	0.08	0.01	0.29	0.34	0.02
Middle East	0.09	0.00	0.09	0.24	0.55	0.03
North America	0.19	0.14	0.00	0.30	0.331	0.03
OECD Pacific	0.14	0.08	0.06	0.20	0.42	0.11
S&SE Asia	0.09	0.01	0.03	0.06	0.78	0.03
Western Europe	0.11	0.20	0.01	0.17	0.46	0.05

Table D.6 Diet structure of the animal part of the human diet in the regions.

[6] Except for mutton, lamp and goat meat, where the value is taken as an value between those for pigmeat and beef.
[7] Meat from beaf, veal, buffalo, horse, asses and camels.
[8] Meat from chicken, duck, goose, turkey, pigeon and eggs from chicken, duck and goose.

Finally in **Table D.7** the total biomass production from agricultural and grazing land needed to cover the food demand in each region is summarised.

Region	sub-Saharan Africa	China +	E. Europe	FSU	Latin America	Middle East	N. America	OECD Pacific	S&SE Asia	W. Europe
Pop. Million	1789	1701	121	285	807	751	387	145	2923	446
BV *GW*	235	255	16	37	121	112	51	19	438	58
BA GW	165	382	34	77	209	143	137	44	492	133
B GW	400	637	50	114	329	256	188	63	930	191

Table D.7 Total biomass production needed to cover the vegetable and animal part of the food demand in each region.

D.4 Calculation of the potential energy production from biomass

We now have the framework ready to calculate the potential energy production. This is done in a series of steps:

1. The food waste from kitchen preparation and cooking and plate waste is calculated by using the information in **Table D.4**. 20 % is used as animal feed, 60 % used to energy production and 20 % lost by decomposition.
2. The necessary areas needed to cover the rest of the food demand in each region are calculated by combining Table D.1, Table D.2 and Table D.3. Each region prioritise self sufficiency of food higher than the production of energy crops, therefore if necessary all the land available to food and energy crops will be used to produce food crops. The areas are used in the following order; A. Dryland and irrigated cropland and pasture (I + II), B. Grassland for covering the roughage part of the animal feed (V), C. Cropland/woodland and cropland/grassland mosaic (III + IV).
3. The calculation shows that the regions Middle East and sub-Saharan Africa can not cover their demands for food, and it is therefore necessary to import food from other regions. Rather arbitrarily we decide, that the two regions will import equal amounts from the four regions Western Europe, North America, OECD Pacific and FSU, and these regions will use some area for producing food crops for export.
4. The manure from the animals is used to biogas production. The energy content of the manure production is calculated as 50 % of the energy content in the feed. Manure from animals living on the land type grassland is not considered recoverable, but will instead fertilise the grassland. Of the remaining manure 50 % is considered recoverable for energy purposes.
5. The energy content of the food production residues available for energy production is calculated. It equals half of the energy content in the food crops, as can be derived from the factors given in Table D.3.
6. The areas not used to food crops are used to produce energy crops, and the resulting energy production from this is calculated.
7. The energy content of the residues from industrial roundwood production from forests is calculated by assuming an industrial roundwood production of 0.2 tons of wood per capita per year, which equals the production per capita in 1989 [5]. For each ton of industrial roundwood one ton of residues in the form of milling and manufacturing waste is produced, the energy content of which is 16 GJ/t assuming an moisture content of 20 % [5]. The industrial roundwood is used for wood, pulp and paper products, but a large part of these products will in the end be utilised to produce energy. Therefore we assume that 75 % of the industrial roundwood will be used to produce energy. In total 0.35 t of wood per capita per year is available for energy production with energy content of 178 Wy/y. In Table D.8 the result of the calculations is given.

Biomass potential for energy production in GWy/y	Residues from retail level	Residues from food crops	Manure for energy	Residues from industrial roundwood production	Energy crops on remaining land of type I and II	Energy crops on rest of available land (III and IV)
sub-Saharan Africa	27	141	18		0	0
China+	41	311	95		44	645
Eastern Europe	3	24	8		108	236
FSU	7	76	19		415	546
Latin America	19	161	52		209	2430
Middle East	18	34	27		0	0
North America	9	113	34		400	795
OECD Pacific	3	51	11		177	53
S&SE Asia	70	453	111		0	496
Western Europe	11	114	33		164	832
Total	208	1480	410	1665	1517	6032
Biofuels total	104	740	205	833	759	3016

Table D.8 The energy content of biomass available to energy production in GWy/y. Where the residues from industrial roundwood production are produced can not be determined with the simple calculation used, and therefore only the total value is given. Africa must use all areas for food production and has a small food import of 18 GWy/y. Middle East has a large food deficit of 147 GWy/y, that is imported. The landtype grassland is used fully as grazing land in the regions Middle East, sub-Saharan Africa, and S&SE Asia, and surprisingly enough in the remaining areas the grassland is not used at all. The conversion efficiency from biomass to biofuel is assumed to be 50 %.

D.5 Comparison

Region/Cal. number	Total food deliveries, GW	Pot. biofuels from crop residues and stable animal manure, GW	Pot. biofuels from forest residues, GW	Pot. biofuels from energy crops, GW	Total[9], GW
1/Cal. 1	213	91	208	98.4	610
North America/Cal. 2	72	78	-	598	748
2/Cal. 1	230	104	80	64.1	478
W. Europe + OECD Pacific/Cal. 2	104	112	-	613	829
All regions/Cal. 1	1979	720	1700	650	5049
All regions/Cal. 2	1614	1049	833	3775	7271

Table D.9 Comparison between the results obtained from calculation 1 (see table 5.2) and the calculation (cal. 2) described in this appendix (see Table D.8). The only regions that are more or less the same in the two calculations are region 1 in cal. 1 together with the region North America in cal. 2., and region 2 in cal. 1. together with the union of the regions West Europe and OECD Pacific in cal. 2. Therefore these regions are used in the comparison together with the global values. The biomass production needed to cover the animal part of the food demand in cal. 2 has been multiplied with 0.15, to facilitate a comparison with the calculation of the food deliveries in cal. 1 (see section 5.2.4, food production). The potential biofuels production from forestry waste has only been calculated on a global basis in cal. 2.

[9] For calculation 2. and the regions North America and W. Europe + OECD Pacific the biofuels from forestry waste are not included in the total values.

The comparison between the two calculations summarised in Table D.9 reveals three interesting points:

1. The method used in calculation 1 to calculate the potential biofuels production from forestry waste gives a result about twice as big as the method used in calculation 2. The two methods are very different, where calculation 1. is based on utilising a fraction of the yearly growth in all forests in the world, and calculation 2. is based on utilising a fraction of the yearly industrial roundwood production.
2. The production of food deliveries is around 20 % bigger in calculation 1, than calculation 2. In calculation 1 there is a surplus production of food of around 30 % of the demand, where as the food production in calculation 2 exactly covers the food demand.
3. The total biofuels and food deliveries production excluding biofuels from forestry waste is 3349 GWy/y in calculation 1 and about twice as big in calculation 2 namely 6438 GWy/y. This difference is explained with the more optimistic assumptions used in calculation 2: The scaling factor from NPP to crop yields are 1 in calculation 1, and 1.25/1.6 for agricultural/energy crops in calculation 2. The harvest index is 0.4 in calculation 1., and 0.6 in calculation 2.

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Country	Region
Afghanistan	Middle East
Albania	East Europe
Algeria	Middle East Africa
Angola	sub-Saharan Africa
Anguilla	North America
Antigua & Barbuda	North America
Argentina	Latin America
Armenia	FSU
Aruba (neth.)	North America
Australia	OECD Pacific
Austria	West Europe
Azerbaijan	FSU
Bahamas	North America
Bahrain	Middle East
Bangladesh	S&SE Asia
Barbados	North America
Belarus	FSU

Belgium	West Europe
Belize	Latin America
Benin	sub-Saharan Africa
Bhutan	S&SE Asia
Bolivia	Latin America
Bosnia And Herzegovina	East Europe
Botswana	sub-Saharan Africa
Brazil	Latin America
British Virgin Islands	North America
Brunei Darussalam	S&SE Asia
Bulgaria	East Europe
Burkina Faso	sub-Saharan Africa
Burundi	sub-Saharan Africa
Cambodia	S&SE Asia
CaMiddle Eastroon	sub-Saharan Africa
Canada	North America
Cape Verde	sub-Saharan Africa
Cayman Islands	North America
Central African Republic	sub-Saharan Africa
Chad	sub-Saharan Africa
Chile	Latin America
China	China+
Colombia	Latin America
Comoros	sub-Saharan Africa
Congo	sub-Saharan Africa
Cook Islands	OECD Pacific
Costa Rica	Latin America
Croatia	East Europe
Cuba	Latin America
Cyprus	West Europe
Czech Republic	East Europe
Denmark	West Europe
Djibouti	sub-Saharan Africa
Dominica	North America
Dominican Republic	Latin America
Ecuador	Latin America
Egypt	Middle East Africa
El Salvador	Latin America
Equatorial Guinea	sub-Saharan Africa
Eritrea	sub-Saharan Africa
Estonia	East Europe
Ethiopia	sub-Saharan Africa
Falkland Islands	Latin America
Fiji	OECD Pacific
Finland	West Europe
Fmr Yug Rep Macedonia	East Europe
France	West Europe
French Guiana	Latin America
French Polynesia	OECD Pacific
Gabon	sub-Saharan Africa
Gambia	sub-Saharan Africa
Georgia	FSU
Germany	West Europe

Ghana	sub-Saharan Africa
Gibraltar	West Europe
Greece	West Europe
Greenland	West Europe
Grenada	North America
Guadeloupe	North America
Guam	S&SE Asia
Guatemala	Latin America
Guinea	sub-Saharan Africa
Guinea Bissau	sub-Saharan Africa
Guyana	Latin America
Haiti	Latin America
Honduras	Latin America
Hungary	East Europe
Iceland	West Europe
India	S&SE Asia
Indonesia	S&SE Asia
Iran	Middle East
Iraq	Middle East
Ireland	West Europe
Israel	Middle East
Italy	West Europe
Ivory Coast	sub-Saharan Africa
Jamaica	Latin America
Japan	OECD Pacific
Jordan	Middle East
Kazakhstan	FSU
Kenya	sub-Saharan Africa
Kiribati	OECD Pacific
Korea Dem.people's Rep.	China+
Korea, Republic Of	S&SE Asia
Kuwait	Middle East
Kyrgyzstan	FSU
Laos	China+
Latvia	East Europe
Lebanon	Middle East
Lesotho	sub-Saharan Africa
Liberia	sub-Saharan Africa
Libya Arab Jamahiriy	Middle East Africa
Lithuania	East Europe
Luxembourg	West Europe
Madagascar	sub-Saharan Africa
Malawi	sub-Saharan Africa
Malaysia	S&SE Asia
Mali	sub-Saharan Africa
Malta	West Europe
Martinique	North America
Mauritania	sub-Saharan Africa
Mauritius	sub-Saharan Africa
Mexico	Latin America
Micronesia, Fed Stat	OECD Pacific
Moldova, Republic Of	FSU
Mongolia	China+

Morocco	Middle East Africa
Mozambique	sub-Saharan Africa
Myanmar	S&SE Asia
Namibia	sub-Saharan Africa
Nauru	S&SE Asia
Nepal	S&SE Asia
Netherlands	West Europe
New Caledonia	OECD Pacific
New Zealand	OECD Pacific
Nicaragua	Latin America
Niger	sub-Saharan Africa
Nigeria	sub-Saharan Africa
Niue	S&SE Asia
Northern Mariana Islands	OECD Pacific
Norway	West Europe
Oman	Middle East
Pakistan	S&SE Asia
Palau Islands	OECD Pacific
Panama	Latin America
Papua New Guinea	S&SE Asia
Paraguay	Latin America
Peru	Latin America
Philippines	S&SE Asia
Poland	East Europe
Portugal	West Europe
Puerto Rico	Latin America
Qatar	Middle East
Reunion	sub-Saharan Africa
Romania	East Europe
Russian Federation	FSU
Rwanda	sub-Saharan Africa
Saint Lucia	North America
Sao Tome & Principe	sub-Saharan Africa
Saudi Arabia	Middle East
Senegal	sub-Saharan Africa
Seychelles	sub-Saharan Africa
Sierra Leone	sub-Saharan Africa
Singapore	S&SE Asia
Slovakia	East Europe
Slovenia	East Europe
Solomon Islands	OECD Pacific
Somalia	sub-Saharan Africa
South Africa	sub-Saharan Africa
Spain	West Europe
Sri Lanka	S&SE Asia
St.kitts & Nevis	North America
St.vinct & Grenadine	North America
Sudan	sub-Saharan Africa
Suriname	Latin America
Swaziland	sub-Saharan Africa
Sweden	West Europe
Switzerland	West Europe
Syrian Arab Rep.	Middle East

Taiwan	China+
Tajikistan	FSU
Tanzania	sub-Saharan Africa
Thailand	S&SE Asia
Togo	sub-Saharan Africa
Tonga	OECD Pacific
Trinidad & Tobago	Latin America
Tunisia	Middle East Africa
Turkey	West Europe
Turkmenistan	FSU
Turks And Caicos Islands	North America
U.s. Virgin Islands	North America
Uganda	sub-Saharan Africa
Ukraine	FSU
United Arab Emirates	Middle East
United Kingdom	West Europe
United States	North America
Uruguay	Latin America
Uzbekistan	FSU
Vanuatu	OECD Pacific
Venezuela	Latin America
Vietnam	China+
Western Sahara	Middle East Africa
Western Samoa	OECD Pacific
Yemen	Middle East
Yugoslavia	East Europe
Zaire	sub-Saharan Africa
Zambia	sub-Saharan Africa
Zimbabwe	sub-Saharan Africa

Table D.10 List of the countries belonging to each region (used in Appendix D; for the country assignment used in the main model see Appendix A).

APPENDIX E: SUMMARY FIGURES

The following colour Figures summarise the four supply scenarios in their attempt to cover the common demand scenario with the total requirements for delivered energy given in Fig. E.1. Figure E.2 shows the geographical distribution of total energy supply minus demand for the clean fossil scenario, Fig. E.3 the same for the safe nuclear scenario (but in units of tons of thorium oxide, because there is no unique translation into energy units: the "breeding factor" for the nuclear fuel ranges from 1 to 60 for different reactor types, with the energy amplifier used in the scenario lying around 10). Figure E.4 gives supply minus demand for biofuels in the transportation sector for the two renewable energy scenarios, and Figs. E.5 and E.6 the surplus/deficit for the other sectors of energy use (electricity etc.), where in this case the decentralised and centralised scenarios differ.

Energy flow W/m2	
5	to 10
2	to 5
1	to 2
0.5	to 1
0.2	to 0.5
0.1	to 0.2
0.05	to 0.1
0.02	to 0.05
0.01	to 0.02
0.005	to 0.01
0.002	to 0.005
0.0001	to 0.002
all others	

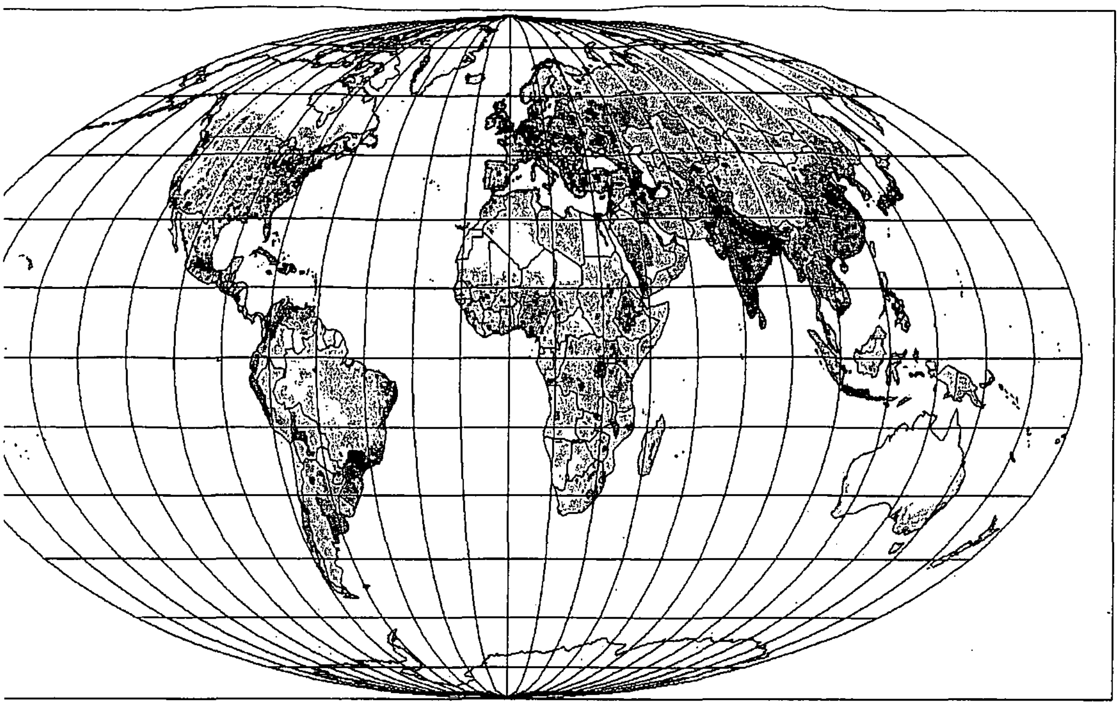
Surplus/deficit of Th in country (kt/y)	
0.2	to 1
0.1	to 0.2
0.02	to 0.05
0.005	to 0.01
-0.002	to -1e-008
-0.005	to -0.002
-0.01	to -0.005
-0.02	to -0.01
-0.05	to -0.02
-0.1	to -0.05
-0.2	to -0.1
-1	to -0.2

Supply minus demand (W/m2)	
0.1	to 0.5
0.05	to 0.1
0.01	to 0.05
0.005	to 0.01
0.0001	to 0.005
-0.005	to -0.0001
-0.01	to -0.005
-0.05	to -0.01
-0.1	to -0.05
-0.5	to -0.1
-1	to -0.5
-2	to -1
-10	to -2
all others	

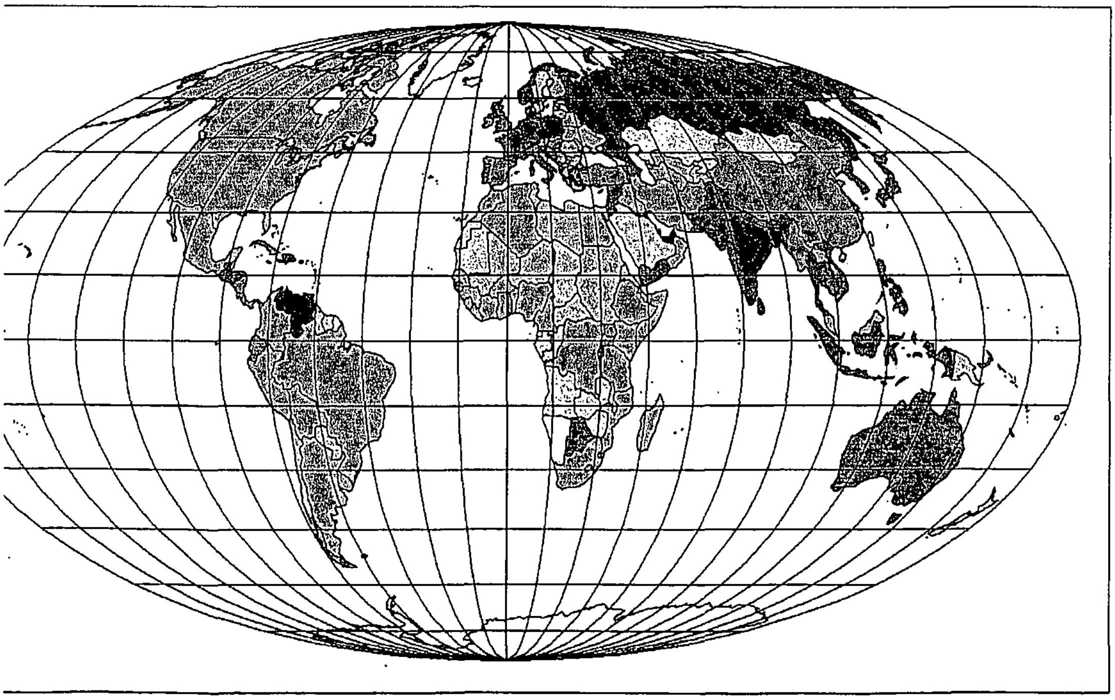
Figure E.1a (left). Scale used for total delivered energy demand flow (W/m^2).

Figure E.2a (right). Scale used for energy supply minus demand flows in fossil and renewable energy scenarios (W/m^2).

Figure E.3a (middle). Scale used for nuclear fuel supply minus demand flow in the safe nuclear scenario (kt of thorium oxide per year per country).



:1. Total energy that must be delivered to the end-users in the 2050 energy demand scenario (including direct delivery of fuels and electricity, environmental heat and food energy), expressed as W/m^2 of land area. The scale is given in Fig. E.1a.



:2. The clean fossil fuel scenario energy production (coal and natural gas) minus demand, expressed as average energy flows in W/m^2 for each country (scale shown in Fig. E.2a).

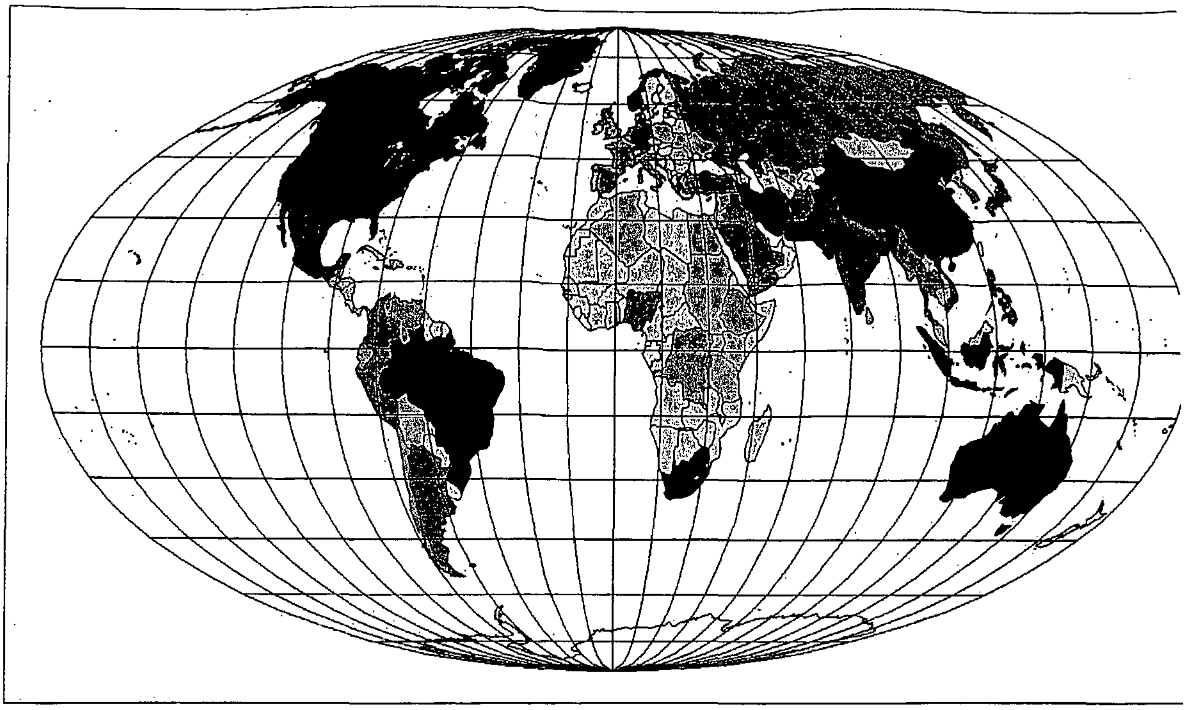


Figure E.3. The safe nuclear scenario energy production (thorium fuel) minus demand, expressed average energy flows in kt thorium oxide per year for each country (scale shown in F E.3a).

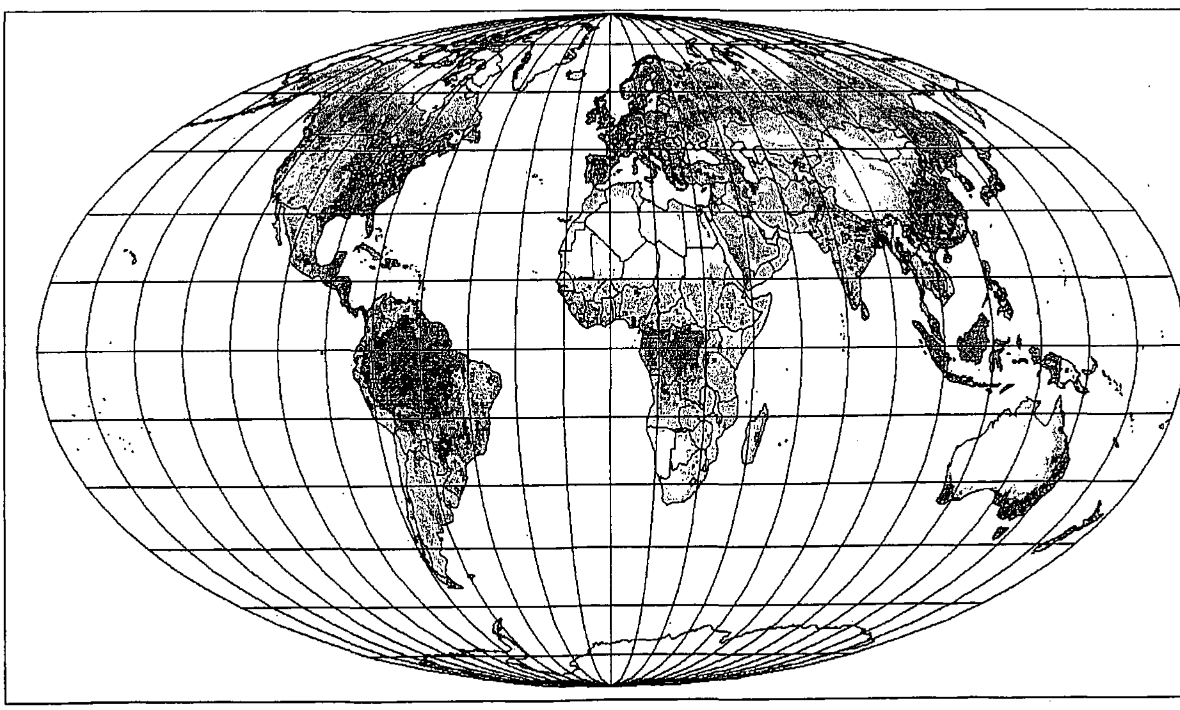


Figure E.4. The renewable energy scenario biofuel energy production (methanol or hydrogen) min demand, for use in the transportation sector, expressed as average energy flows in W/ı of land area. Valid for both the decentralised and the centralised renewable energy sc nario (scale shown in Fig. E.2a).