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Published in:
The Hydrogen Planet

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Sørensen, B. (2002). Handling fluctuating renewable energy production by hydrogen scenarios. In *The Hydrogen Planet: 14. World Hydrogen Energy Conf., Montréal*

Handling fluctuating renewable energy production by hydrogen scenarios[*]

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Abstract

The aim is to identify ways of handling the large deficits and surpluses of electricity, particularly from wind energy expected in the future Danish energy system, by use of hydrogen as an energy carrier and an energy store.

System-wide aspects of the choice of hydrogen production technologies, distribution methods, infrastructure requirements and conversion technologies are assessed. Two types of hydrogen use are investigated: in the transportation sector, or as a storage option in connection with stationary power and heat production.

For the mid-2100 century, where the existing fossil energy is expected to have been largely phased out, scenarios combining the above hydrogen uses are constructed: a complete decentralisation of the use of hydrogen, converting and storing surpluses within individual buildings for later use in vehicles or regeneration of power and heat. Alternatively retaining some centralised infrastructure, such as hydrogen cavern stores and a network of vehicle filling stations.

The analysis tracks hydrogen conversions in time and space, using hourly simulation and a 500m×500m grid, in order to model variations in wind power production and energy demand. Components in an implementation strategy are identified, including a time sequence of necessary decisions and technology readiness requirements.

1. Shaping the future Danish energy system

Danish energy policy aims to create a sustainable energy system primarily based on renewable energy sources. This is achieved by a replacement of the current, mainly fossil energy system over a period of time long enough to ensure that system components are not retired before having reached economic break-even or better. Danish governments has established a plan for phasing out coal over a thirty-year period, and at the same time phasing in renewable energy (with wind power as the largest component), so that it covers more than 50% of the energy demand projected 30 years ahead. The continuation of this plan after 2030 is not formulated in quantitative terms, but will entail a complete phasing out of fossil energy sources, in favour of renewable ones. Problems foreseen for this development are primarily expected to be associated with the variable inflow of renewable resources, and their time-wise mismatch with expected load profiles. Handling these problems may use one of - or a combination of - the following four methods:

1) Load management aimed at shifting loads to the times convenient from the point of view of the energy generating system.

2) Trade of energy, and particularly the energy forms most affected by energy source variations, such as electricity, with trade partners with which Denmark has grid connections or other means of exchange.

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[*] Based upon parts of study performed for the Danish Energy Agency under contract 1763/99-0001.

3) Converting surplus energy, i.e. energy, which at a given time cannot be used directly, to other energy forms for which there is a demand.

4) Storing surplus energy for later regeneration of the same or another useful energy form.

The options of load management and international exchange, particularly of electricity, have been the subject of several previous studies (Meibom et al., 1999; Sørensen, 2000). I here focus on the introduction of hydrogen as an energy carrier, in the light of the two last methods described above:

Excesses of wind power and photovoltaic power are converted to hydrogen, for which uses are created in the transportation sector. The maximum power production from current wind turbines is typically 3-4 times the average, which is the reason that the other solution of grid exchange of power is likely in periods to lead to very low selling prices, at least in the Nordic system, where large reservoir based hydro power provides a cheap backstop generation during wet years.

Hydrogen is assumed to be used in the future in most vehicles of transportation, through fuel cell technology, i.e. an electric motor fed by electricity from a fuel cell. The fuel by which the fuel cell is operating is taken as hydrogen (although this is not the only possibility, it is the one presently closest to viability), either from on-board storage or generated on-board by reformation of methanol. The latter option, which is currently researched by some automobile manufacturers, involves (in a renewable scenario) the use of methanol generated either from biomass or from hydrogen. This is one additional, loss-creating energy conversion, and direct use of hydrogen would seem preferable. However, to make it preferable, convenient hydrogen storage and distribution systems must be made available.

The scenarios consider two alternative infrastructure systems: one where road vehicles are served by filling stations distributed roughly as today, and one where decentralised filling takes place at individual buildings, which all are assumed to possess hydrogen production facilities, in the form of electrolysers or (perhaps more likely) reversible fuel cells. In the latter case, regeneration of electricity, with associated heat, may serve the needs of the building during times of insufficient direct power supply from the renewable sources. This makes centralised production facilities unnecessary, and one aim of the study is to establish what level of storage, each building must possess in order to achieve complete coverage of demands (of all kinds, including domestic, industry and service sector uses, in addition to all transportation needs).

In the centralised scenario, hydrogen production, storage and electricity regeneration is performed in central facilities such as the current power and heat plants and the existing natural gas storage facilities in underground caverns (aquifers or salt dome intrusions). Again the aim of the study is, based on hour-by-hour time simulations, to determine the amount of storage that will allow all demand to be matched. The final scenarios pertain to the year 2050, but an implementation strategy is proposed, which orders the time-sequence of introduction of the novel technologies by their expected technical and economic viability.

2. Energy demand assumptions

In dealing with the Danish energy system developments to 2050, we explore one scenario (termed "centralised"), which is a natural continuation of the 2030 plan scenario of the Danish government, and another, where hydrogen production and dispatch are highly decentralised. This is probably more costly than the centralised scenario, but it offers social benefits that perhaps will make the price acceptable. Present building-integrated heating systems (using oil, gas or solar) takes advantage of the often lower distribution costs (in the case of oil or gas) relative to district heating lines, but for reversible fuel cell systems, it would be possible to have only electricity networks extending to the buildings in question, which is certainly less expensive than both hydrogen pipelines and district heating lines. The question is thus, if the cost of reversible fuel cell systems, including hydrogen stores, is favourable enough to balance the savings in distribution costs. Also the conversion efficiency matters, independent of cost, because of the limited total renewable energy resources.

The energy demands to year 2030 are simply taken from the official Danish energy plan (Danish DoE, 1998/99). For 2050, each scenario has its own demand assumptions, with the centralised scenario continuing the trend of the current planning, while the decentralised assumes a further reduction in energy use at the end user. These assumptions correspond to the analysis made in previous global energy scenarios (Meibom and Sørensen, 2000; Sørensen, 2000). The lower demand in the decentralised scenario may be thought of as a reflection of the value system underlying the decentralised scenario, but it also reflects the more tangible fact that the proposed system clearly has a higher cost per energy unit produced, than the cost of avoiding the use of that unit, e.g. by investing in efficiency. Several studies have shown that break-even between efficiency improvement and additional supply lies at a specific consumption some 4-5 times lower than the present (Kuemmel, Nielsen and Sørensen, 1997; Sørensen, 2000). It is therefore inherently inconsistent, when most energy scenarios suggest the introduction of new supply components at a higher cost than efficiency measures not introduced, but the reason is of course "social opposition", a complex entity that reflect current conditioning to a growth paradigm, which seems to be assumed more difficult to influence than the choice of energy supply technology.

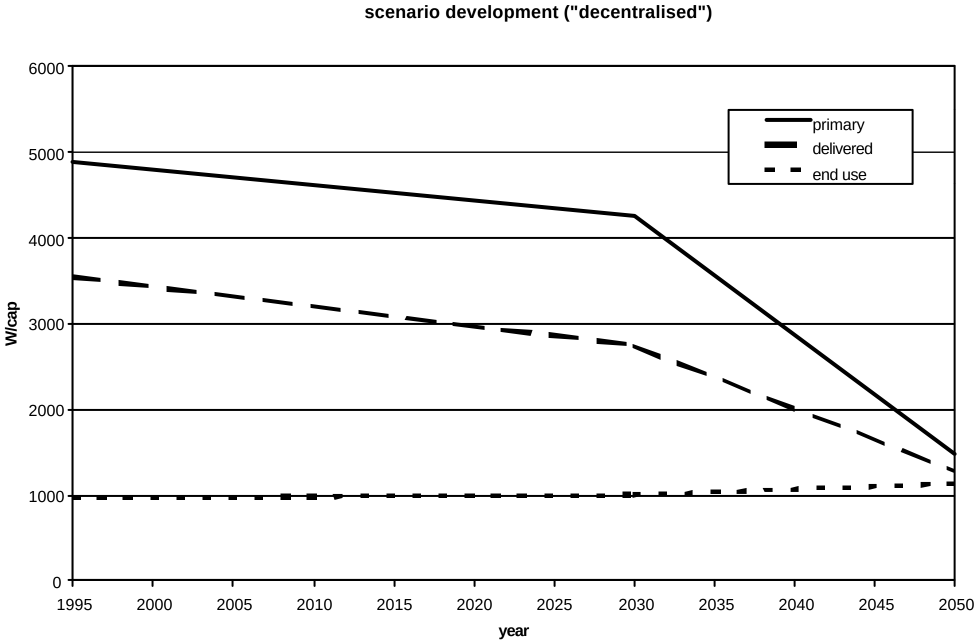

Figure 1. Trends in primary energy, delivered energy and energy made useful at the end-user for the decentralised scenario (Sørensen et al., 2001; for definition of end-use see Sørensen, 2000).

Figures 1 and 2 show the trends in energy produced, delivered end finally used, for the two lines of scenarios. The development to 2030 is that of the official Danish plan, but from 2030 to 2050 the two scenarios differ: the decentralised scenario has end use growth only in electricity use, whereas the "delivered energy" indicates considerable improvements in end-use efficiency, and the "primary energy" similarly for the conversion steps before reaching the final user. The centralised scenario exhibits much larger increase in end use, comprising both increases in electricity use and in energy for transportation. The technical efficiency level is the same as in the decentralised scenario, but due to the end use increase, the primary and delivered energy decrease less than for the decentralised scenario.

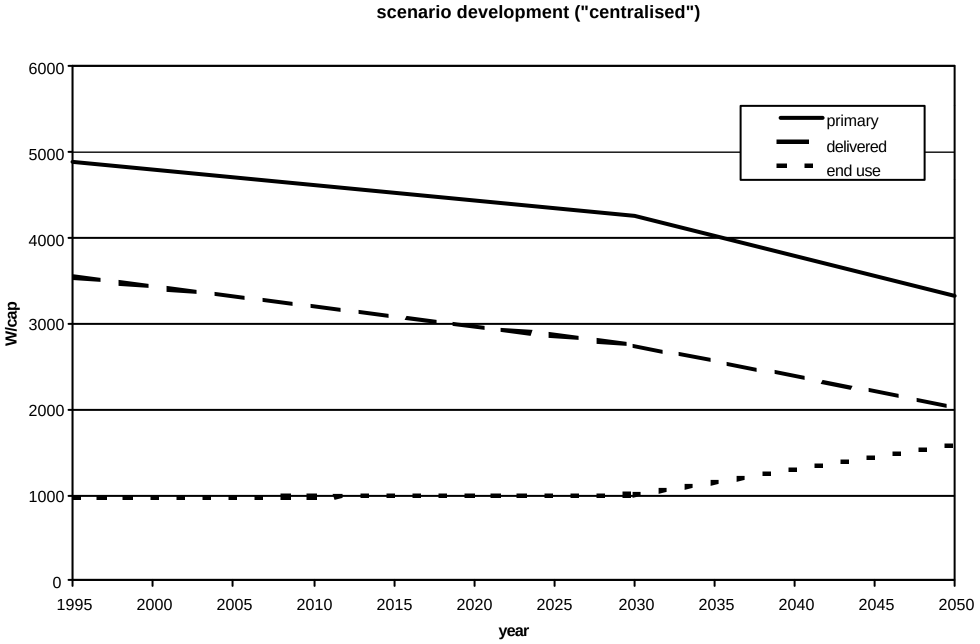

Figure 2. Trends in primary energy, delivered energy and energy made useful at the end-user for the centralised scenario (Sørensen et al., 2001; for definition of end-use see Sørensen, 2000).

3. Details of the decentralised 2050 scenario

As energy demand is modest in the decentralised scenario, it is possible to restrict the use of biomass to very low values, and thus avoid criticism from some parts of the ecological community, who claim that it is important to return not just nutrients but also carbon from biomass residues back to the fields. The basic idea of the scenario is illustrated in the Figure 3, with indication of the use of building-integrated, reversible fuel cells in situations of power surplus or deficit.

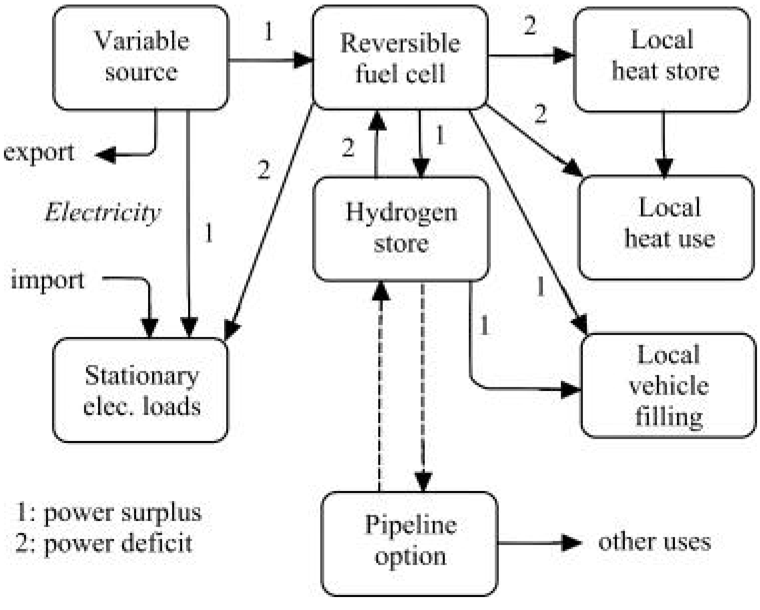

Figure 3. Outline of decentralised scenario (Sørensen, 2000b).

The actual annual primary energy input consists of 16 PJ from biomass (to be used for lorries), 67 PJ from wind turbines on land (essentially replacing the existing ones by 2 MW units) and 99 PJ from turbines off-shore. To this adds 20 PJ solar electricity and 40 PJ solar heat, plus 40 PJ environmental heat drawn by heat pumps in the system. Because electricity in this scenario must cover nearly all high- quality energy demand, either directly or converted to hydrogen (heat pumps and waste heat from the conversion processes are used for heat requirements), there is a high level of average electricity production compared with direct electricity demands, with the associated problem of occasionally very large surpluses, as shown in the time series of Figure 4, using a particular year of actual data (Eltra/Elkraft, 2001), scaled to the 2050 demand assumption.

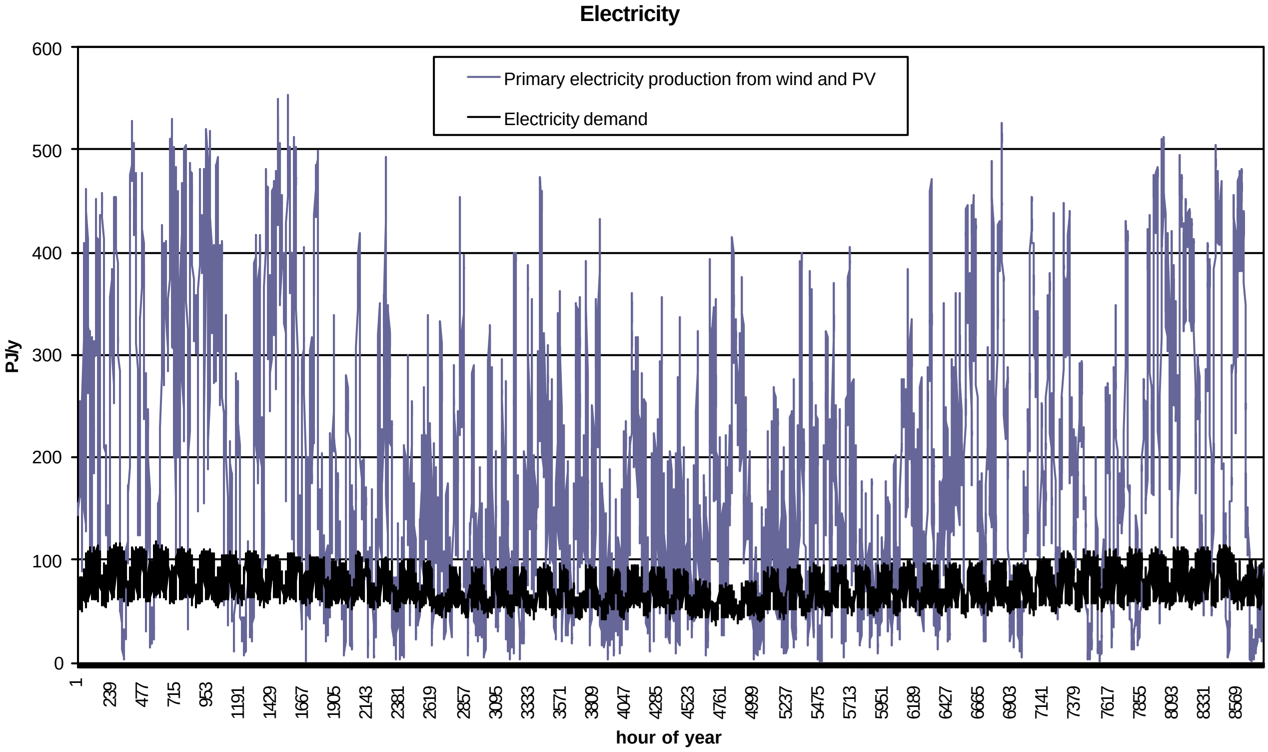

Figure 4. Time series for total Danish electricity production (from PV and wind turbines) in the decentralised 2050 scenario, shown together with gross electricity use (Sørensen et al., 2001; simulation software developed by NOVATOR (2001) has been used for all time-simulations)

After local conversion of the surpluses of electric power into hydrogen, this is either filled into the stores of vehicles parked at the building, or into local stationary hydrogen stores, likely to be metal hydride stores. The time series of storage levels, shown in Figure 5, indicates storage needs of 60000 PJh or roughly 0.3 m^3 of a typical metal hydride store in each of 2 million buildings. There is insufficient energy transferred to the store only during some 50 hours of the year, and it is considered less expensive to obtain these by international trade than by increasing the wind power production capacity.

4. Details of the centralised 2050 scenario

In the centralised scenario, due to the higher energy demand assumed, biomass production is not restricted as much as in the decentralised scenario (200 PJ is produced and used for methanol and hydrogen production). Also off-shore wind power production is considerably higher (213 PJ), and hydrogen storage is in centralised caverns, assumed to be located where the present (two) natural gas stores are. Hydrogen is assumed to be filled onto vehicles through a network of filling stations, slightly less in numbers compared with current gasoline stations. The system layout is indicated in Figure 6.

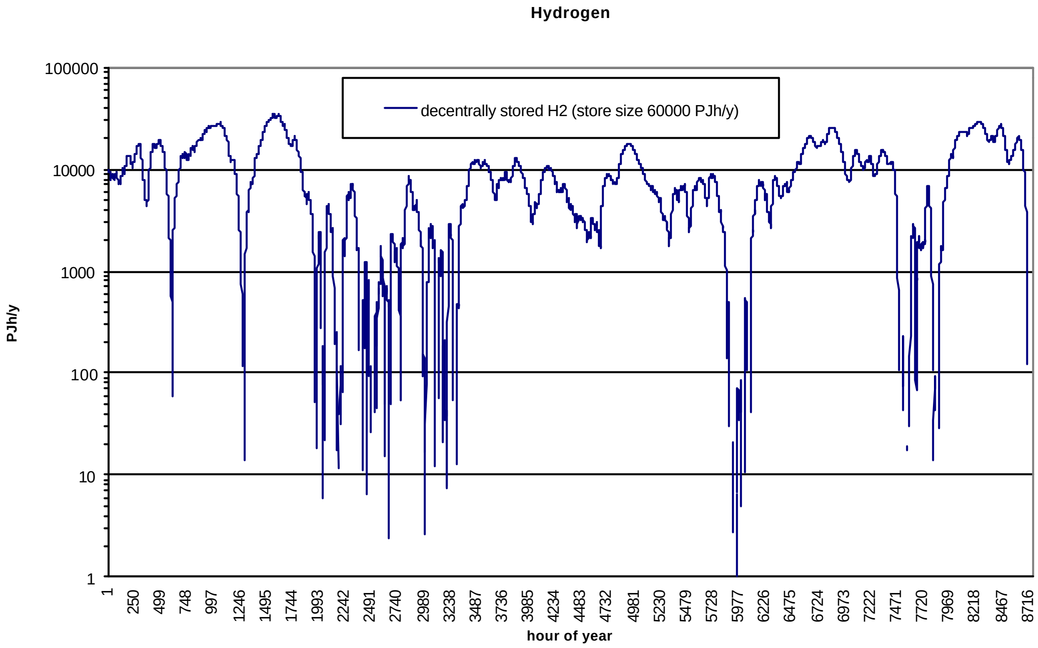

Figure 5. Total energy stored in building-integrated stores for each hour of the year, in the decentralised 2050 scenario (the unit PJh/y is PJ divided by 8760). The main contribution to the annual hydrogen production is 99 PJ from off-shore wind turbines (Sørensen et al., 2001)

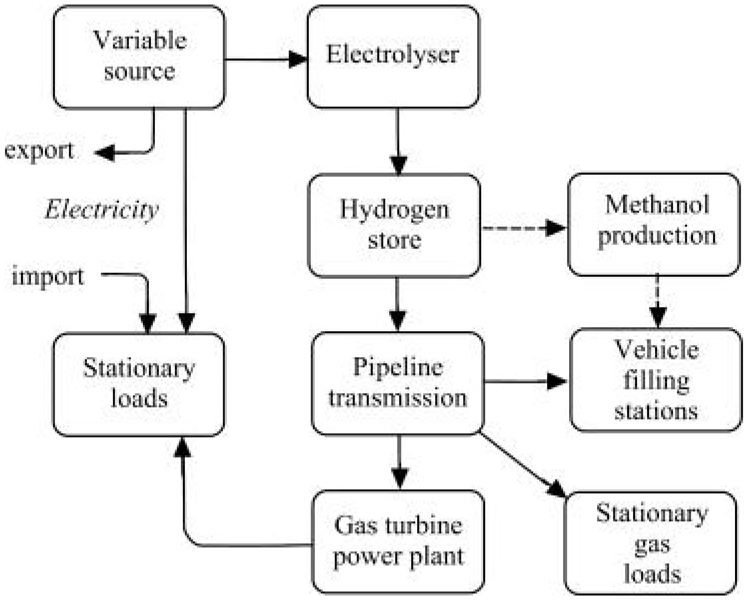

Figure 6. Outline of centralised scenario (Sørensen, 2000b).

The off-shore wind production makes use of around half of the areas currently designated for such use. The locations are indicated in Figure 7.

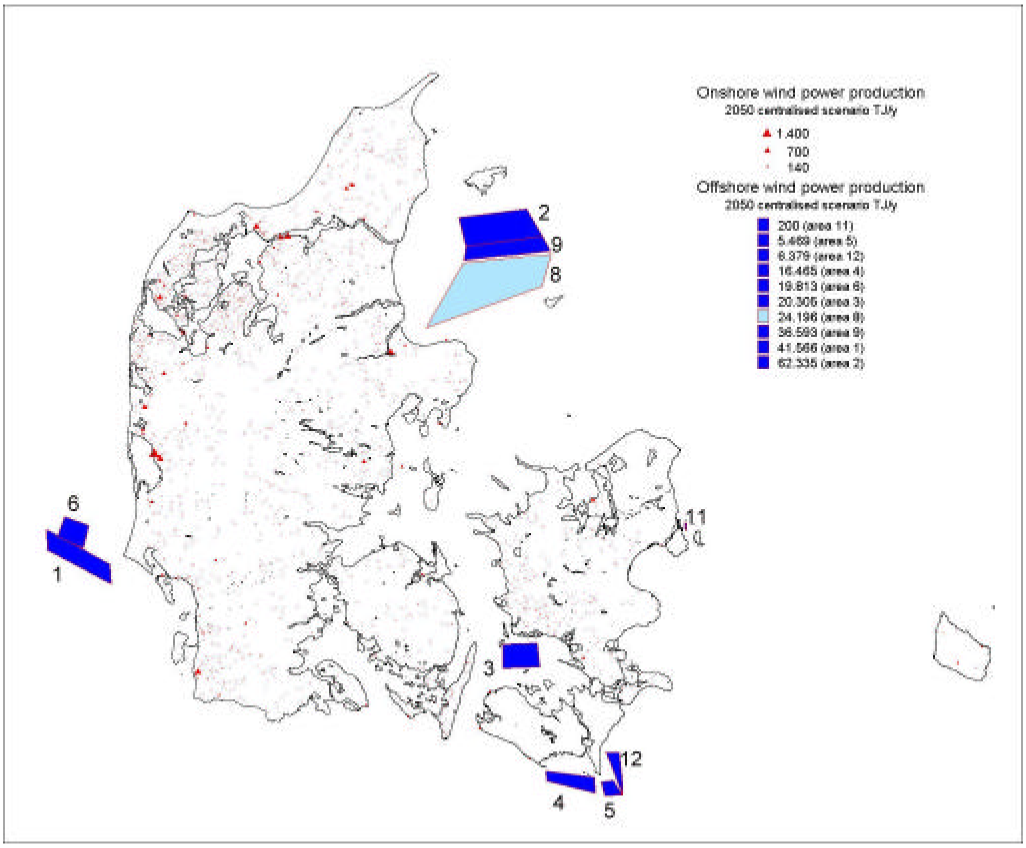

Figure 7. Geographical location of wind power plants in the 2050 centralised scenario (Sørensen et al., 2001).

With the same 60000 PJh of storage as in the decentralised scenario, all demands can be matched for every hour of the year for which data are considered. This corresponds to two hydrogen stores totalling 13 million m^3 at a hydrogen pressure of 5 MPa, which is only a fraction of the existing gas stores. Figure 8 shows the variations in stored energy, as well as production of hydrogen from biomass, varied according to direct demands.

5. Implementation considerations.

The fuel cell and automobile industry has repeatedly stated that the first commercial hydrogen passenger cars will be on the market in 2004. There will likely be a period of 2-3 decades before hydrogen could achieve a complete penetration into the transportation sector, but an optimistic view would be that major vehicle classes could be converted already during the first decade. This would comprise passenger cars and buses, while the transition is likely to take longer for trucks and vans. For ships, the introduction could be fast, but there are no current efforts underway, so it is still most probable that the penetration will take more than one decade. For planes, the conversion time will probably be the longest, maybe 2-3 decades. All the technologies could be in place before 2030, and it is not very meaningful to speculate on the precise year of introduction for a given technology, since it depends on two uncertain factors: how soon the cost of the new technologies will become acceptable, and whether non-economic barriers will impede the introduction, once the price is right.

Production of hydrogen is not likely to be a problem. As soon as there is a demand, the wind power surplus could be used to produce hydrogen (first by standard electrolysis), and along the way, the already substantial wind capacity may be expended as fast as necessary. Production of hydrogen from natural gas is likely to take off in several other countries, and the production based upon biomass may develop during the first or second decade. The gasification and shift reactions are well known, but cost reductions are required. Hydrogen from photovoltaic electricity is likely to be 20 years away, and direct production based upon new types of solar cells such as organic dye and polymer devices may never be able to out-compete photovoltaic cells.

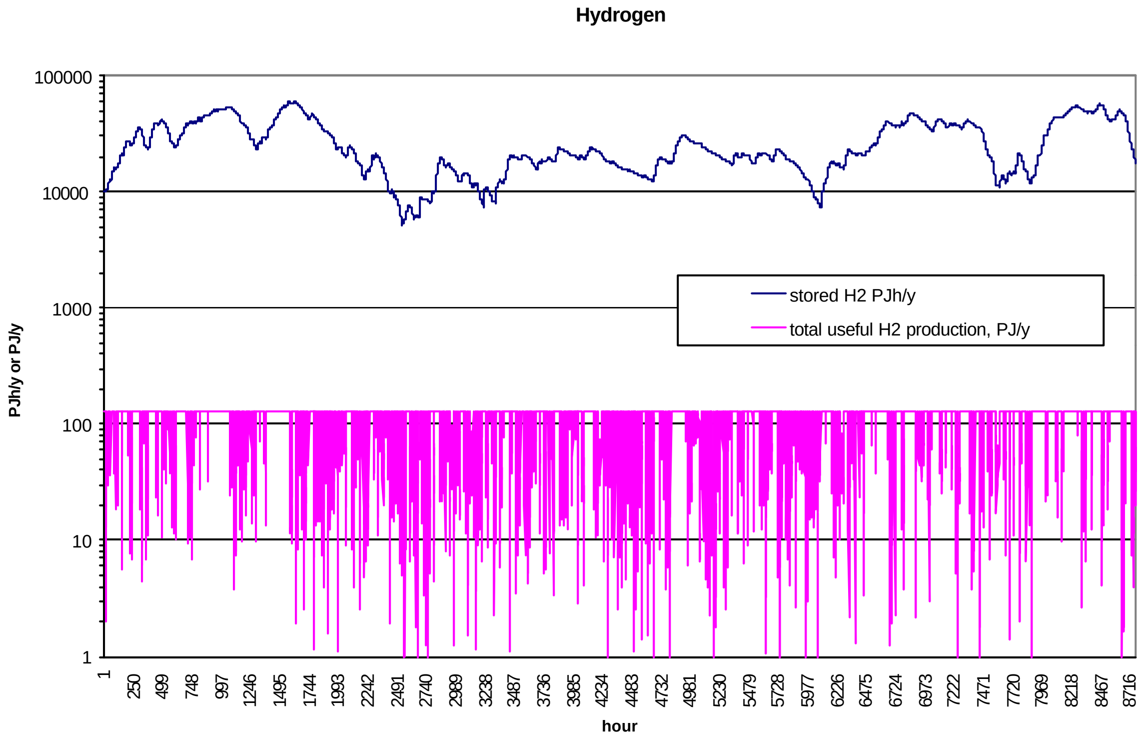

Figure 8. Hydrogen stored in central caverns for each hour of the 2050 scenario, and hydrogen production based upon biomass (Sørensen et al., 2001; the unit PJh/y is PJ divided by 8760).

Central hydrogen storage facilities may be built when needed, whereas stores for vehicles and building use are likely to have to undergo a continued development over a decade or two. All in all, the scenario time horizon chosen seems to be realistic, but depending on the success in developing the key technology for hydrogen to play a role: a technically and economically viable fuel cell. Due to the low efficiency, the alternative of direct hydrogen combustion techniques cannot furnish a long-term solution, and using them for an "enhanced introduction" of hydrogen seems a dubious route, because only large-engine cars can be converted, implying that the advantage of introducing hydrogen in this limited sector could as well be obtained by encouraging people to use smaller, more energy-efficient motor cars.

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