SUMMARY IN ENGLISH

Hydrogen as an energy carrier - scenarios for future use of hydrogen in the Danish energy system

a project carried out 1999-2001 by Roskilde University, Risø National Laboratories, Danish National Oil and Gas Company, Elkraft Systems and Energy E2 for the Danish Energy Agency under contract 1763/99-0001.

Challenges posed by the restructuring of the Danish energy system

The goal of Danish energy policy is 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 long enough to ensure that system components are not retired before having reached economic break-even or better. The Danish government 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.

Our project focuses on the formulation of solutions to the problems foreseen for the development sketched above. Such problems 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 will use one of - or a combination of - the following four methods:

- Load management aimed at shifting loads to the times convenient from the point of view of the energy generating system.
- 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.
- 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.
- 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. This study focuses on the introduction of hydrogen as an energy carrier, in the light of the two last methods described above:

Converting excesses of wind power and photovoltaic power to hydrogen, for which uses are created in the transportation sector. The maximum power production from current wind turbines is typically around 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 in the future to be used 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, lossy energy conversion, and direct use of hydrogen would seem preferable. However, to make it preferable, a convenient hydrogen distribution system must be created.

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 we consider stages on the road, by looking at the situation in 2030, and by proposing an implementation strategy, which orders the time-sequence of introduction of the novel technologies by their expected technical and economic viability.

Hydrogen technologies proposed to be used in the future Danish energy system

One main energy carrier in the project is hydrogen and therefore the technologies include production, storage, distribution and utilisation of hydrogen, covering both mobile and stationary applications. In addition, however, methanol is used both for direct application and as an intermediary step for conversion to hydrogen (for instance onboard vehicles). The main reason for introducing methanol is that it generally offers longer range per refuelling, at the expense of poorer overall energy efficiency.

Although both hydrogen and methanol can be generated from fossil fuels such as natural gas, the main focus of this project is production technologies based on renewables. The two principal production paths covered are based on biomass conversion and electrolysis, possibly supplemented at some stage by advanced technologies such as photo-electrochemical conversion (converting sunlight directly to hydrogen). The table shows projected conversion efficiency (based on the hydrogen/methanol output) and costs by the year 2030 for key production technologies.

	Conversion efficiency, %	Investment costs DKr/kW
Hydrogen, biomass gasification	57	3000
Methanol, biomass gasification	51	4500
Solid-polymer electrolysis	94	1200
Alkaline electrolysis	80	2000

As regards hydrogen storage, the situation is quite different for stationary stores on the one hand and storage on board vehicles on the other. Whereas the former can be perceived as primarily a question of relatively limited further development of existing technologies, the latter represents one of the key challenges of a large-scale application of hydrogen. In both cases reducing the required volume of the storage, without reducing the energy efficiency too much, is an important objective, but for mobile applications this is a vital issue and here, moreover, there is generally a need for reduction of the weight of the storage. Therefore, a range of different storage concepts is being investigated for onboard storage, none of which are considered totally satisfactory as of today. The option offering the highest energy density at present, liquid hydrogen, has very poor overall energy efficiency, mainly due to the energy losses in connection with the liquefaction process. The table shows projected key features by the year 2030 of selected technologies for onboard hydrogen storage.

	Energy density per mass, MJ/kg	Energy density per volume, MJ/litre	Costs, DKr. per MJ storage capacity
Compressed hydrogen (as gas)	7-8	3-3.5	10
Liquid hydrogen	20-22	7-8	10
Metal hydrides	4.5-5	13-15	45

Stationary storage is carried out both as compressed gas, in liquid form and in metal hydrides. For large stores underground storage is an important option.

The distribution and transport of hydrogen from production locations to the point of utilisation may take place in many different ways, as is the case in the present energy system. The major options are pipeline systems, similar to the present natural gas system, and tank distribution - e.g. in the form of compressed gas, liquid hydrogen or methanol - by means of ships or lorries. A key issue is whether the present natural gas system may be used, in total or in part, for hydrogen distribution. Our investigation of this issue concludes that certain key studies must be made in order to fully answer the question and determine the cost involved, but that there seems to be basis for optimism.

As far as utilisation technologies are concerned, the most interesting perspectives are linked to fuel cells, since these offer superior environmental characteristics including very efficient conversion of energy to useful purposes. In this field, there is a strong ongoing development process leading both to improvements of known applications and development of new applications. In this project, the main focus has been on applications in either stationary power and heat generation or mobile applications (in the form of drive systems for transportation means). The development so far, notably during the most recent decade, has resulted in improvements by several orders of magnitudes regarding both technical and economical performance, particularly the latter. However, further substantial development is needed, especially with respect to costs.

	Electric efficiency %	Heating efficiency %	Costs, DKr. per kW
Hydrogen (ICE)	46	50	4000
Hydrogen (gas-turbine)	48	44	7000
Hydrogen, fuel cell (solid-polymer)	57	33	8000
Hydrogen, fuel cell (solid oxide)	58	32	8000

Stationary applications (co-generation systems) may be based on both internal combustion engines (ICE), gas turbines and different types of fuel cells. The fuel cell types vary with regard to costs and efficiency (power and heat) but also aspects such as development stage and requirements to fuel. Certain fuel cells may use other fuels than hydrogen directly. The table above shows the projected development of efficiency and costs by the year 2030 of selected technologies for power and heating generation.

For mobile applications drive trains based on fuel cells allow improvements of the energy efficiency of given vehicles by a factor 2 to 3 compared to both the present vehicles and the use of hydrogen in vehicles driven by internal combustion engines. The table illustrates key features by 2030 of selected drive trains based on an average passenger car. A methanol system allow longer range between refuelling (depending on the development of the hydrogen storage technology) but also leads to poorer energy efficiency.

	Total efficiency % from tank to wheel	Total costs of drive trains DKr/kW
Hydrogen, ICE	20	250
Hydrogen, fuel cell	50	480
Methanol, fuel cell	35	600

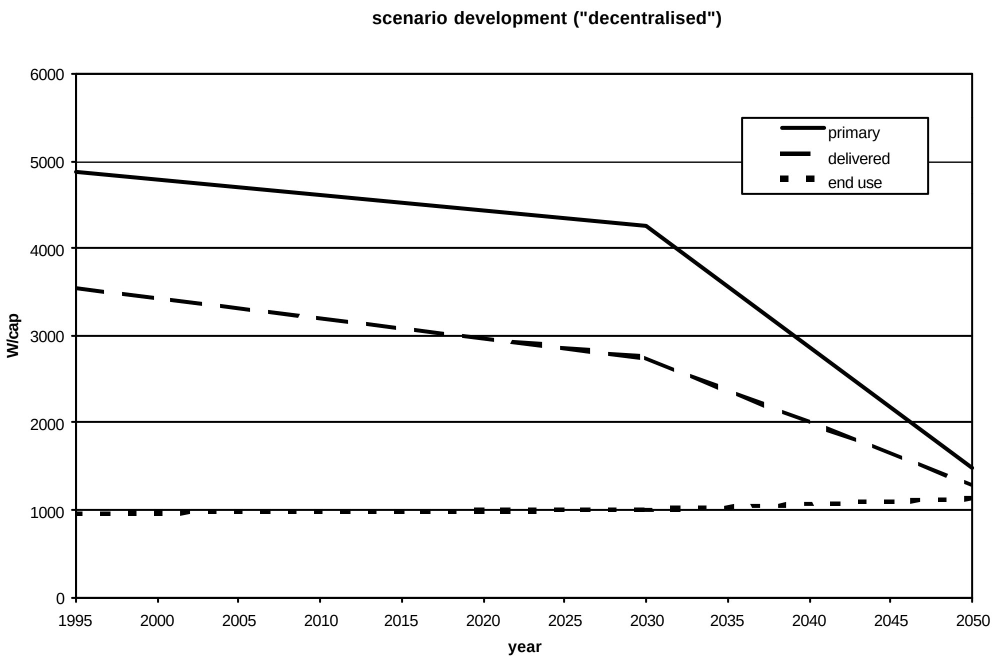
Scenario construction and lessons learned

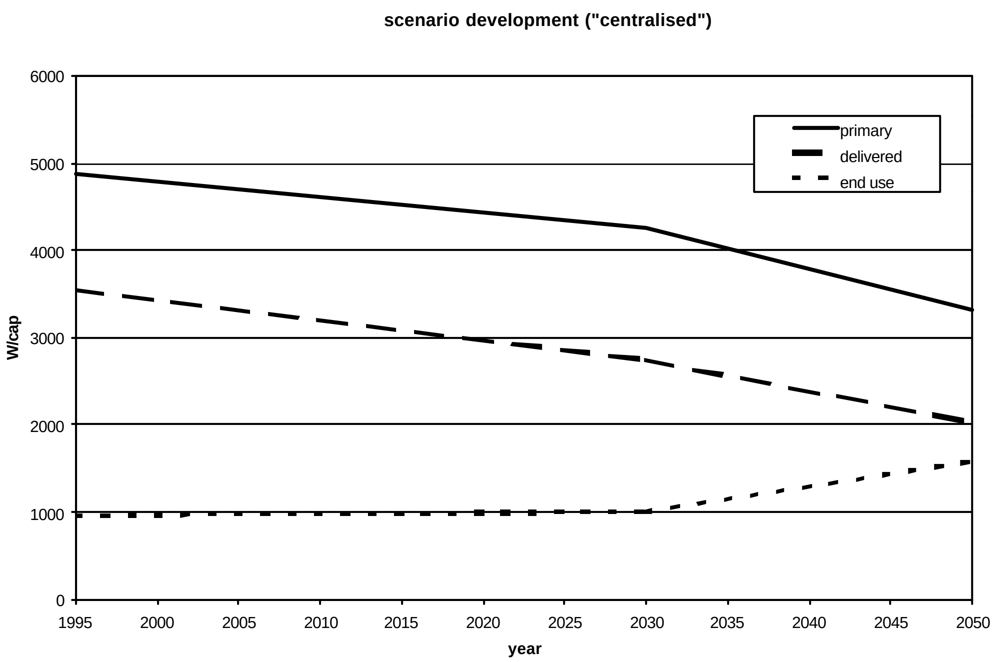
Scenarios are constructed for the entire energy system, in order to have consistency, even if the main interest in this study is the part of the system amenable for introduction of hydrogen technologies. The scenarios considered in the project explores two avenues, one which leads to a much more decentralised energy system than the present, while the other looks more like the present system, with its mix of centralised and decentralised features.

In the 2030 substitution scenario, the emphasis is on introducing hydrogen in the transportation sector, while the surpluses and deficits of wind energy are assumed to be handled through international power trade. This addresses the sorest point of the Danish energy plan: How to make the energy use in the transportation sector more sustainable. Another 2030 scenario looks at the use of hydrogen storage to avoid electricity trade, if the international market prices are unattractive. Since future prices of energy and hydrogen equipment are highly uncertain, the scenario rather aims at finding what prices would make the approach attractive.

Continuing the reflections on system developments to 2050, we explore one scenario (termed "centralised"), which is a natural continuation of the 2030 substitution scenario, 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 those of the official Danish energy plan. 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 improvement of energy conversion efficiency at the end user. This 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 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. 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 seem to be assumed more difficult to influence than the cho ice of energy supply technology.





The two figures above 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 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.

The Substitution Scenario

The overriding objective of the Substitution Scenario is to investigate the potentials for substituting Danish transportation energy with hydrogen and methanol fuels based on renewable energy. This scenario highlights the options within the scope of the official energy and transport planning, hence taking the planning scenario of the Danish government's energy plan, Energy 21 - notably the state in the year 2030 - as starting point for the analysis. The hydrogen and methanol fuels are used as energy carriers for renewable energy sources - primarily wind power and biomass - in the transportation sector, and in addition significant improvements of the energy efficiency of the fuel chain is achieved (mainly due to large-scale introduction of fuel cells). To ensure that the transportation fuels are not simply displacing renewable energy in the stationary part of the energy sector, the scenario is based on the presumption of using only renewable resources registered in conjunction with Energy 21 but not exploited in its planning scenario.

The scenario covers both the domestic Danish transport sector and international air transport to and from Danish airports, with the latter reinforcing substantially the challenges of the scenario due to the projected strong growth of this subsector. Except for about 5% of the transport energy demand that is envisaged to be covered by electrical propulsion (rail transport and a share of battery electrical vehicles), the general conclusion of the scenario analysis is that it is indeed possible to meet the entire Danish transport demand by renewable hydrogen and methanol - albeit not by the year 2030. According to the scenario, slightly less than 80% of the transport energy can be converted to hydrogen and methanol by this year, with the remainder (just under 20%) being still covered by gasoline and diesel fuels. The split between hydrogen and methanol is roughly three-quarters of the former and one quarter of the latter (primarily utilised in long distance vehicles such as trucks).

With the exception of aviation, all drive systems are assumed to be based on fuel cells after the conversion to hydrogen/methanol, either in the form of so-called “direct-hydrogen fuel cell systems”, driven by hydrogen stored onboard as compressed gas, or as “indirect-methanol fuel cell systems”, in which the fuel is methanol converted onboard to hydrogen. The latter option allows for easier onboard energy storage but also has poorer energy efficiency. For aircraft propulsion hydrogen jet turbines are applied with on-board storage as liquid hydrogen.

Hydrogen and methanol is generated by means of biomass gasification and electrolysis based on power from wind turbines (as well as a small percentage of photovoltaics that may be disregarded without substantial overall impacts on the scenario). Roughly two thirds of the hydrogen/methanol is expected to be distributed through pipelines with the rest being distributed through tanks (by means of lorries, ships etc.). The pipeline system has the same coverage of Denmark as the present natural gas system and it may be an option to use this. Whether this is possible, depends on further studies and also presumes a plan for conversion of the pipeline system from natural gas to hydrogen, and therefore it is assumed in the scenario that a new pipeline system is established.

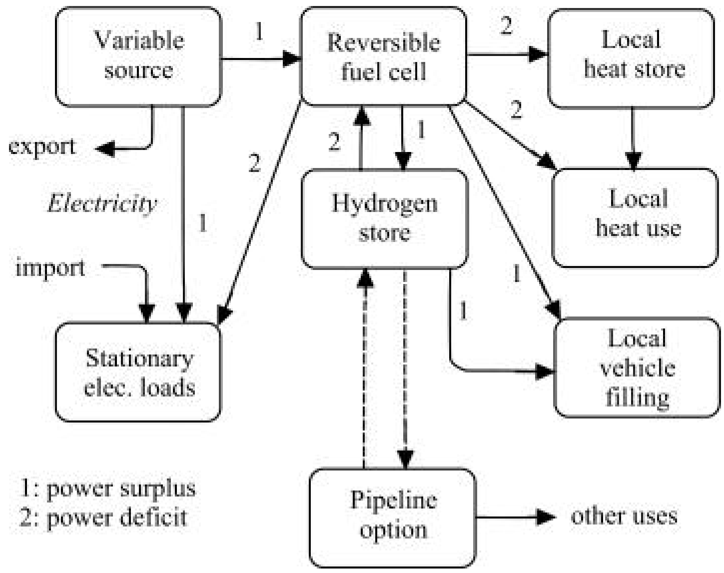
The scenario results in a reduction of the CO_2 emissions of transport by almost 80%, equivalent to a reduction of the CO_2 emissions of the entire energy sector by 40%. The calculated costs per tonne CO_2 saved are in the range of 600-900 DKr per tonnes, depending on the cost assumptions used. This result, which is conditional on a successful technological development with regard to lowering the costs to the long-term projections of the Technology Catalogue of the project, is in the same order as other CO_2 reduction options in the transport sector. While not being among the cheapest measures, the scenario on the other hand does not represent excessive costs - and the scenario would result in better long-term position with respect to supply with environmentally benign fuels in the transport sector. Based on the scenario, it can be concluded that it is viable to cover the transport fuel by renewable energy based on surplus resources and using hydrogen, and possibly methanol, as energy carrier. On the other hand the utilisation of renewables, especially on a large scale, will almost inevitably be met by resistance and barriers, and thus it is still vital to economise with the transport fuels by means of improved energy efficiency and other measures.

3.3. Sc2 (1-2 sider)

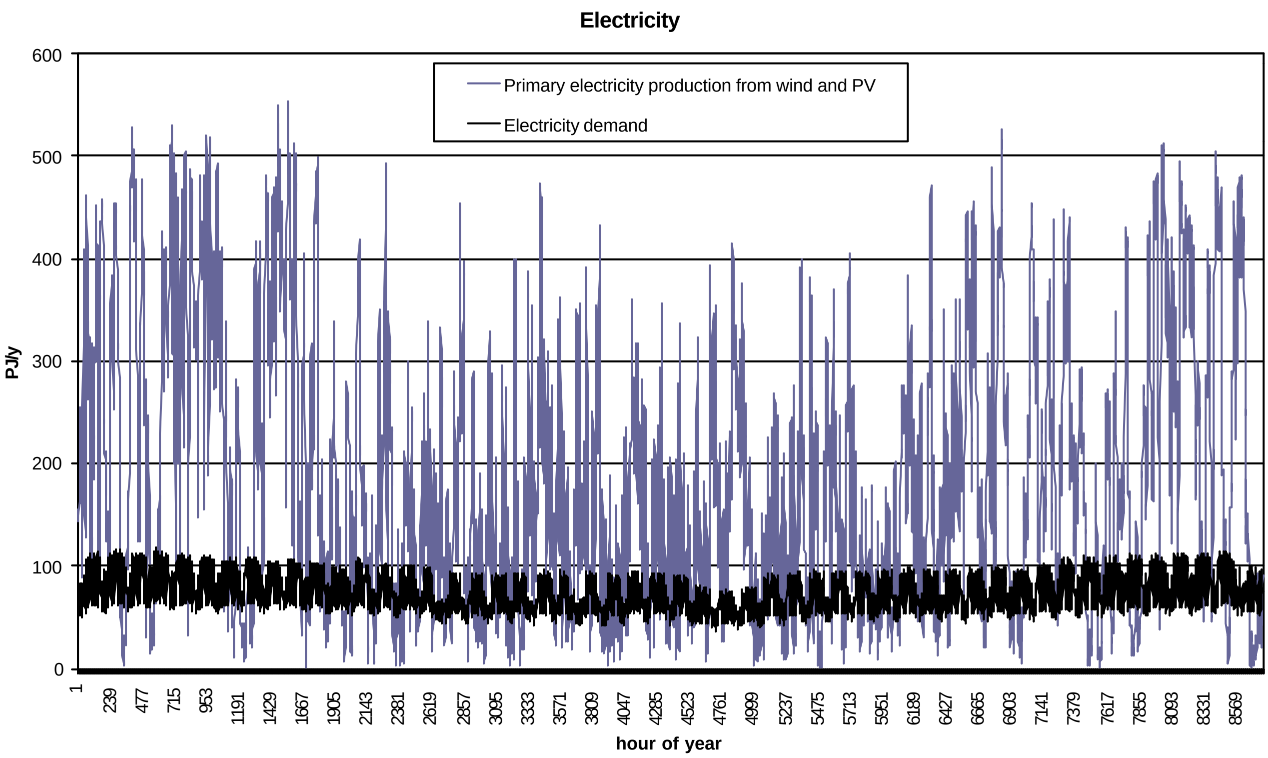
Der beskrives, således som den enkelte scenarieanalyse og beskrivelse, som den foreligger tillader det: Systemudformninger vedr. brint, Energibalancer, Nødvendige tiltag (lagre, ……..), Miljø (CO2 primært) , Økonomi (herunder bl.a. CO2-skyggepriser).

The decentralised 2050 scenario

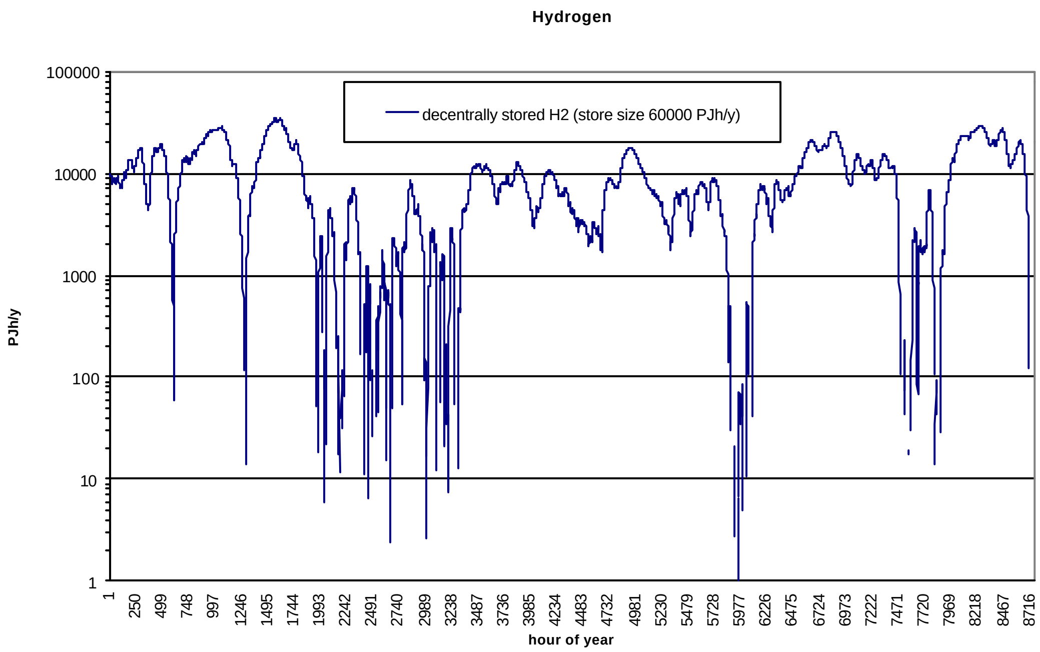
Because the energy demand is modest in the decentralised scenario, it is possible to restrict the use of biomass to very low values, and thus avoid criticism from some parts of the ecological community, who claim that it is important to return not just nutrients but also carbon from biomass residues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



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 below, using a particular year of actual data.

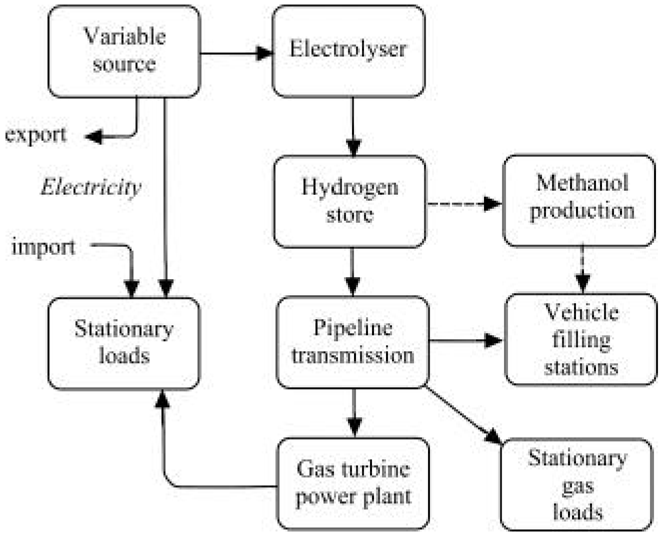


After local conversion of the surpluses of electric power into hydrogen, this is either filled into the stores of vehicles parked at the building, or into local stationary hydrogen stores, likely to be metal hydride stores. The time series of storage levels, shown below, indicates storage needs of 60000 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.

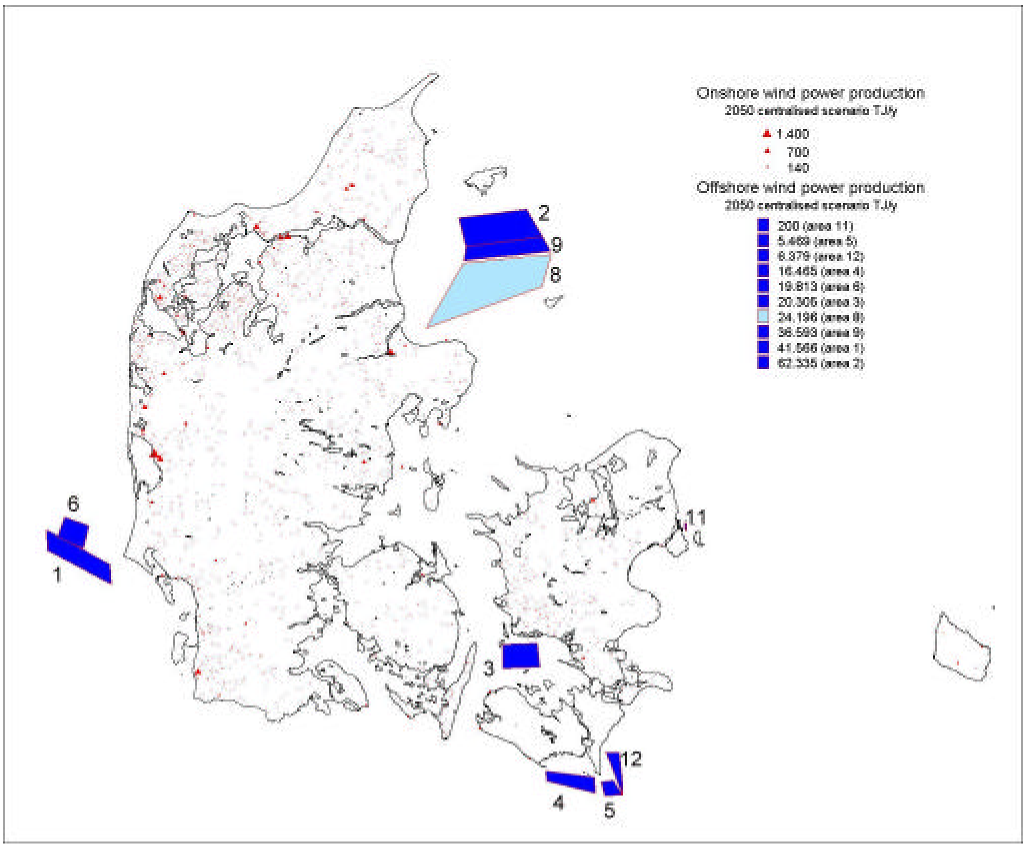


The centralised 2050 scenario

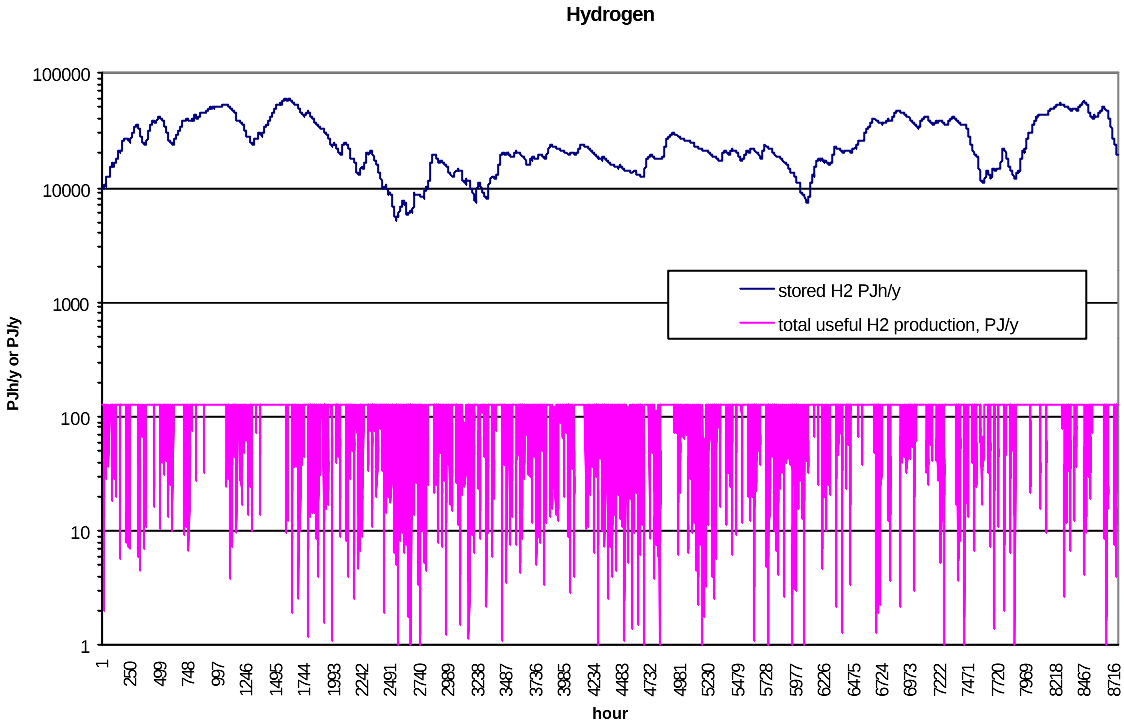
In the centralised scenario, due to the higher energy demand assumed, biomass production is not restricted as much as in the decentralised scenario (200 PJ is produced and used for methanol and hydrogen production). Also off-shore wind power production is considerably higher (213 PJ), and hydrogen storage 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 below:



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



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. The figure below shows the variations in stored energy:



Considerations on speed of implementation

The fuel cell and automobile industry has repeatedly stated that the first commercial hydrogen passenger cars will be on the market in 2004. The 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 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 our first scenario year (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, 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 devices may never emerge.

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 pending the success in developing the key technology for the hydrogen to play a role: a technically and economically viable fuel cell. Due to the low efficiency, 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, energy-efficient motor cars.