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Hydrogen as an Energy Carrier

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Abstract The purpose of this report has been to investigate the possibilities for introducing hydrogen as an energy carrier in the Danish energy system in the future and to point out the economic and environmental consequences.

In the report technologies for production, storage, distribution and utilisation of hydrogen are described, and the most relevant technologies for the Danish energy system have been pointed out and used in different scenarios for the introduction of hydrogen in the Danish energy system in the year 2030.

The report is an extract of the Danish report "Brint som energibærer" financed by ELSAM og ELKRAFT and EFP-90 j.nr. 151/90-0030 and EFP-92 j.nr. 151/92-0030.

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Resumé This report is an extract of a main report in Danish called "Brint som energibærer" (Hydrogen as an energy carrier) Risø-R-675(DA). The main purpose has been to investigate the possibilities for introducing hydrogen as an energy carrier in the future energy system in Denmark.

In order to define different scenarios the whole hydrogen cycle from production to distribution to storage and utilisation has been considered. The most relevant technologies for the Danish energy system have been pointed out and used in different hydrogen scenarios for year 2030.

Electrolysis, coal gasification and biomass gasification have been pointed out as interesting options for producing hydrogen in the Danish energy system. Most important possibilities for using hydrogen in Denmark are fuel cells placed in central plants or hydrogen as fuel in the transport sector. Hydrogen is presumed stored in large underground caverns and distributed through the natural gas network.

The introduction of the different hydrogen technologies in the Danish energy system has been regarded concerning safety, and this has been incorporated in the realistic total scenarios.

The different scenarios have been calculated in a model system consisting of two submodels. The first simulates the operation of the energy system by introducing different hydrogen technologies, while the second assesses the consequences from a technical, economic and an environmental point of view by introducing the different hydrogen technologies in the Danish energy system.

Three types of total scenarios have been calculated:

- *A scenario concerning the electricity system.* Together with renewable energy hydrogen is introduced to the energy system as a possibility for storing electricity.
- *A scenario concerning production of hydrogen.* The electricity system is assumed to function as a producer of hydrogen, which is used as fuel in the transport sector.
- *A scenario concerning environmental impacts.* Hydrogen is introduced to the energy system in order to reduce the emissions of carbon dioxide.

In the *scenario concerning the electricity system* hydrogen is introduced as a facility for electricity storage. When surplus electricity is produced by for instance wind energy the surplus electricity is converted to hydrogen by electrolysis. Furthermore hydrogen production via gasification of biomass and coal is considered. The hydrogen is stored in large caverns, and is utilised later in the energy system in e.g. solid oxide fuel cells in centralized CHP plants.

43% of the total electricity demand and 57% of the heating demand are covered by renewable energy (wind energy and biomass) utilizing hydrogen as an energy carrier. A system like this results in an increase in average costs of the electricity production on 0.002 US$/kWh. Based on wind, biomass and hydrogen it is possible to reduce the CO_2 emissions from the total energy system by 23% to a rather low reduction price of 7.4 US$/ton CO_2.

In the *scenario concerning hydrogen production* it is assumed that there is a need for hydrogen in the transport sector. Hydrogen is produced by coal gasification, and the hydrogen is utilised in the transport sector, substituting diesel.

An amount of hydrogen able to cover 21% of the energy demand for transport is produced in this scenario. Based on coal gasification integrated in the CHP system the hydrogen is produced at a price of 7.2 US$/GJ, which is 25% lower than the Danish price for diesel. The infrastructure regarding hydrogen in vehicles has not been considered in this scenario.

In the *scenario concerning environmental impacts* a large amount of renewable energy is introduced in the energy system. Wind energy and electrolysis is introduced together with biomass gasification in order to produce hydrogen. Hydrogen is utilised in the transport sector and in solid oxide fuel cells on central CHP plants.

By utilising hydrogen as an energy carrier in this system a large amount of the total energy demand is covered by renewables. 55% of the electricity demand and 57% of the heating demand are covered by renewable energy, while 21% of the energy demand for transport is covered by hydrogen. The increase in average costs for the production of electricity is only 0.004 US$/kWh. The CO_2 emission from the total Danish energy system is reduced by 34% to a reduction price of 10.2 US$/ton CO_2.

The report points out different advantages by utilising hydrogen as an energy carrier in the Danish energy system. It is possible to integrate large amounts of renewable energy into a well functioning energy system by introducing hydrogen as a storage capacity. In an energy system with a large amount of renewable energy the utilisation of hydrogen can be economically attractive. Hydrogen energy may be used in centralized fuel cells and in the transport sector, resulting in a reduction of carbon dioxide from the energy system to an attractive reduction price for CO_2.

Contents

Introduction

This report is an extract of the final report on the project called "Hydrogen as an energy carrier."

The report describes the whole cycle from production to storage to distribution and utilisation of hydrogen. These technologies have been used as elements in the composition of different scenarios for the introduction of hydrogen in the Danish energy system in the year 2030.

The project has been carried out at Risø National Laboratory as a collaboration between the Department for Materials and the Department for System Analysis (the Risk Analysis Group and the Energy System Group). The project management has been carried out by the Energy System Group. The following persons have participated in the project:

John Kjøller,	The Department for Materials
Allan Schrøder Pedersen,	The Department for Materials
Carsten D. Grønberg,	The Risk Analysis Group
Dan Sandvik Nielsen,	The Risk Analysis Group
Poul Erik Morthorst,	The Energy System Group
Lars Henrik Nielsen,	The Energy System Group
Lotte Schleisner,	The Energy System Group (project manager)

The prices mentioned in the report are in US$. The rate of exchange used is 1 US$ = 6.8 Dkr.

Conclusions and recommendations

Main conclusions

Hydrogen is a realistic energy carrier for the future energy system. Seen from an environmental point of view introduction of hydrogen technology together with renewable energy will be attractive, when hydrogen is used in the electricity or the transport sector, due to a considerably lower CO_2 emission from the energy system.

Following may be pointed out:

- By introduction of hydrogen as an energy carrier large amounts of renewable energy can fit into a well functioning energy system. From a cost efficient point of view the introduction of hydrogen into a system with large amounts of renewables is attractive.
- Hydrogen technology together with renewable energy may result in a large reduction of CO_2 from the energy system to an attractive CO_2 reduction price.
- The electric utilities are able to produce hydrogen as a transport fuel at a price that is 25% lower than the Danish diesel price. From an environmental point of view the CO_2 emissions will take place at central plants instead of local, with better possibilities for removal.
- Seen from an economic and environmental point of view hydrogen used as a fuel for vehicles or in centralized fuel cells are the most attractive of the utilisation methods pointed out.
- Regarding safety the best way of using hydrogen is in centralized fuel cells or as a fuel for regular service.

Part conclusions

- The cost of the electrolyzer is the most important of the total costs for a hydrogen system based on electrolysis, while hydrogen storage costs form a very small part of the total costs. The utilisation time for the electrolyzer is very important for the total costs through the year.
- The need for storage of very large amounts of hydrogen may be solved by utilising flushed caverns in salt domes, which is a cost efficient and technically attractive way of storing hydrogen.
- Combined cycle plants based on coal gasification together with wind power are attractive, when introducing hydrogen as an energy carrier, with the combined cycle plant operating as a buffer for the wind power, while hydrogen is produced from the syngas in surplus by a shift-process.
- Introduction of larger amounts of renewable energy will result in an overflow of electricity in the existing energy system. Even a small extension of combined heat and power and fluctuating renewable energy in the energy system will result in surplus electricity in the year 2030.
- From an economic point of view import of electricity for hydrogen production can be profitable in a system partly based on electrolysis, as for instance a system with large amounts of wind energy.

- Introduction of advanced technologies with high efficiencies may make the energy system less flexible. Using hydrogen as an energy carrier will make the system more flexible and it will be easier to introduce these advanced technologies into the energy system.

Recommendations

- Investigation of the costs of the technologies in detail, as the stated costs for introduction of hydrogen technology only are overall costs for the individual technology and not to the surrounding function system.
- Investigation of the effectiveness and lifetime of the electrolysers, especially at fluctuating electricity input.
- Demonstration of hydrogen storage in salt caverns in order to obtain operational experience and estimate the total costs.
- Test of the natural gas network for transport of hydrogen, as it is uncertain if the natural gas network can be used for transport of hydrogen, and which changes have to be carried out in order to be able to distribute hydrogen.
- Practical experiences will be necessary, as experiences with handling of hydrogen and the interaction between the different technologies can change the situation for introduction of hydrogen as an energy carrier in the energy system.
- Analysis of introduction of electricity efficient plants into the energy system such as fuel cells, as constraints occur very fast in the system. In this connection the possibility of fitting in larger heat storages in the electricity system ought to be analysed.
- Analysis in detail of the possibilities for utilisation of hydrogen in vehicles and practical experiences will be a substantial source of information for an evaluation of the potential for hydrogen in the transport sector. Analysis of the infrastructure is a substantial parameter.
- Examination of the safety aspects of the introduction of hydrogen technology into different systems in detail.
- Evaluation of hydrogen as an energy carrier compared to other alternative energy carriers, such as methanol, or direct use of syngas (cf. Scenario 2).
- Examination of biomass gasification plants, especially concerning flexibility, effectiveness and costs.
- Analysis of introduction of reversible fuel cells in the system.

1 Introduction of hydrogen as an energy carrier

Hydrogen is generally considered the future energy carrier and storage medium of the next century. Hydrogen can be extracted from water by using of any kind of primary source of high quality energy. Hydrogen can be transformed into water again in a chemical, closed cycle without significant emissions.

All primary energy sources can be used for the production of hydrogen. However, if hydrogen is produced on basis of fossil fuels, CO_2 is produced. CO_2 should be collected and stored permanently in order that the production method may be considered pure. The method used for collecting CO_2 is so far unknown, and the costs involved are uncertain.

Today the method of producing pure hydrogen must be on basis of renewables or nuclear energy. This report disregards production of hydrogen on basis of nuclear energy.

Hydrogen is not an energy source, but like electricity a secondary energy carrier, which demands the presence of an energy source to be produced. Hydrogen and electricity are absolutely compatible energy carriers, as electricity can be used for producing hydrogen through electrolysis, while hydrogen together with oxygen (air) can produce electricity, among other things by utilisation of fuel cells.

Hydrogen and electricity are considered to be the dominating energy carriers in the future energy system. Contrary to electricity hydrogen has the advantage that it can be stored even in large quantities. Also, from an environmental point of view, the utilisation of hydrogen is very attractive. When hydrogen is burnt with supply of oxygen from the air, water steam is produced. However, nitrogenoxides are formed at very high combustion temperatures.

2 Production of hydrogen

Hydrogen can be produced from many different energy sources, but not all production sources and methods are equally attractive, seen from an economic and environmental point of view.

Generally, it is preferred to produce hydrogen from hydrocarbon, as the energy consumption is less than when producing hydrogen on basis of electricity production and subsequent electrolysis. Hydrogen produced on basis of coal, natural gas or oil, however, involves emissions of CO_2 and will, therefore, only be attractive from an environmental point of view, if a permanent method for storing the produced CO_2 can be found.

Thermal, thermotechnical, biochemical and photochemical processes are still not used for industrial purposes.

Different production processes can be used, which is indicated at figure 2.1.

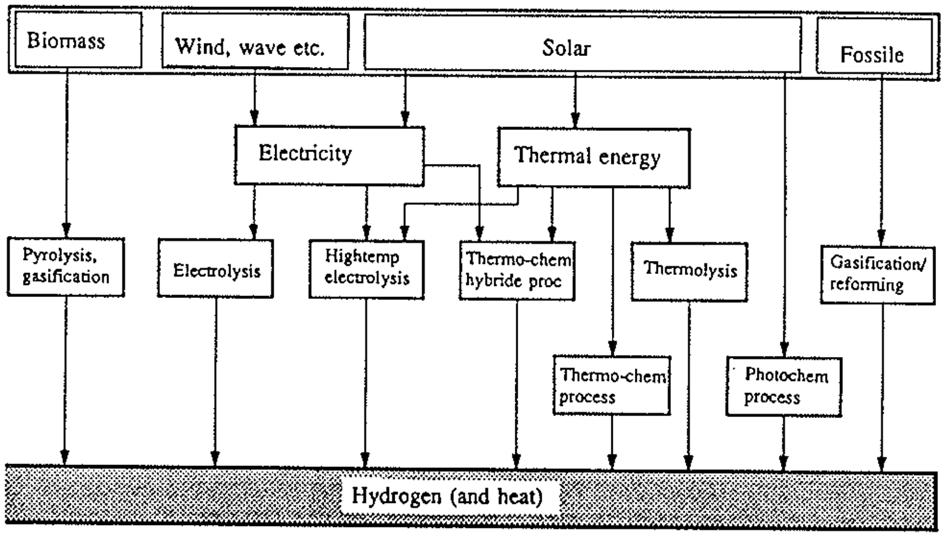


Figure 2.1. Hydrogen production technologies.

2.1 Production technologies relevant to the Danish energy system

With large amounts of renewable energy in the Danish energy system there will in periods be overflow electricity as a result of constraints in the CHP production. Hydrogen may here be utilised as storage medium for this surplus electricity. The surplus electricity may be converted to hydrogen by electrolysis, and stored for later utilisation in the energy system, either for electricity and heating or as fuel in the transport sector.

Furthermore, hydrogen may be produced directly from renewable energy, by pyrolysis of biomass, by photo electrolysis or by electrolysis from direct current wind power. These production methods are relevant if hydrogen is used in a local or decentralised energy system as storage medium and used later on in a local or decentralised energy system or for transport purposes.

If hydrogen is produced centrally, it may be produced in already existing coal gasification plants or reforming plants, or by gasification of biomass. In this way renewable energy resources are used directly for production of electricity, and if the renewable energy should result in a surplus of electricity, the already existing gasification plants can be used for hydrogen production directly. Hereby the processes coal gasification-syngas, syngas-hydrogen are by-passed and hydrogen is produced directly from coal.

2.1.1 Electrolysis

By electrolysis (ref. 1, 2, 3) water is decomposed into hydrogen and oxygen on basis of electricity. Hydrogen is formed at the cathode and oxygen at the anode in an electrolytic cell at a supply of direct current voltage at a minimum of 1.6 volt. The electrolyte is an aqueous solution.

Today conventional electrolyzers have an electricity efficiency at 80 to 88%. The electricity efficiency is expected to increase to 88-94%. This applies to electrolysers using electricity as the only energy supply. New high temperature electrolysers are being developed. These electrolysers are supplied with energy both from electricity and heat. This will result in a slightly higher electricity efficiency.

There are three main kinds of water electrolysis: Alkaline water electrolysis, solid polymeric electrolysis (SPE) and high temperature electrolysis (700-1000°C). Furthermore, research is taking place concerning photo chemical electrolysis. The principle of this type of electrolysis is that the total energy amount or a major part of it, comes from light. In principle this kind of electrolysis can be considered a hydrogen producing photovoltaic cell.

At present, the most common kind of electrolysis is the alkaline electrolysis. This electrolysis is usually performed at small or medium-sized plants (0.5-5 MW, 100-1000 Nm^3/h). The amount of energy, i.e., electricity, needed for the alkaline electrolysis, is approx. 4 kWh/Nm^3, inclusive of energy loss and energy for pumps etc. The electrolysis is carried out at temperatures at 70-100°C.

From an environmental point of view, electrolysis is an ideal method for the production of hydrogen. By electrolysis, water is decomposed into oxygen and hydrogen and this process does not involve any emissions. However, emissions may occur from production of the electricity used for electrolysis.

2.1.2 Coal gasification

Coal gasification (ref. 2, 4, 5, 6) is a process in which hydrogen or hydrogen containing gases are produced by addition of oxygen at high temperatures and under increased pressure. Coal is gasified at high temperatures by adding steam and oxygen, to a synthetic gas consisting of a compound of CO and H_2. The synthetic gas must be cleaned before the further process course. When producing pure hydrogen, CO is converted at the exothermal catalytic process:

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

This process is taking place at lower temperatures.

The remaining traces of CO are removed by a catalytic methane reaction. Pure hydrogen is at last obtained by cryogenic or other gas separation methods.

Coal gasification is a new technology in connection with electricity and CHP production. In the coal gasification plant, coal is gasified and the gas is utilised in a gas turbine, which together with a degas boiler constitutes a combined cycle-plant. The plant is very expensive, and it is based on the utilisation of coal.

Therefore it is suitable as base load plant, but might also be used as medium load plant.

At present a CHP-plant based on coal gasification has an electricity efficiency of about 42-45%, and a total efficiency of 80-85%. Using a coal gasification plant for the production of hydrogen, the efficiency is 60-65% for the hydrogen production alone.

The gas turbine that is a decisive component for the efficiency of the combined plant, is expected to be developed to an extent which will increase the electricity efficiency to over 50% after the year 2000. The efficiency for production of hydrogen is expected to increase even further to approx. 70%.

In future, a further development of the fuel cell technology will be able to replace the gas turbine. CHP-plants based on coal gasification and fuel cells can be expected to obtain an electricity efficiency of approx. 60%.

A coal gasification plant is characterized by the ability to obtain high desulphurization degrees of about 96-100%. If a coal gasification plant is used in combination with a fuel cell, there will be no NO_x-emissions. Burning of coal either directly or at gasification will always result in discharge of CO_2.

Production of hydrogen can take place on a CHP-plant already established as base load or medium load plant based on coal gasification. The plant can function as an electricity and heat production unit during base load situations, whereas in situations of surplus electricity, hydrogen can be produced on the coal gasification plant (f.inst. at supply of large amounts of renewables) instead of electricity. The renewable energy can in this way produce electricity that can be used directly in the electricity system, and which does not have to be converted into hydrogen to be stored for later use.

2.1.3 Biomass gasification

The biomass gasification (ref. 6) takes place in a gasification process, corresponding to the steam reforming process of natural gas. The process can be divided into three main stages: 1) Generation of syngas (the reformer part), 2) Addition of water to the gas (the shift-process) and 3) Gas purification (the PSA-system). The biomass contains a surplus of water and there is therefore less need of steam at the biomass gasification than at the reformation of natural gas.
The biomass gasification process is assumed to have the same efficiency as coal gasification.

From an environmental point of view the big advantage over to coal gasification is, that this process does not result in any CO_2 emissions and the biogas process will therefore in connection with hydrogen, be an environmental attractive process.

3 Distribution of hydrogen

For industrial purposes hydrogen is being distributed in the two states, gaseous or liquid, while the solid state is not commonly used. Most commonly hydrogen is distributed in its gaseous state under pressure in well-known gas cylinders for which there is a worldwide and extended distribution system. The investments in this technique have been significant and the structure is highly developed. This technique is therefore the one which is most flexible and accessible for distribution of hydrogen in Denmark. Besides there is international experience with transport of hydrogen in pipelines, and it is also being considered to transport hydrogen in its liquid state.

3.1 Distribution technologies relevant to the Danish energy system

If hydrogen is to be a major contributor to the energy system, very large quantities must be distributed and for that reason and from a technical point of view, pipeline transport is the best solution. From a cost-efficient point of view it is, however, questionable whether pipeline distribution will be cheaper if investments are to be made in a distribution pipeline network.

The Danish natural gas network consists of two sections, the central transmission network and the local distribution network. During the planning of the natural gas network it was considered, that the network later on should be used for transport of f.inst. hydrogen. The central transmission pipelines can therefore be used for hydrogen purposes. Similar information is not available for the local distribution network. The material used for the local pipelines is different from the material for the central pipelines, and a more thorough investigation will be needed to find out if working with hydrogen is possible in this network. Taking into consideration that 50% of the well-known town gas previously consisted of hydrogen which was distributed via the town gas network, it seems likely that hydrogen can be distributed through the local gas network, perhaps with small modifications.

Thus there is in Denmark an accessible transmission system and it must be assumed that the local distribution network can be used for hydrogen, possibly with small changes of components. There are therefore both technical and economical conditions that show that pipeline distribution will be the most advantageous method of transport of hydrogen.

With regard to the safety aspects pipeline transport is superior to truck or railway transport, for the simple reason that the distribution route is separate from the ordinary transport routes. During the distribution of hydrogen in pipelines it is necessary to compress the hydrogen in compression plants. At a transmission distance of 400 km this will result in a loss of energy of approx. 0.5% (ref 1). The loss of energy is thus very low, and there is an additional environmental advantage: pipeline distribution is more resource efficient.

4 Storage of hydrogen

Storage of hydrogen can take place in all three states, gaseous, solid and liquid. The solid state, however, is not pure hydrogen, but as chemical compounds. Storage of pressurized gaseous hydrogen in steel cylinders is used and has been used for several years in Denmark, but storage of hydrogen in steel cylinders in the quantities required for seasonal and daily adjustments of the load of a 100-300 MW power station, is unrealistic. This kind of storage method might be interesting for transport purposes.

Many geological structures make it possible to store hydrogen in underground caverns as is the case with natural gas. The high diffusivity of hydrogen in comparison with methane has only little effect in terms of leakage. The utilisation of caverns for underground storage of natural gas is widely used in Denmark. The physical and chemical differences between hydrogen and methane make it not possible directly to substitute methane with hydrogen in caverns, but the technique is in principle the same. However, other demands are made on materials and the stability of the caverns, and the storage data will be different as well.

Liquid hydrogen is already used in several countries and Denmark has imported small quantities of liquid hydrogen from Germany. The storage of liquid hydrogen is taking place in vacuum insulated spherical tanks. The volume of the biggest tanks that are available at NASA, are about 4000 m^3 (radius 10 m), but it is considered possible to construct considerably larger tanks, up to 10,000-15,000 m^3 (radius 15 m). A volume of 15,000 m^3 contains approx. $12*10^6$ Nm^3. The storage capacity of liquid hydrogen is thus sufficient to meet the day-and-night requirements of a power station with an effect of some hundred MW.

The storage of hydrogen in its solid state can take place by formation of chemical compounds between metals and hydrogen (metal hydrides).

The reaction is an equilibrium reaction with large sensitivity towards pressure and temperature, and it is combined with reaction heat. For almost all kinds of metal, and in any case for the metals which have practical interest, the reaction is exotherm ,i.e., heat is developed at the formation of the hydride and vice versa the same quantity must be added at the fission of the hydride.

4.1 Storage technologies relevant to the Danish energy system

In Denmark there is only little experience in storing large amounts of energy. Examples are a storage for natural gas in a cavern in Jutland and an aquifer storage in Zealand, also for natural gas. Both types may probably be used for hydrogen storage, and other geological possibilities exist in Denmark for this kind of storages. Underground hydrogen storages will act as a buffer for fluctuations in the energy consumption if pipelines are used for transportation.

On the short view liquid hydrogen for stationary storage in Denmark seems unrealistic. Storage of liquid hydrogen is connected with many technical difficulties, and the storage has a constant loss with time. There also exist complicated demands to safety and in this area Denmark is without experience.

Hydrogen stored in pressurized gas or in metal hydrides is not qualified for storage of large amounts of energy. On the contrary, for smaller mobile storages for transportation purposes metal hydrides seem relevant.

5 Hydrogen for electricity production or heating

Hydrogen can be converted to electricity and heat, e.g. by gas motor plants, gas turbines or fuel cells. Gas motors have a higher electrical effect than the smaller gas turbines. In return, the waste heat from a gas turbine has a higher temperature, which leaves a better possibility of production for high-pressure steam.

Gas motors are the sure winners in the CHP-technology in the smaller sizes up to a couple of MW, while the big gas turbines are the sure winners at the other end of the scale, i.e., in sizes over 10 MW (ref. 7).

In a fuel cell system, electricity and heat is produced by addition of fuel and air. Thus hydrogen can be converted into electricity with a much higher efficiency than in a thermal power plant based on fossil fuels. The efficiency of electricity produced on a thermal power plant is approx. 45%, while fuel cells in practice have an efficiency of 40 to 60%. The total efficiency of the fuel cells (electricity and district heating) is expected to be 80 to 95%. Fuel cells from a few hundred watts and up to several MW have already been demonstrated and in some few cases the fuel cells are in operation.

The fuel cells that are being developed and are expected to be used for power stations, are phosphoric acid, carbonate cells and the solid oxide cells. The three types of fuel cells are on different stages of development, and they have individual properties.

5.1 Electricity/heating technologies relevant to the Danish energy system

Both gas motors and gas turbines are conventional electricity production technologies currently used in the energy system in Denmark. Both technologies can be used directly for decentralized CHP production based on hydrogen, while the gas motors are used for smaller plants and the gas turbines for larger plants. The fuel cells can be used for both small and big plants without any loss of efficiency. As the fuel cells are highly efficient, they are expected to replace both gas motors and gas turbines in the future energy system when the technology has been developed. In the subsequent scenarios for the energy system in the year 2030, it has been chosen exclusively to use fuel cells for electricity production based on hydrogen. The fuel cells offer the additional advantage that they can be used reversibly, i.e., the same unit can be used as electrolyser for the production of hydrogen, when there is no demand for electricity, and later on for production of electricity based on hydrogen. In this way the electrolyser and the fuel cells form one unit, and the costs are thus expected to be lower than for separate electrolysers and fuel cells. According to the German company, Dornier, SOFC is especially suitable as reversible fuel cell.

The high temperature fuel cells have a high electricity efficiency of 60-65% dependent on the size of the fuel cell plants. It is expected that approx. 90% of the remaining energy can be used for heat production and the total efficiency will thus be about 96%.

The utilisation of fuel cells for electricity and heat production is environmentally attractive as the fuel cells do not produce any NO_x emission. And by using hydrogen as fuel in the fuel cells there will not be any CO_2 emission, either.

6 Hydrogen for vehicles

Utilisation of hydrogen for transport purposes has been the subject of several studies, and internationally there has been considerable experimental research in several car factories. In the former USSR experiments have been carried out with hydrogen as fuel of a big airplane. The car factories have primarily been working with burning hydrogen in internal combustion engines, but use of fuel cells have also been considered, although to a small extent.

The use of combustible gas for internal combustion engines has been known for many years, also in Denmark. The mostly used gas has been propane and lately experiments have been made with natural gas. The problems with the use of hydrogen as a propellant compared to the well-known kinds of gas are small. Only minor technical alterations of the engine are necessary.

In principle only water is produced at the combustion of hydrogen in an engine, and water is not polluting. In practice, however, an unacceptable large amount of nitrogen oxydes is produced. Therefore, Daimler-Benz is working very intensively to reduce the NO_x values.

6.1 Hydrogen for the Danish transport sector

The utilisation of hydrogen as a fuel in the transport sector can reduce the air pollution considerably, as the combustion of hydrogen in an engine only produces water. The future development in the engine technological area (including catalyst technique) will, however, probably result in gasoline and diesel engines in new cars which will pollute no more than a hydrogen engine and as regards NO_x, the pollution from gasoline and diesel engines will perhaps be less. Before long there might be environmental benefits by changing to hydrogen in the heavy-traffic urban areas. Hydrogen can also be used as a propellant in cars with hydrogen based fuel cells. In this case, there will be neither emissions of NO_x nor CO_2.

Pressurized hydrogen in gas cylinders will be a possibility in the Danish transport sector. The already known steel cylinders can be used, and as to weight it would be an advantage if new, light materials could be approved for pressurized usage of hydrogen.

Hydrogen storages in the form of metal hydrides is another possibility, which is relevant to the Danish situation. Compared to plastic based pressurized cylinders, a metal hydride will be heavier, but on the other hand it will be working under a much smaller pressure, and this means much higher safety when handling the systems, f.inst. when filling hydrogen in the tank (ref. 8).

There are no immediate energy savings by using hydrogen for transport purposes. On the contrary there will be a certain loss, as conversion of f.inst. electricity to hydrogen will result in a loss of energy. But it will make it possible to utilise a number of energy sources more efficiently, and it will also be possible to reduce the use of fossil fuels in the transport sector. It is obvious that it will be more expensive to use hydrogen for transport purposes instead of the propellants we know at present. The extra costs that are involved, are primarily the storage costs, but extra costs are acceptable, if the advantages obtained are given significant importance. This is a decision of a political nature that can be carried through f.inst. by means of taxation or by pricing the environmental damages.

7 Scenario data

In the previous chapters the different hydrogen technologies from production, storage, distribution to utilisation have been described. Of these technologies a few have been selected as being relevant to the Danish energy system, and based on these technologies the following different hydrogen scenarios have been established. The scenarios are calculated in a model system consisting of the ES^3 model, which deals with the more detailed electrical system, and the BRUS model that is describing the total energy system as a whole.

7.1 Models

The ES^3 model (Energy Supply System Simulator) which has been developed at Risø, is used in the analysis of the scenarios for examining the capacity dimensioning, the energy conversion and the storage demand. The ES^3 model is a consequence calculation tool that for a certain system configuration and operation strategy simulates the working of the system during f.inst. a year in intervals of one hour. The model presents time series, duration curves, technical key figures etc. for the categories of the system's production plants, storages etc. based on certain time profiles with regard to demands for the secondary energy carriers electricity, heat and hydrogen.

The chosen operation strategy for the components of the energy system is essential for the dimensioning of the system. A schematic survey of the typical operational location of the energy system's categories of electricity producing plants is shown in figure 7.1. Several of the scenarios presented later are based on the outlined operation strategy, but other plant categories and other methods of operation are also used.

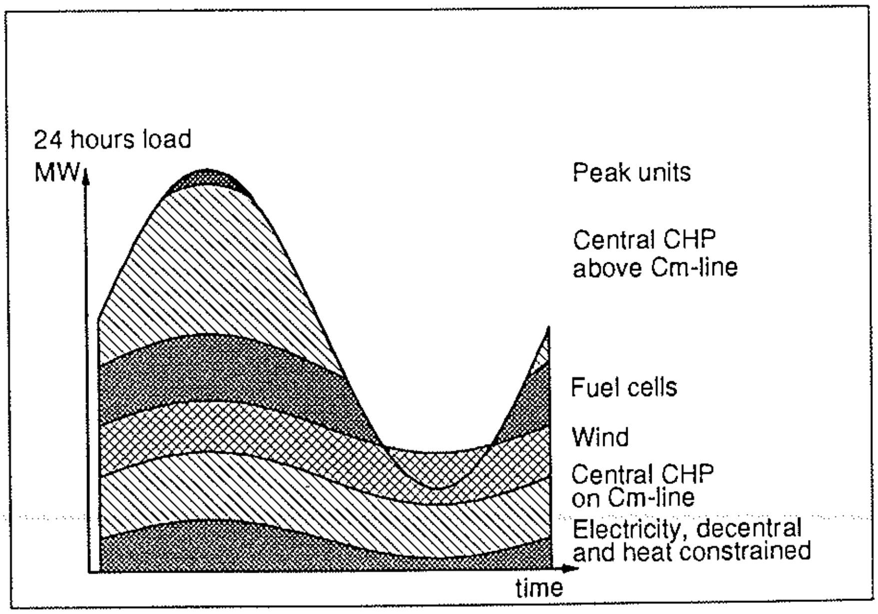


Figure 7.1. Typical operation strategy for the energy system.

After having attuned the technical conditions according to the ES^3 model, the further socio-economic energy and environmental calculations are carried out with the BRUS model. This model is constructed as a tool for setting up alternative future perspectives for the Danish energy system, so-called scenarios. It is a long-term simulation model that covers the period until the year 2030. The BRUS model works on a technical aggregation level that corresponds to the output-side of the ES^3 model.

The interaction between these two models can thus provide consistency from the technical assumptions on an hourly level up to consequence calculations in the overall system analysis, where the time scale is on a yearly level.

Both models are described in detail in the main report "Hydrogen as an energy carrier", Risø-R-675 (in Danish).

7.2 Assumptions for the system simulations

Technical simulations of electrical and heat supply systems are carried out in this project in order to examine the number of possibilities of action on system level. The focus is long term, up to year 2030, as many of the present constraints in the energy system will be dissolved on a long-term basis. On this time scale the assumptions concerning energy demands and energy supply will, of course, be uncertain and there will be a great deal of uncertainty especially with regard to the development in the technological areas.

Technical conditions within the CHP production have been discussed with the operation department of ELKRAFT in order to examine long-term possibilities and constraints. Based on this discussion a system description has been chosen, which is considered to be suitable for simulations on a superior system level.

The annual electricity and heat demand in the Base Scenario in 2030 and the part covered by central and decentral CHP production, is assumed to be 121 $PJ_{electricity}$ and 93 PJ_{heat} respectively, of which 22 PJ_{heat} are produced decentrally. The seasonal fluctuations of the energy demands are significant elements in the dimensioning of the production capacity in the system.

Table 7.1 shows the main figures of the Base Scenario concerning the demand for electricity and heat in the central and decentral part of the system. Furthermore industrial heat from burning of waste etc. are included in the Base Scenario.

The demand for electricity is presumed to be on a connected electricity network in the year 2030, whereas the heat demand can be spread on several district heating networks.

Table 7.1. Electricity- and heat demand in the Base Scenario in the central and decentral part of the CHP system.

Year 2030	Central	Decentral
Electricity demand PJ_{el}	121	
Max. capacity GW_{el}	6.4	
Utilization time h/year	5230	
Heating demand PJ_{heat}	71	22
Max. capacity GW_{heat}	5.8	1.5
Utilization time h/year	3410	4030

The more detailed conditions concerning the electricity system have been covered in chapter 7 of the main report.

7.3 Composition of the scenarios

The scenarios of hydrogen production and consumption are calculated by combining the ES^3 model for the detailed electricity system and the BRUS model, which on a more superior level describes the total energy system.
The purpose of the scenarios is to illustrate:

- In which way and to which extent can hydrogen be produced in relation to the electricity system?
- How can hydrogen be used, both in the transport system and in the electricity and heat system?
- How will the production and consumption of hydrogen interact with the other energy system; which demands will be made on the capacity of a hydrogen production plant (f.inst. electrolysers), the size of hydrogen storage facilities and the capacity of the conventional electricity system?

In addition to the technical data such as capacity, electricity overflow etc. the essential key figures will comprise as well the annual expenses for the system as a whole, as the costs for the hydrogen plants, hydrogen production and consumption, as well as gross fuel consumption, and the related emissions, especially CO_2.

7.3.1 Reference Scenario

All calculations made on the hydrogen scenarios are valid for the year 2030. In this way it is feasible to operate with a wide spectrum of possible alterations in both the energy supply system and within the area of consumption - in short, the number of constraints in the system that relate to the current plants, will be reduced to a minimum in the year 2030. Finally, the far horizon means that the necessary hydrogen technologies have been developed and are commercially available before year 2030.

The analyses are based on the Base Scenario for the "Energy 2000" Action Plan (ref 9) supplemented with the Reference Scenario from the Transport Action Plan. However, a number of elements make the "Energy 2000" Scenario in its fundamental form less interesting in relation to hydrogen consumption and production. It is expected that cost-savings will be the main objective, and the CHP will probably be expanded more than presumed in the Base Scenario. This alone will lead to a significantly changed energy system compared to the Base Scenario and the consequence will be more constraints in the system. For the hydrogen analysis a corrected Base Scenario has been made, called the Eco-base. The Base Scenario is consequently corrected within certain essential areas, but the structure in the energy supply system has been maintained unchanged.

This means that the Eco-base Scenario is primarily based on coal-fueled CHP-plants with a major part of decentral CHP and a minor part of wind power.

The difference between the Base and the Eco-base Scenario is shown in table 7.2.

The installed capacity in the Eco-base Scenario is shown in table 7.3.
The 8000 MW is the total installed capacity incl. 15% reserve capacity.

Table 7.2. The difference between the Base- and Eco-base Scenario, year 2030.

	Base	Eco-base
Gross energy consumption, PJ	854	643
Electricity consumption, PJ	183	133
CO_2-emission, mio.t.	63	46
Increase compared to today :		
- electricity consumption	+ 65%	+ 22%
- net heating consumption	+ 11%	- 30%
- transport consumption	+ 15%	+ 15%

Table 7.3. Capacity in the Eco-base Scenario.

Wind power	500 MW
CHP, central	6400 MW
CHP, decentral	950 MW
Industrial capacity	650 MW
Total capacity excl. wind	8000 MW

7.3.2 Scenario strategy

As a basis for all the hydrogen scenarios a number of partial scenarios have been calculated with only a few changes compared to the Eco-base. The impact of the different changes on the energy system can in this way be evaluated individually.

The strategy has been:

1. To analyse the possibilities of production of hydrogen: How to produce hydrogen and how much can be produced? These analyses are carried out presuming that the total hydrogen production can be sold gradually over the year.
2. To analyse the possibilities of consumption of hydrogen: How can the hydrogen be used, and how much can be used? The report goes into both central, decentral and local use, primarily within the electricity sector and the transport sector (hydrogen supply). These analyses are carried out with a given constant hydrogen supply.
3. Based on both the consumption and the supply analyses a number of total scenarios are outlined from criteria about the function of the system, the extent to which hydrogen is used and considerations of the CO_2 reduction.

As to the hydrogen production the following partial scenarios are analysed:

- The use of renewables as the basis of hydrogen production, primarily wind power connected to the electricity network. How does the use of larger quantities of renewables affect the electricity system in the form of electricity overflow, and how can it be converted to hydrogen?
- High utilisation of existing (conventional) electricity capacity, i.e., base load operation of big electricity plants for the production of surplus electricity as a basis for the hydrogen production, for inst. conventional CHP plants running constantly.

- The utilisation of coal gasification plants, in which the syngas is used either for electricity production (combined cycle) or as a basis for hydrogen production. The coal gasification plant is especially suited for use in connection with renewables and for hydrogen production, when a surplus of electricity from renewables is available.
- Utilisation of imported electricity for the production of hydrogen.

The individual scenarios are analysed with regard to their interaction with the assumed existing system. The different scenarios' influence on the design of the hydrogen system is evaluated.

The consumption of hydrogen is specially connected to the electricity and heating system and the transport sector. The following partial scenarios are analysed:

- The use of hydrogen based fuel cells in central production plants. The fuel cells are incorporated as electricity dependent middle to heavy load units.
- The use of hydrogen based fuel cells in decentral electricity and heat production. The costs of the system are based on the possibility of using the natural gas network for distribution of hydrogen, i.e., there will be no construction of new pipelines for the distribution of hydrogen.
- Local utilisation of hydrogen based fuel cells to replace oil or natural gas furnace in dwellings.
- Evaluation of the possibilities of selling hydrogen to the transport sector, covering what kind of fuels could be substituted and the extent of substitution.

All the scenarios are analysed concerning the interaction with the other energy system, and the extent of hydrogen production is evaluated, especially in relation to the dimensioning of hydrogen production plants and storage facilities.

The total scenarios must illustrate the possibilities and outline the consequences related to the introduction of a hydrogen system connected to the electricity system. Below three total scenarios are described:

- The electricity system scenario, in which the hydrogen production and consumption are narrowly limited to the electricity system, so that the electricity system is functioning properly at the introduction of renewables.
- Production Scenario for hydrogen, in which the electricity system produces hydrogen in an expedient and cost-efficient way and sells the hydrogen as fuel in the transport sector.
- Scenario based on environmental considerations, especially the necessity of CO_2 reduction. Hydrogen is produced and used in the most attractive way seen from an environmental point of view.

The partial scenarios are dealt with in the main report, while only the total/complete scenarios will be mentioned in this report.

8 Risks of utilising hydrogen as an energy carrier

Hydrogen is an energy carrier that interacts easily with oxygen. The following properties must therefore be taken into consideration when the risks of using hydrogen as an energy carrier are evaluated:

- Hydrogen has a wide range of inflammability, i.e., the mixture of hydrogen and oxygen is inflammable in very different concentrations (4-75 vol%).
- The energy necessary to ignite mixtures of hydrogen and oxygen is very small (0.02 mJ).
- Within a rather large part of the mixture area, the mixtures of hydrogen and oxygen are explosive (18.3-59 vol%).

Most of the safety precautions therefore aim at keeping hydrogen and oxygen apart and at the same time avoiding ignition sources.

Another property of hydrogen that might cause problems is that it is very volatile. Small molecules and low viscosity mean that hydrogen easily penetrates through small leaks. Furthermore, hydrogen has a low density that means that it rises very quickly.

The demands for tightness concerning hydrogen are bigger than for almost all other gases.

The low density means that indoor leaks can be very problematic as the gas spreads to the floors above and part of the gas remains under the ceiling for sometime.

Hydrogen is capable of causing brittleness in various metals. The exact mechanisms are unknown, but it is rather well investigated which metals and alloys that are very sensitive (f.inst. Ni-alloys), and which are not very sensitive (f.inst. Cu-alloys). Materials for the construction of tank walls, pipes, valves etc. must therefore be carefully selected taking into consideration the factors that may lead to hydrogen brittleness (f.inst. temperatures, pressure, variation of pressure, the chemical compound and micro structure of the materials, constructive working out).

Summarizing the hydrogen and safety question it can be pointed out that although it offers many practical advantages, hydrogen makes great demands on safety control. In some scenarios this will make the economy aspect less attractive.

9 Total perspectives for utilising hydrogen as an energy carrier in the Danish energy system

9.1 Total scenarios

The main results from the partial scenarios and the evaluation of the risks are summed up in the following chapter in order to outline various conclusive scenarios that include technologies for both production and subsequent use of hydrogen.

It is the aim to draw up three different types of scenarios, each with their individual main purpose:

- E - *Electricity System Scenario.* In this scenario it is expected that a larger amount of renewable energy is included in the energy system. Hydrogen technology is introduced into the scenario with the purpose of getting the CHP system to function technically at the introduction of a large amount of renewable energy.
- P - *Hydrogen Production Scenario.* In this scenario it is assumed that the utility companies will introduce various technologies to make it possible to produce hydrogen and sell it to the transport sector. The technologies which are introduced in this scenario are aiming at producing the hydrogen at a favourable price.
- M - *Environmental Scenario.* In this scenario hydrogen technology is introduced with the primary purpose to reduce the CO_2 emissions. Hydrogen is therefore produced and used in the environmentally most attractive way.

At the penetration of a larger amount of renewable energy in the energy system, an overflow of electricity might occur, and this overflow cannot be utilised immediately. By introducing the hydrogen technology in the system, electricity overflow can be used for production of hydrogen that can be stored and later on be used for production of electricity.

This will be the typical situation in the *Electricity System Scenario.* It will be possible to convert electricity in surplus to hydrogen via electrolysis, the hydrogen is stored in large scale in caverns and can be converted to electricity in fuel cells. Coal or biomass gasification plants will be able to form part of an energy system with a large quantity of renewable energy, as it will be possible to use the coal gasification plants for electricity production during periods with a small amount of wind produced electricity, while the gasification plants in periods with large amounts of wind produced electricity only produce hydrogen. In this way the coal gasification plants can act as a buffer for the renewable energy, and electrolysers are not included in the system.

Also in the *Hydrogen Production Scenario* the coal gasification plants will normally be included as production plants for hydrogen, as the plants if they are already existing in the energy system, can produce hydrogen at very low costs. This also goes for the conventional plants in continuous operation, as these by means of the continuous running can spare investments for regulation equipment.

In the Hydrogen Production Scenario the electricity plants are included as hydrogen producers for utilisation in other sectors, in this case the transport sector. The hydrogen will also be of use elsewhere f.inst. in the industry. This purpose is not included in the present analysis.

From an environmental point of view both the conventional plants in continuous operation and the coal gasification plants will have a negative effect on the system, and these plants are therefore not included in an *Environmental Scenario.*

On the contrary, gasification based on biomass will be an obvious possibility for production of hydrogen, perhaps together with wind energy. In order to use the hydrogen in an environmentally advantageous way it can be used within the transport sector to replace diesel or in centrally placed fuel cells in which the hydrogen replaces coal.

How the various technologies are taking part in the stated scenarios is shown in table 9.1. In the following only the Electricity System Scenario E2, the Production Scenario P2 and the Environmental Scenario M3 will be dealt with, as these scenarios are fulfilling the various preconditions best. The remaining scenarios are dealt with in the main report "Hydrogen as an energy carrier."

Table 9.1. Composition of total scenarios.

Scenarios	Production technology	Storage	Utilisation technology
E1	- Wind / electrolysis	- Cavern	- Central fuel cells
E2	- Wind / coal- or bio gasification	- Cavern	- Central fuel cells
P1	- Conventionel plants operating constantly / electrolysis	- Cavern	- Transport sector
P2	- Coal gasification	- Cavern	- Transport sector
M1	- Wind / electrolysis	- Cavern	- Transport sector
M2	- Wind / bio gasification / electrolysis - Bio gasification / wind	- Cavern	- Transport sector
M3	- Bio gasification / electrolysis / wind	- Cavern	- Transport sector / central fuel cells

The listing of the various scenarios also includes an analysis of risks. As regards safety it is better if hydrogen is produced and utilised in central plants, away from the consumers with long safety distances. The utilisation of hydrogen in the transport sector is problematic as to safety, especially if the hydrogen is handled by unexperienced consumers in private cars. In the stated scenarios it is implied, however, that the hydrogen is only used for regular traffic with skilled drivers. In all the stated scenarios it is implied that the storage of hydrogen is taking place in underground caverns, that are evaluated to be the most safe storing method. The distribution of hydrogen is not specifically dealt with in the scenarios, but is presumed to take place via the existing natural gas network, possibly with small modifications. The major safety problem will be the siting of the natural gas network close to areas with a high density of population, and a thorough analysis of the network will therefore be necessary in order to evaluate the transportation of hydrogen.

9.2 Total Scenario: Hydrogen in the electricity system (E)

The main idea with this scenario is that the hydrogen primarily shall be used as storing medium for surplus electricity from renewable energy technologies in order to be used later on in the electricity system for the running of fuel cells. The scenario is considering the electricity system (incl. electricity producing wind turbines) as a closed world in which production and use of hydrogen only takes place. The scenario can be considered as a possible way to adapt the electricity system to absorb large quantities of electricity produced by renewable energy.

The scenario is constructed as follows:

E2) Installation of totally 1.1 GW wind power and 1.5 GW coal gasification plant with combined cycle and shift process. The combined cycle part of the plant is used as "absorber" (buffer) for the wind power. The gasification plant runs continuously and the surplus syngas, which is produced, is converted into hydrogen via the shift-process. There are no electrolysers included in the system. The hydrogen is stored in caverns and consumed later in central fuel cells. A quantity of 20 PJ of hydrogen is produced and consumed.

The essential characteristics are shown in table 9.2.

Table 9.2. System data for Scenario E2.

Wind energy	1100 MW
Coal gasification	
- combined-cycle	1500 MW
- shift-process	1800 MW
Hydrogen production	20 PJ
Hydrogen storage (cavern volume)	6.4 mill. m^3
Central fuel cells	600 MW

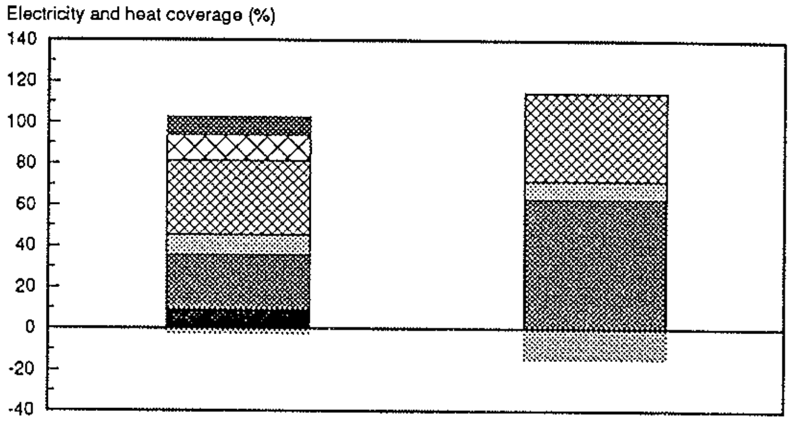
Figure 9.1 shows how the demand for electricity and the central heat demand is covered. Wind power and hydrogen based fuel cells are covering approx. 20% of the demand for electricity. Coal gasification and combined cycle cover approx. 25% and CHP plants approx. 35% of the electricity demand. The electricity overflow of approx. 25% is partly a result of the introduction of wind and coal gasification, partly the result of the combination of electricity and heat production. In the Eco-base Scenario there is also an electricity overflow of about 2%.

The conventional installed capacity (exclusive wind power) increases by approx. 200 MW compared to Eco-base. This means that the installations of approx. 600 MW extra wind power, 1500 MW gasification plants and 600 MW fuel cells only replace approx. 1900 MW conventional CHP capacity. This is among other things due to a more complex interaction of the technologies in the system, and heat constraints that could be relaxed by incorporating thermal heat storages.

Table 9.3 shows the annual costs in the E2 Scenario compared with the Eco-base. The shift part costs are approx. 35 mill. US$/year, but the price of the fuel is constituting the major part of the costs for the gasification of the syngas that forms the basis of the hydrogen production. The total annual additional costs in the Scenario are, however, only approx. 85 mill. US$, as there are cost savings in the remaining system.

Table 9.3. Additionel costs per year for Scenario E2 compared to Eco-base.

Costs for the hydrogen system - storage - shift-process - fuel for hydrogen production In total	 27.9 mill. US$/year 35.3 mill. US$/year 98.5 mill. US$/year 161.7 mill. US$/year
Savings in the remaining energy system	76.5 mill. US$/year
Total additional costs	85.3 mill. US$/year



	electr. coverage (%)	heat coverage (%)
Wind	9,1	
IGCC(biogasification)	26,5	62,9
fuel cells	9,6	8,9
CHP central	36,0	42,7
CHP decentral	12,4	
industrial	8,7	
rest	(2,5)	(14,5)

Figure 9.1. Coverage of electricity demand and central heat demand (Scenario E2).

The consequence for the CO_2 emissions is shown in figure 9.2, both for a coal and a biomass based gasification. If the gasification is based on coal, the CO_2 emission remains almost unchanged compared to the Eco-base in spite of the fact that there is less wind power in the system. If the gasification, however, was based on biomass, there would be a considerable reduction in the CO_2 emissions, a reduction of 23% compared to the total emissions from the energy system in the Eco-base.

Table 9.4 shows the economic key figures for both a coal and a biomass variant compared to Eco-base. It is implied that the investment in the bio gasification plant is the same as the investment in the coal gasification plant. Only fuel price and emission conditions differ in these two variants.

When the additional costs are distributed on the total electricity consumption, they are relatively low for both the coal and biomass variant, 0.0024 US$/kWh and 0.0021 US$/kWh. This corresponds to an average increase in the price of electricity of 3-5% in the year 2030.

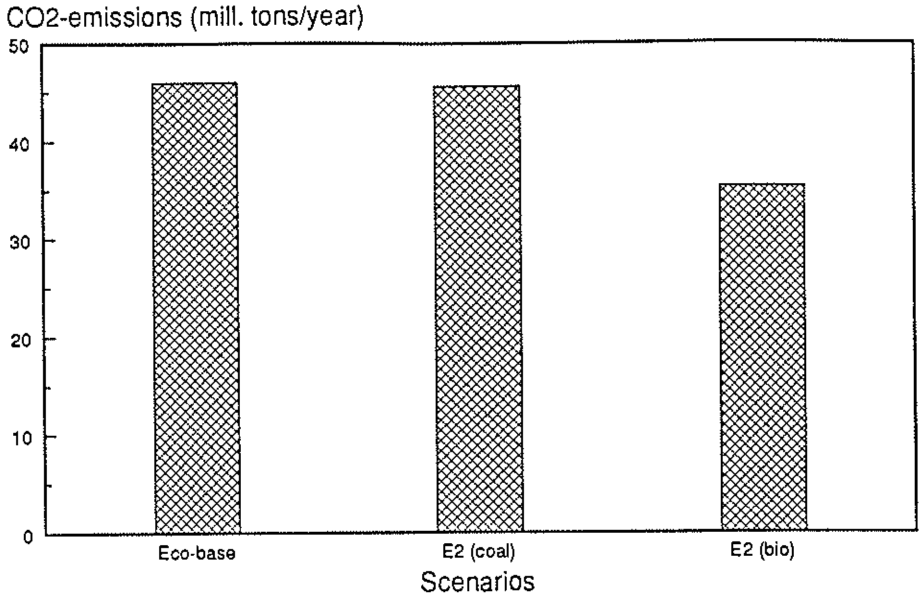


Figure 9.2. CO_2emissions compared to Eco-base.

As the additional costs in the two variants are almost identical, and the CO_2 reduction at the same time varies extremely, it is obvious that the price of the CO_2 reduction must be very different in the two variants. As shown in table 9.4 the coal gasification variant is not the optimum, if the purpose is a CO_2 reduction at reasonable cost. However, the biomass variant seems to be promising with a relatively low reduction price of CO_2 - approx. 7.4 US$/ton reduced CO_2.

Table 9.4. Economic key figures for Scenario E2.

	Coal gasification	Bio gasification
Total additionel costs	85,294 US$/year	79,412 US$/year
Additionel costs for electricity CO_2 reduction price	0.0024 US$/kWh 213 US$/ton CO_2	0.0021 US$/kWh 7.5 US$/ton CO_2

9.3 Total Scenario: The electric utilities as hydrogen producers (P)

The following demonstrates a scenario in which the electricity sector is functioning as hydrogen producer and the hydrogen is sold for use in the transport sector. It is here implied that there is a demand for hydrogen in the transport sector, but that the price for hydrogen is decisive for the sales. The main purpose is, therefore, to produce hydrogen at prices that can compete with traditional transport fuels.

The scenario is composed as follows:

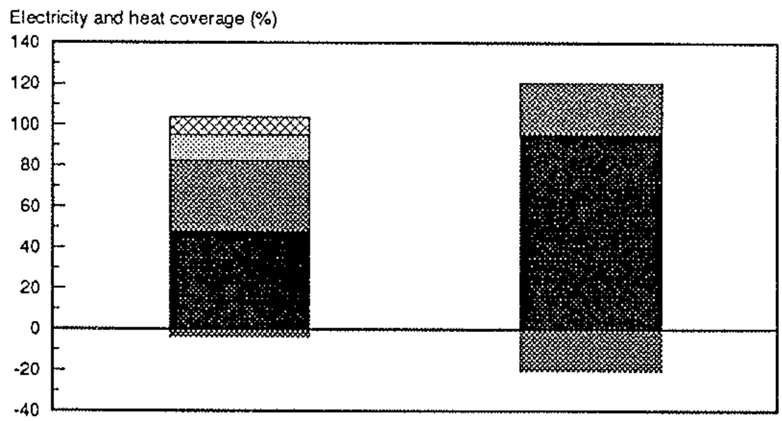
P2) It is presumed that there are already coal gasification plants with combined cycle existing in the electricity system (at least 2.6 GW). The gasification part is in continuous operation and a shift part is installed in order to produce hydrogen, which is sold to the transport sector. The production of hydrogen is 30 PJ.

The most essential characteristics of the composition of the scenario are shown in table 9.5. It is implied that there is a 2.6 GW coal gasification plant with combined cycle in the electricity system. In connection with these components, a 1.8 GW shift part is installed for production of 30 PJ hydrogen based on syngas. The hydrogen is used in the transport sector and covers approx. 20% of the demand for transport.

Table 9.5. System data for Scenario P2.

Coal gasification	
- combined-cycle	2600 MW
- shift-process	1800 MW
Hydrogen production	30 PJ
Hydrogen storage (cavern volume)	10.4 mill. m^3
Hydrogen for transport	30 PJ

Figure 9.3 shows how the demand for electricity and the central heat demand is met. The coal gasification is covering approx. 95% of the heat demand, primarily replacing CHP plants. A minor overflow of electricity will occur in this scenario as a result of the interaction between the electricity and the heat part.



	electr. coverage (%)	heat coverage (%)
coalgasification	47,9	95,3
CHP central	34,6	25,1
CHP decentral	12,5	
industrial	8,7	
rest	(3,7)	(20,4)

Figure 9.3. Coverage of electricity demand and central heat demand (Scenario P2).

The additional costs in the scenario represent investments and operation, maintenance costs of the shift part, storage costs, and the consumption of fuel for the shift process. This is shown in table 9.6. The transport savings stated are given as the value of the replaced transport fuel (diesel).

Table 9.6. Additionel costs per year for Scenario P2 compared to Eco-base.

Costs for the hydrogen system - storage - shift-process - fuel for hydrogen production In total	 39.7 mill. US$/year 35.3 mill. US$/year 141.1 mill. US$/year 216.1 mill. US$/year
Additionel costs in the energy system Savings in transport	0 mill. US$/year 285.3 mill. US$/year
Total additional costs	-69.2 mill. US$/year

The use of coal for coal gasification plants leads to increased CO_2 emissions. Totally the CO_2 emissions is increased by 2.5 million tons/year, corresponding to an increase of approx. 5% compared to the energy system's emissions on the Eco-base.

The key figures for the scenarios are stated in table 9.7. As can be seen in the table, there is a total cost-saving in the scenario. The break-even price for hydrogen will be approx. 7.2 US$/GJ, which can be compared with the expected diesel price of 9.6 US$/GJ year 2030.

Table 9.7. Key figures for Scenario P2.

Total additional cost	-69.2 mill. US$
Break-even - additional cost for electricity - price of hydrogen - costs for shift-process	 -0.002 US$/kWh 7.2 US$/GJ 515 US$/kW
Price of diesel (year 2030)	9.5 US$/GJ

This cost-saving is to compensate for the necessary investments in hydrogen distribution plants etc. in the transport sector to obtain break-even. If the price of hydrogen is equivalent to the price of diesel, the break-even price of the shift part can be calculated to approx. 515 US$/kW, i.e., the price the shift part may cost if the hydrogen is produced at the same price as diesel - the above-mentioned calculations are based on a price of 176 US$/kW.

If coal gasification plants are in use in the electricity system, a hydrogen production based on a shift process with syngas, could seem promising, presuming that the necessary investments in the hydrogen distribution network are not prohibitive. There are no environmental improvements in the scenario, on the contrary, the emission of CO_2 is increasing slightly. If biomass is used instead of coal, the picture changes radically.

9.4 Total Scenario: Focus on the environment (M)

The following gives a scenario for the energy system with focus on the environment. Especially the CO_2 emissions are taken into consideration, but both SO_2 and NO_x emissions will to a large extent follow the CO_2 emissions. The scenario shows the possibilities of exploiting renewable energy - wind and biomass - in the production of hydrogen for transport fuel and in this way obtain a large CO_2 reduction.

The scenario is set up as follows:

M3) Installation of 5.5 GW wind-power and 3.3 GW electrolysers. Furthermore a 1.5 bio gasification is installed with shift part. In total 50 PJ of hydrogen is produced (approx. 8% of the gross energy consumption) of which 30 PJ is used in the transport sector, and the rest in central fuel cells, 1000 MW of which are installed.

The essential characteristics are shown in table 9.8.

Table 9.8. System data for Scenario M3.

Wind power	5500 MW
Bio gasification	
- combined cycle	1500 MW_{el}
- shift-process	1800 MW_{H2}
Electrolysers	3300 MW_{el}
Hydrogen consumption	49.3 PJ
Hydrogen for transport	30 PJ
Hydrogen internal in the system	20 PJ
Hydrogen storage (cavern volume)	3.5 mill. m^3
Central fuel cells	1000 MW_{el}

How the electricity demand and the central heat demand are met are shown in figure 9.4. If the figures are corrected for the consumption of electricity of the electrolysers, bio gasification and hydrogen use in central fuel cells will meet more than 55% of the demand for electricity. Conventional CHP plants are only going to meet approx. 33% of the demand for electricity. The same applies to heat, where bio gasification and hydrogen based fuel cells are covering approx. 55% after adjustment for the acceptable heat overflow. Of the surplus electricity production of approx. 26% of the electricity demand, approx. 23% is used - primarily in the electrolysers and the remaining 3% is overflow. 30 PJ hydrogen covers approx. 20% of the energy demand in the transport sector.

The economy in Scenario M3 is shown in table 9.9.

The total costs of the hydrogen system constitute totally approx. 376 millions US$/year. As shown in table 9.9 the major part of this amount is for annuity investments, operation and maintenance costs of electrolysers and shift part, in total 254 millions US$ per year. The remaining annual costs include wind power and bio gasification, corrected for the saved fuel expenses on conventional plants and a minor saved investment in conventional plants.

The saving in the transport sector is fixed as the value of the replaced fuel (diesel).

This scenario shows the biggest reduction in the CO_2 emissions. Totally the yearly CO_2 emissions from the energy system is reduced to approx. 30 mill. tons, a reduction of 16 billion tons/year compared to Eco-base. This corresponds to a reduction of approx. 34%.

Table 9.10 shows the key figures of Scenario M3.

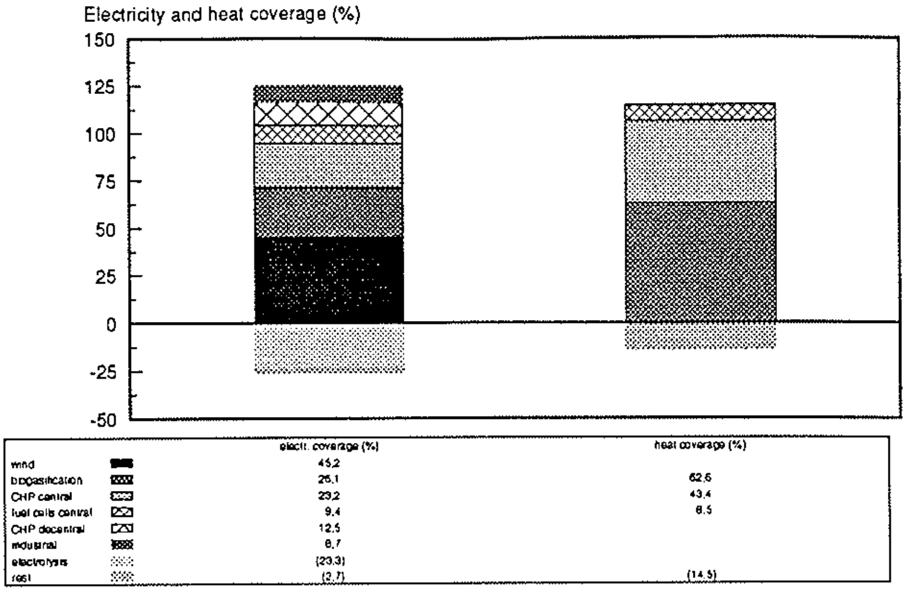


Figure 9.4. Coverage of electricity demand and central heat demand (Scenario M3).

Table 9.9. Annual additional costs for Scenario M3 compared to Eco-base.

Costs for the hydrogen system - storage - electrolysers and shift-process - fuel for hydrogen production In total	 29.4 mill. US$/year 254.4 mill. US$/year 92.6 mill. US$/year 376.4 mill. US$/year
Remaining costs Savings in transport	83.8 mill. US$/year 285.3 mill. US$/year
Total additional costs	174.9 mill. US$/year

Table 9.10. Key figures for Scenario M3.

Total additional costs incl. transport savings	174.9 mill. US$
Break-even - additional costs for electricity - price of hydrogen - CO_2 reduction price	 0.004 US$/kWh 14.9 US$/GJ 10.1 US$/ton CO_2
Price of diesel (year 2030)	9.5 US$/GJ

It is costly to go as far as in this scenario. The total additional costs, inclusive the saving in transport, estimated as the value of the replaced fuel, amount to approx. 175 millions US$/year. If the additional costs are evaluated in comparison to the use of hydrogen in the transport sector, the break-even of hydrogen will be approx. 15 US$/GJ, about 55% more than the price of diesel. This price has been calculated on the assumption that the hydrogen used in the fuel cells is replacing coal. If the break-even price is calculated as an additional cost for the electricity consumers, the price increase is moderate - the additional cost - 0.004 US$/kWh is approx. 6-9% of the price of electricity in year 2030 (socio economical).

The big CO_2 reduction in the scenario means that the CO_2-reduction price will be moderate, 10.2 US$/ton/year. If it is the goal to obtain significant CO_2 reductions, this scenario is on the right way.

9.5 Conclusion for the scenarios

The three types of scenarios, the Electricity Scenario, the Hydrogen Production Scenario and the Environment Scenario cannot be compared directly, as they each have their individual angle in the energy system. The most important data for the three selected main scenarios are stated in table 9.11.

The above-mentioned scenarios are the most suitable scenarios within each of the three categories - electricity system, production of hydrogen and environment. Furthermore, in the main report various other scenarios have been calculated. The conclusions of all scenario calculations are as follows:

- Coal gasification plants with combined cycle are working well in combination with wind power, if hydrogen is introduced as energy carrier. The combined cycle part of the plant is working as buffer for the wind power, and the surplus syngas that is produced, is converted into hydrogen via a shift process.
- The bio gasification plants are attractive in connection with hydrogen as energy carrier, as they have the same buffer capacity as the coal gasification plants. Furthermore, the use of bio gasification plants results in a significant reduction of the CO_2 emissions.
- If there is a demand for hydrogen, it can be produced on conventional continuous operating plants at a price that is approx. 25% lower than diesel. Such a hydrogen production is, however, resulting in an increase of the CO_2 emissions from the total energy system, but the CO_2 emission will then take place centrally and not locally, and the possibilities of dealing with the problem will probably be better.
- The conventional plants (f.inst. fluid bed plants) might be based on straw-firing etc., and in this way the CO_2 emissions will be reduced.
- From an environmental point of view the best way to use hydrogen is in the transport sector replacing diesel, or in central fuel cells replacing coal.
- Even if there is a large amount of wind power in the electricity system, it is possible to obtain a well-functioning system by the introduction of hydrogen. Production of hydrogen by electrolysis, based on surplus electricity from wind power is, however, a relatively expensive process, but costs can be reduced by combining other production technologies as f.inst. coal gasification or reversible fuel cells.

Table 9.11. Key figures for the three scenarios.

	Scenario for the electricity system	Scenario for hydrogen production	Scenario for environmental impact
Installed capacities			
Wind energy	1100 MW	500 MW	5500 MW
Gasification	biomass	coal	biomass
- combined-cycle	1500 MW_{elec}	2800 MW_{elec}	1500 MW_{elec}
- shift-process	1800 MW_{H2}	1800 MW_{H2}	1800 MW_{H2}
Central solid oxide fuel cells	600 MW	-	1000 MW_{elec}
Electrolysis	-	-	3300 MW_{elec}
Renewable energy			
Electricity demand	43%	0%	55%
Heating demand	57%	0%	57%
Energy demand for transport	0%	21%	21%
CO_2-emissions	36 mill. ton/year	48,5 mill. ton/year	30 mill.ton/year
Reduction compared to reference	23%	5,4% increase	34%
CO_2-reduction price	7.4 US$/ton CO_2	-	10.15 US$/ton CO_2
Hydrogen price	-	7.2 US$/GJ	15 US$/GJ
Increase in electricity cost	0.002 US$/kWh	-	0.004 US$/kWh
Diesel price	9.5 US$/GJ	9.5 US$/GJ	9.5 US$/GJ

10 Research and development concerning hydrogen as an energy carrier in the Danish energy system

In the mentioned scenarios there is a minor electricity overflow caused by a bound CHP production in the year 2030. If an amount of renewable energy is introduced in the system, this electricity overflow will increase considerably, and an electricity overflow of 15-20% does not seem unrealistic at the introduction of about 4000 MW renewable energy, corresponding to 30% of the expected demand for electricity.

In most of the scenarios electrolysers are introduced in order to convert surplus electricity to hydrogen, and caverns are introduced for large-scale storage of hydrogen. It is assumed that the hydrogen can be sold to the transport sector. The annual production costs of the hydrogen technology are more or less the same as the costs in the Eco-base Scenario, in which the electricity overflow is not utilised. I.e., hydrogen must be considered an absolutely realistic possibility for storage of surplus electricity in the established energy system in Denmark.

The environmental advantages of the introduction of hydrogen technology and utilisation of the hydrogen within the transport sector are essential. Through the addition of a considerable quantity of wind power in the Danish electricity system and by exploiting an electricity overflow of f.inst. 15% for production of hydrogen and replacing diesel in the transport sector by hydrogen, it will be possible to obtain an annual reduction of 4 million tons CO_2.

The hydrogen technology seems to be a realistic energy source in Denmark's future energy system. In the following are focused on some areas in the hydrogen technologies that call for further research and development in order to make it possible to use hydrogen as an energy carrier in Denmark.

Furthermore we will point out areas in which a Danish research effort might result in an export of hydrogen technologies.

10.1 Research and development necessary in Denmark for the use of hydrogen as an energy carrier

As mentioned in the particular chapters there is already a considerable knowledge about the hydrogen technology in Denmark within certain areas.

However, there will be areas where further research and development is necessary if hydrogen is going to be used as an energy carrier in a future energy system in Denmark. In several cases it will be possible to learn from experiences abroad, but it will also be necessary to make own research.

From the listed and calculated scenarios it is evident that some system analysis is still required to be able to use the hydrogen technology in Denmark.

Introduction of electricity-efficient plants in the Danish energy system f.inst. fuel cells, has to be carefully analysed as heat constraints arise very quickly in the system. These constraints might be minimized at the introduction of big heat storages maybe on a seasonal basis.

Other production methods also need to be closely analysed. From an environmental point of view the gasification of biomass is attractive together with hydrogen.

The positive interaction between coal gasification and gasification of biomass should be analysed in order to evaluate the possibilities of a combined production of electricity, heat and hydrogen.

The costs of the technologies should be examined in detail, as the stated costs in connection with the introduction of hydrogen technology, are only the superior costs connected to the technology and not the costs of the system functional.

It is very essential to analyse the natural gas network for distribution of hydrogen. The natural gas companies and the gas supply companies have some experience that makes it possible to develop a suitable method of transport for hydrogen in conformity with local conditions and regulations. A test of the natural gas network would be of great importance, as there is at present doubts about the suitability of the network for transport of hydrogen.

It will also be necessary to obtain experience with large scale storage of hydrogen. There is comprehensive know-how in Denmark with regard to storage of natural gas and a cooperation between the natural gas companies, the gas supply companies and the research institutions should make it possible to develop the storage technique of hydrogen at large scale. Today storage of natural gas in caverns is a well-known technique in Denmark, and experience from this technique will be useful in connection with storage of hydrogen in caverns. Also storage of hydrogen in aquifers is an interesting perspective, and this technology is also known in connection with storage of natural gas.

Practical experience will be necessary to support the theory about the introduction of hydrogen as energy carrier in the energy system, as the interaction between the various technologies can change the picture. F.inst. a constantly high efficiency of the electrolysers has been assumed. However, this efficiency will probably be affected by fluctuating electricity input. In this matter it will be possible to gain experience from abroad.

A detailed analysis of the possibilities of using hydrogen in the transport sector, and practical experience will be essential in order to evaluate the use of hydrogen in this sector. An analysis of the infra-structure will be a substantial parameter.

10.2 Research and development in Denmark for exportation

There is an extensive research and development going on abroad in the hydrogen technology, and Denmark will only to a small extent be able to contribute to this knowledge.

In this connection can be mentioned that there has been some research in the type of fuel cells that are based on solid oxide materials. The research has been going on in cooperation with a number of institutes and companies that have good relations to similar activities abroad.

The Danish project has already demonstrated useful results of industrial interest, but further research will be necessary in the coming years. There is a lot of research in materials and this experience will later on be subject for export. Solid oxide cells can immediately be used as high temperature electrolysers and they are highly efficient in the hydrogen production. The fact that the same part can be used both as fuel cell and as electrolyser is an economic advantage in the energy storage system.

Finally, it must be mentioned that there is substantial know-how in Denmark about light construction materials based on plastic compounds that could be suitable for mobile storage of hydrogen on a small scale, f.inst for transport purposes. There is professional expertise available and a cooperation between production companies, labour inspection authorities, and research institutes could develop a light-weight pressure container that could be approved for use in Denmark. This would have a large export potential.

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A Appendix 1

A.1 Key figures for hydrogen technologies used in the scenarios

A condition of the calculations of the various hydrogen scenarios is that useful key figures can be found for the technologies in the year 2030. The key figures which are used in the scenarios for each technology are as follows:

- Efficiency.
- Lifetime.
- Environmental emissions (here only CO_2).
- Investment per MW hydrogen installed.
- Annual running and maintenance costs in percentage of the investment.

The following key figures indicate which are the basis of the scenarios in chapters 8 and 10. The key figures are stated for the year 2030, and where it could be of interest, the reference figures for the year 1990 are also mentioned. Key figures that are not stated in the following have been collected from "Energy 2000". This is f.inst. the case with the conventional plants which are not hydrogen specific.

Table A.1. Data for the hydrogen production technologies.

	Efficiency (%)		Life-time (year)	CO_2 kg/GJ	Investment (US$/MW)		Annual operating costs (% of inv.)
	Electricity	Hydrogen			Electric ity	Hydrogen	
Electrolysis		94 (80-90)	20	0		338	10
Coal gasification	53 (40-45)	70 (55-65)	30	100	765	295	3
Biomass gasification	53	70	25	0	765	295	3

The stated electrolysis process is an alcalic pressure electrolyser.

Table A.2. Storage data.

Storage	Efficiency	Lifetime	Investment	Annual operating costs (% of inv.)
Cavern	99% ⁻	30 year	44 US$/m^3	1,6%

The calculations are based on an efficiency of 97% incl. of loss in connection with the distribution of hydrogen from the storage.

Table A.3. Data for hydrogen consumption technologies.

Fuel cells		Efficiency (%)	Lifetime (year)	CO_2 kg/GJ	Investment (US$/MW)	Annual operating costs (% of inv.)
PAFC	central	45-55	10-20	0	735	7,5
	decentral	36-40	10-20	0	925	7,5
MCFC	central	55-65	10-20	0	735	7,5
	decentral	50-60	10-20	0	925	7,5
SOFC	central	50-65	10-20	0	555	7,5
	decentral	47-60	10-20	0	740	7,5

The stated efficiencies for the fuel cells have natural gas as fuel, but they are expected to be in the same interval or even a little higher with hydrogen as fuel.

The investments are inclusive of plant and installation costs.

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Abstract (max. 2000 characters)

The purpose of this report has been to investigate the possibilities for introducing hydrogen as an energy carrier in the energy system in the future in Denmark and to estimate the economic and environmental consequences.

Different technologies for production, storage, transport and utilisation of hydrogen are described in the report and the most relevant technologies for Denmark have been used in the different scenarios, estimating how hydrogen can be introduced in the Danish energy system in the year 2030.

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Descriptors INIS/EDB

AIR POLLUTION ABATEMENT; BIOMASS; COAL; COMPUTERIZED SIMULATION; DENMARK; ELECTROLYSIS; GASIFICATION; HEATING SYSTEMS; HYDROGEN; HYDROGEN-BASED ECONOMY; HYDROGEN FUEL CELLS; HYDROGEN PRODUCTION; HYDROGEN STORAGE; POWER SYSTEMS; SOCIO-ECONOMIC FACTORS; TECHNOLOGY ASSESSMENT; TRANSPORT; TRANSPORTATION SECTOR; WIND POWER.

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