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Scenarios for future use of hydrogen and fuel cells

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Abstract: Scenarios for a transition to a hydrogen society are constructed. The scenarios are detailed on both a geographical scale (500m by 500m grid) and a time scale (hourly), for Denmark. The physical basis for the scenarios is the exploitation of renewable energy resources already in progress in Denmark. Hydrogen is proposed as a convenient energy carrier due to its versatility in use, transmission and as an energy storage medium. Two main scenarios are constructed, differing in the degree of decentralisation of energy production and management: one resembles the current system with centralised facilities and commercial management, the other being based upon a projected scale-independent cost structure of energy producing and handling equipment, that will allow extreme decentralisation of the physical energy conversion system, possibly accompanied by a similar decentralisation of ownership and control.

1. Purpose of study

For some years, Denmark has enjoyed broad parliamentary agreement on an energy future laid down in a road map stretching 30 years into the future [1]. This plan uses annual time steps and looks at the whole country as one planning unit, in its call for massive introduction of renewable energy supply and particularly wind power into a changing society continuing to place emphasis on efficient use of resources. The authors of the plan realise that more study is needed to determine the implications of variations in renewable energy production in terms of need for energy trade or energy storage. This is the task taken up by the current study, the basic parts of which have been presented in Danish through work for the Danish Energy Agency [2]. This paper highlights the role to be played by hydrogen and fuel cells in creating the conditions for the Danish Energy Future Plan to become a realistic path to follow. It uses a geographical grid of 500m×500m to match demand and supply, and works on a time-grid of one hour in order to capture the supply-demand mismatch that may call for management solutions (import-export, demand adjustments, etc.) or the addition of energy storage, locally or in centralised facilities.

2. Defining the problem caused by high penetration of fluctuating energy sources.

Wind power is the only of the new renewable energy technologies (as contrasted to hydro and conventional geothermal power or biomass combustion) that has significantly penetrated the market and has reached a price level being considered competitive to fossil and nuclear alternatives in all societies concerned about the full social costs of energy provision [3]. Wind power onshore and offshore currently cover around 20% of the total electricity demand in Denmark, and the official plan mentioned calls for continued growth of wind power implementation on a number of (particularly offshore) sites already designated for the purpose (see Fig. 1). The potential wind power that may be derived from these sites by far exceeds any expectation for the total future electricity demand.

Wind power exhibits a number of interesting characteristics, as illustrated in the hourly production curve shown in Fig. 2 for a period of a year: The overall seasonal variation matches that of expected electricity demand very well, and mismatches happen on the time scale of a week or two, corresponding to the passage of weather systems over the limited extent of the Danish main territory. Clearly, the minimum wind production is nearly zero (Fig. 3), as the smoothing obtained by using different sites does not significantly involve new weather systems. However, the maximum can be very large, depending on the wind turbine design and particularly the blade aerodynamics. For current commercial turbines, the maximum is 3-4 times the average power production. This explains the need to cope with occasional huge excess production that cannot be matched to the actual demand at the time.

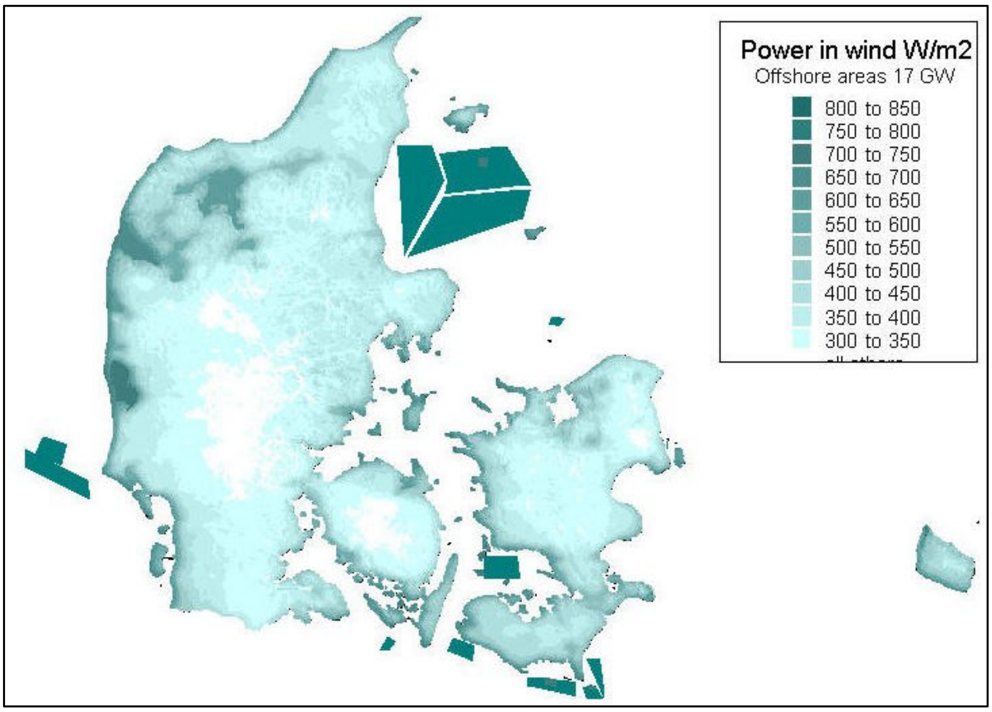


Figure 1. Power in wind for Danish land areas and indication of offshore areas set aside for wind power utilisation [6-8]. All Figures in this paper are derived from [2], [4] or [5], are © Bent Sørensen (2001) and are used by permission.

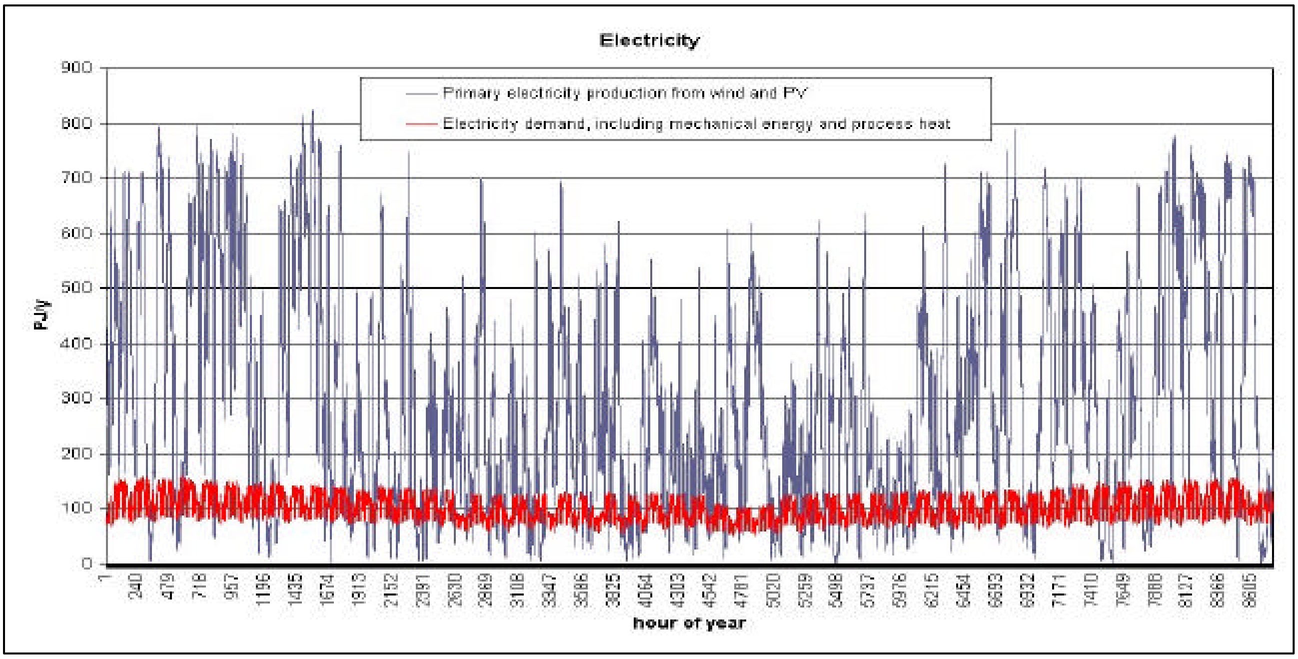


Figure 2. Hourly renewable energy electricity production, mainly wind power, in centralised scenario for 2050, along with scenario electricity demand

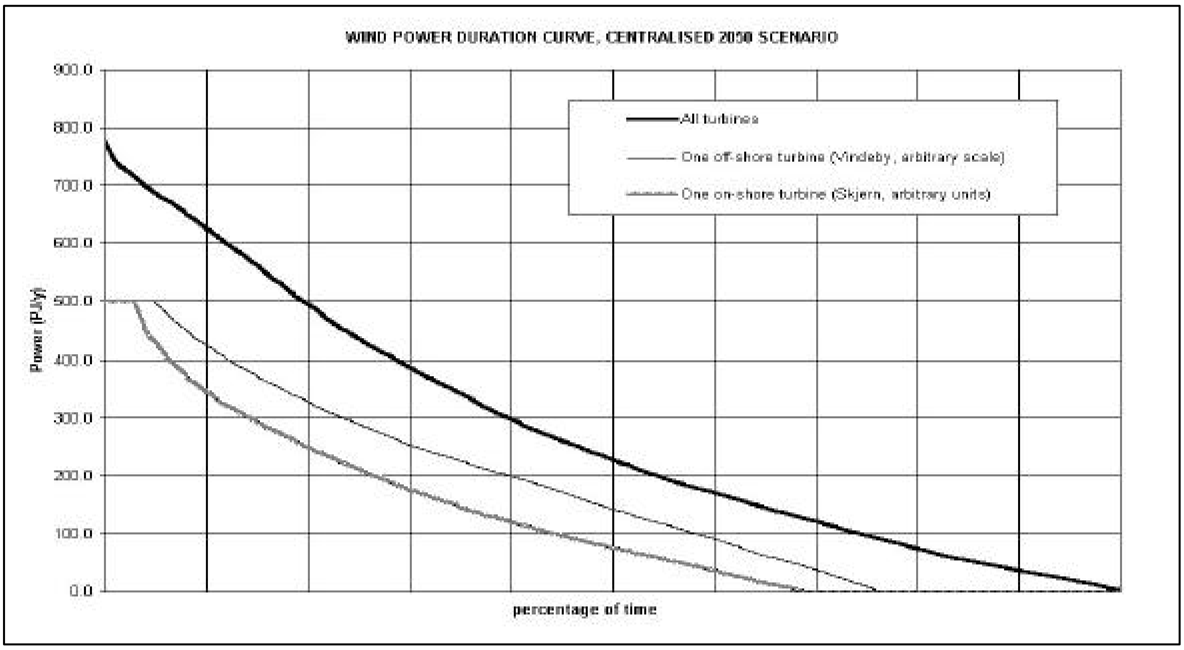
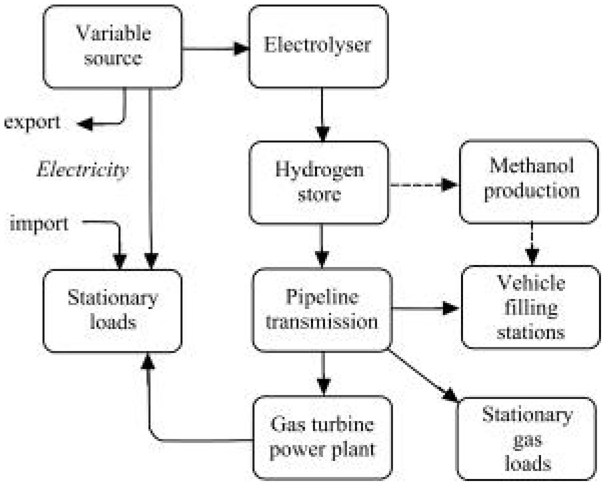


Figure 3. Power duration curves for all wind turbines in the centralised 2050 scenario, compared to that of a single turbine placed onshore and offshore.

Due to this characteristics of wind power variations, no seasonal storage is required, but only storage corresponding to a few weeks of demand. The alternative of selling surplus power and buying in case of a deficit relative to demand, on the Nordic or the European power pools, is less attractive because of the often short notice, upon which large needs for export or import occur, leading to very low selling prices and very high buying prices. It is thus proposed to use hydrogen storage as the means to deal with the problem.

Two hydrogen storage options have been devised for dealing with the issue, tied to the two types of future energy systems considered in the scenarios constructed for year 2050 (this year selected because the fossil components of the Danish energy system are assumed to have gone by then as a result of the greenhouse gas abatement policy facing out coal fired power stations, and the exhaustion of Danish North Sea gas and oil reserves combined with the unlikeness of Denmark being awarded any share of the lute from wars over the Middle East oil and gas). Figs. 4 and 5 shows the overall schemes of the two scenarios, to be dealt with in more detail in the next sections.



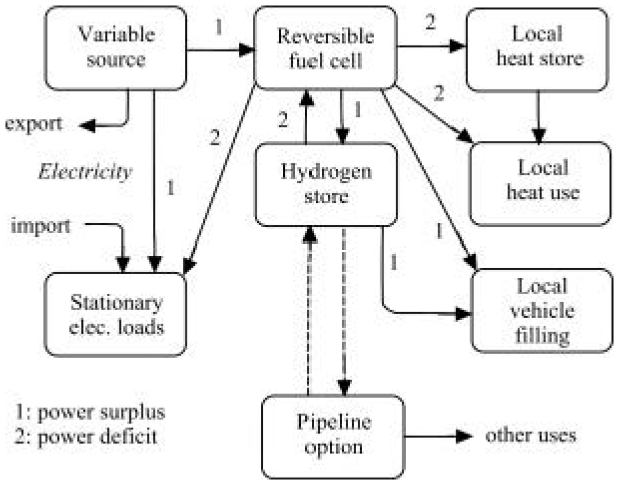


Fig. 4. System layout for centralised scenario.

Fig. 5. System layout for decentralised scenario.

3. A conventional scenario based on centralised conversion and storage facilities.

The centralised scenario stipulates hydrogen to be produced from excess wind power at the site of existing power plants, where conversion is expected to be made using modern electrolysis plants (efficiency near 90%). If reversed fuel cells by the time are developed to similar efficiency and acceptable price, they may be used instead (currently single plate hydrogen producing PEM fuel cells have been developed to that level of efficiency, but at very high cost. Two-way PEM cells usually produce hydrogen at an efficiency as low as 50%). Fig. 6 shows the distribution of hydrogen producing plants, which have been taken as the sites of the roughly 2000 fossil (combined heat and power) plants presently existing in Denmark.

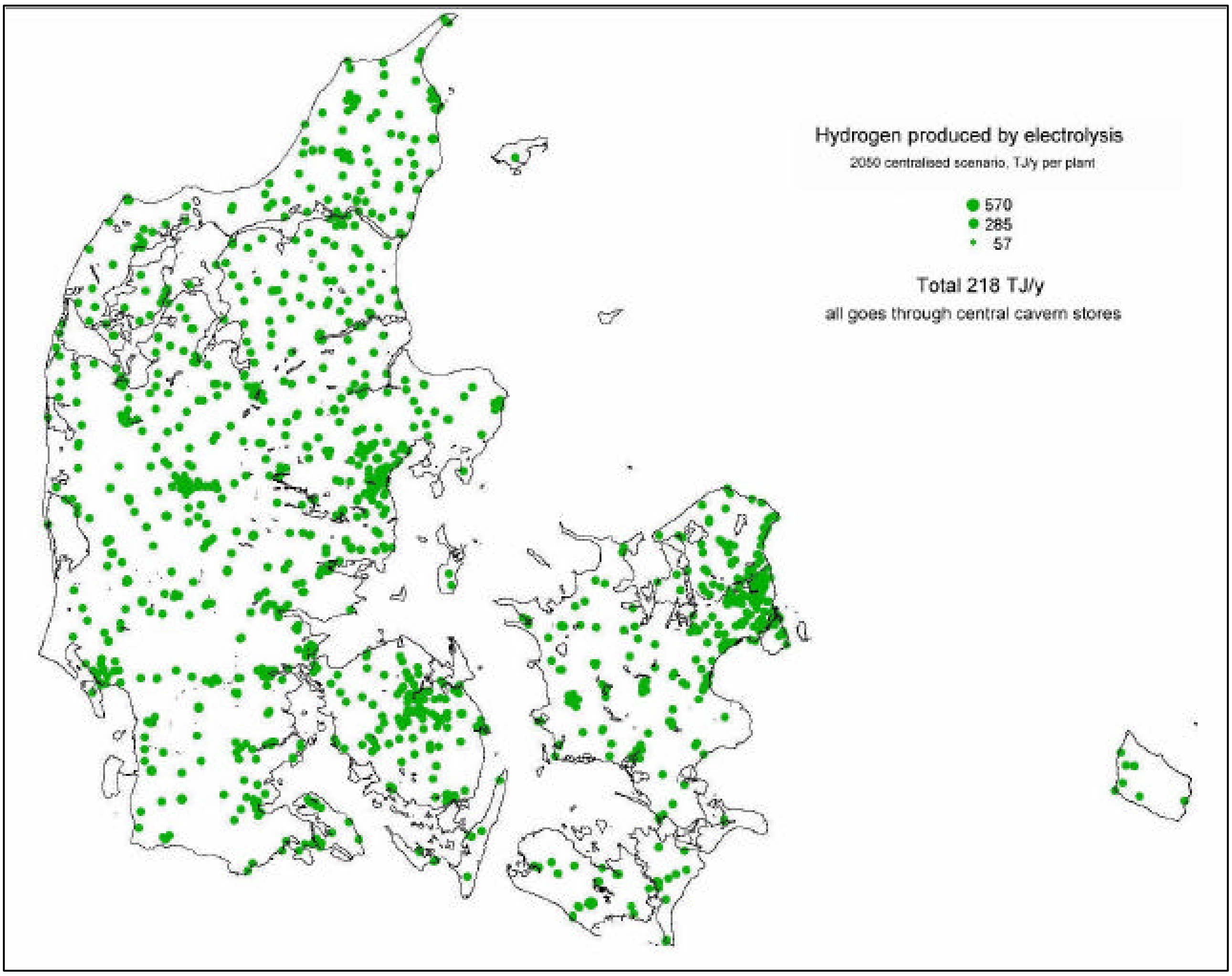


Figure 6. Hydrogen production from surplus wind power in the centralised 2050 scenario.

The time pattern of wind and PV power production used directly or giving rise the surpluses converted to hydrogen for storage was shown in Fig. 2. Fig. 7 shows the amount of wind power used directly alone, on a logarithmic scale, and Fig. 8 the part converted to hydrogen, exhibiting a somewhat stronger time variation, but on a short time scale as expected and in line with the capacity of required storage being limited (also shown is an amount of surplus power used to cover heating needs through heat pumps – this being another way of making sensible use of excess power, to make up for periods where heat requirements cannot be covered by fuel cell waste heat and solar thermal installations alone). The scenarios deal with all types of energy demand and have segments not described here [2].

The choice of hydrogen storage facility in the centralised scenario is underground caverns, of which the Danish underground is rich. Two are already at present in use for storing natural gas (as security against failure of the sea pipes to the North Sea extraction sites). One is a washed-out salt intrusion dome and the other an aquifer upward bend, with cavity sizes of 750 and 1000 million m^2 [6]. The capacity of these stores for hydrogen storage – assuming that they can be made sufficiently tight by suitable sealing – by far exceed the modest 13 million m^2 needed according to the time simulation shown in Fig. 9 for storage at a pressure of 5 MPa, where the energy content of compressed hydrogen is 150 kWh/m^3 [7].

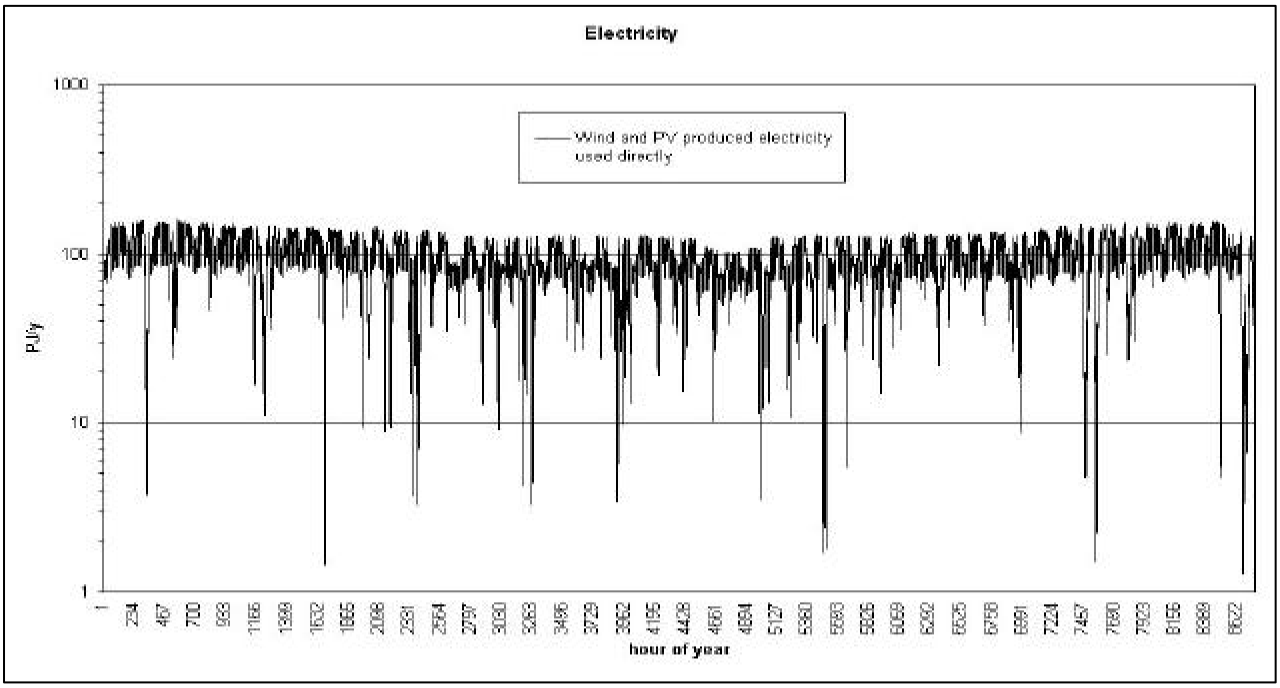


Figure 7. Electricity produced by renewable energy (mainly wind) in the centralised 2050 scenario, and used directly without need for storing.

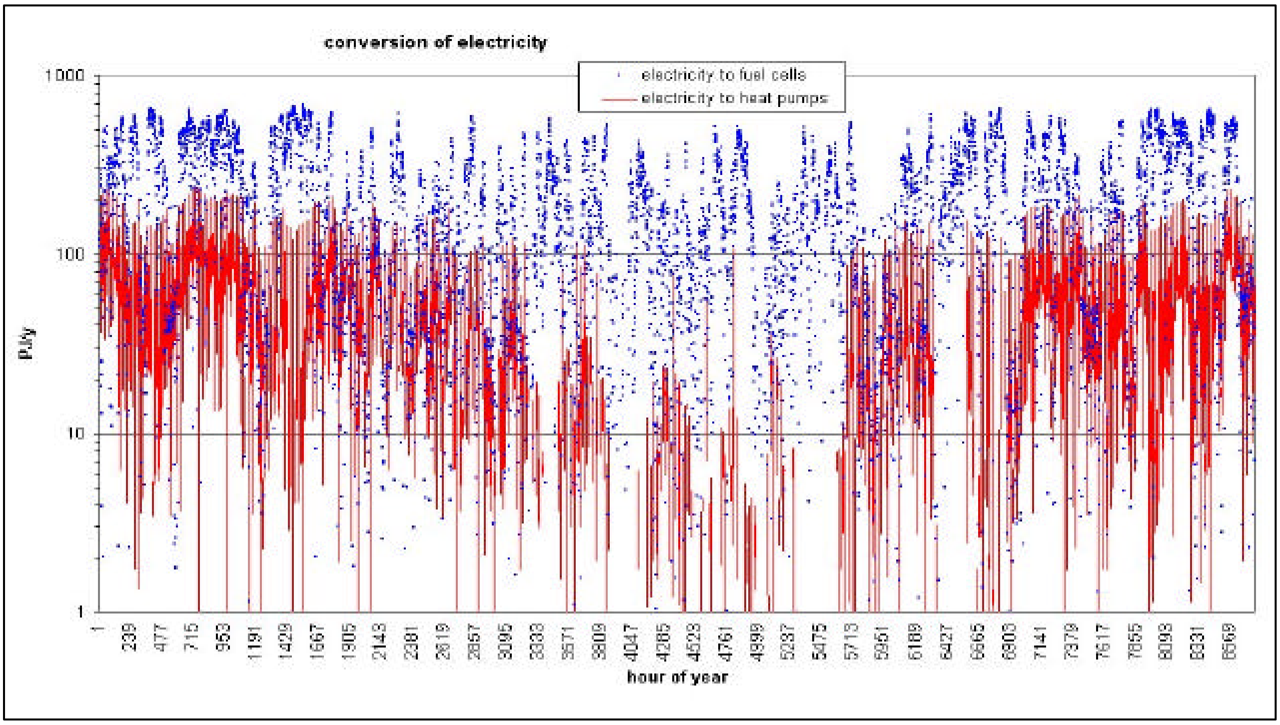


Figure 8. Remaining electricity production in the centralised scenario, passed to the electrolysis units for hydrogen production and storage. Also shown are the smaller amounts used to power heat pumps.

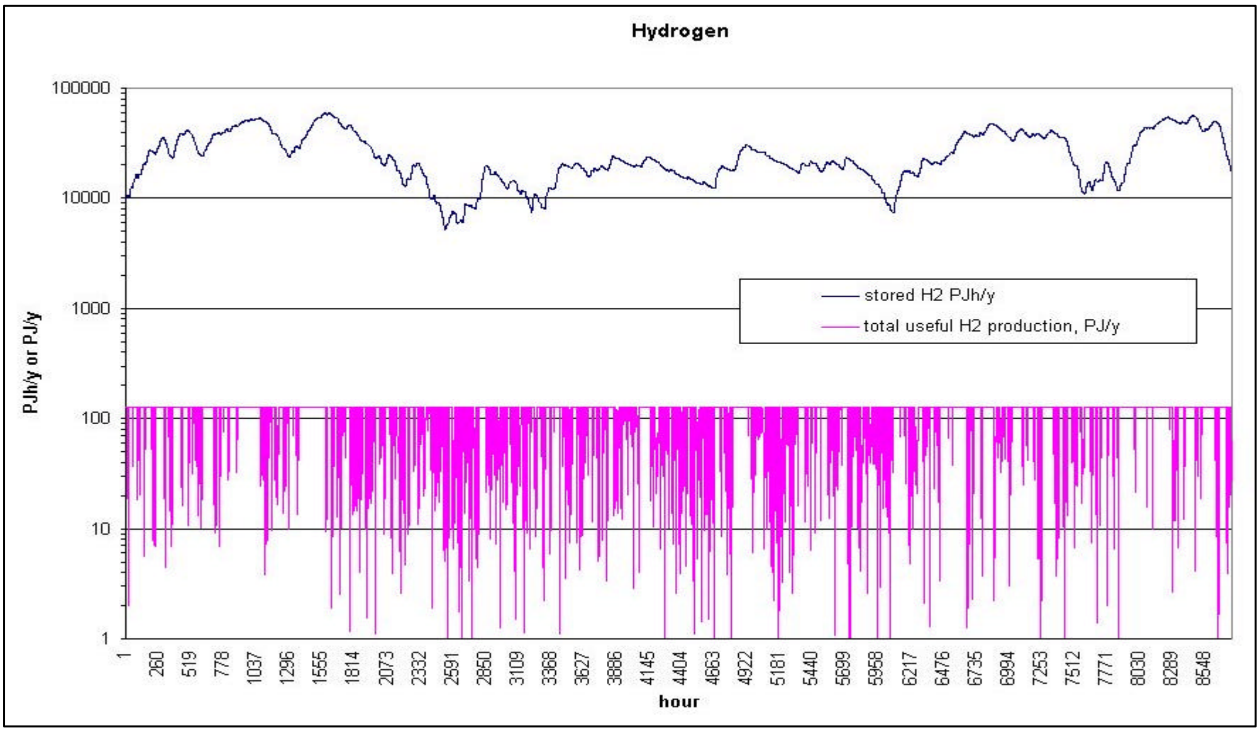


Figure 9. Time development of storage filling for the underground cavern stores used in the centralised 2050 scenario. Below is shown an additional small amount of hydrogen production on the basis of biomass residues from Danish agriculture. *Figure 10 below: see caption next page*.

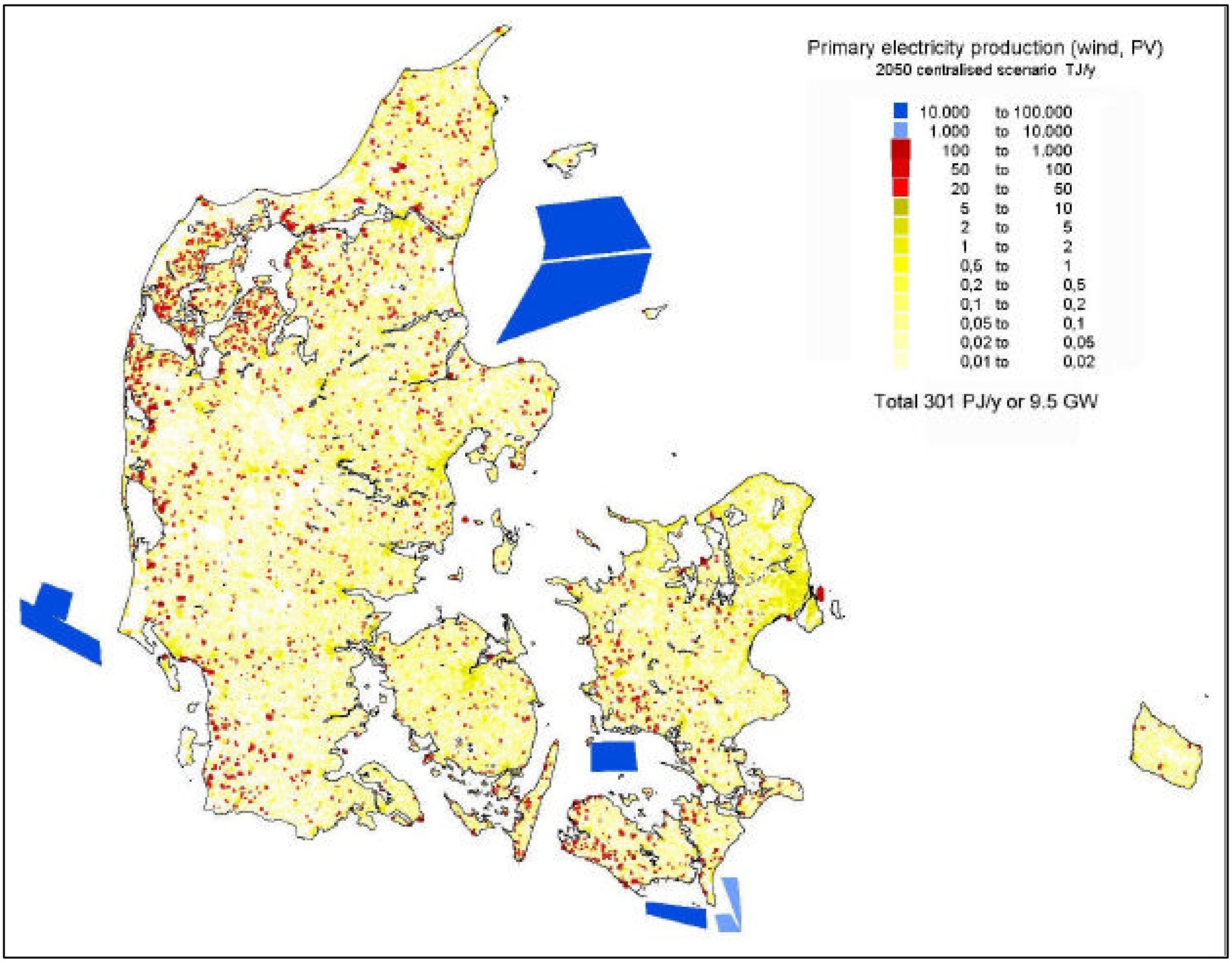


Figure 10 (previous page). Renewable production of electricity in the centralised 2050 scenario. The fainter areas are locations of PV integrated into buildings, the dots are wind turbines or wind parks, and the offshore wind farms are a selection of the possible sites, of which the largest one is only partially filled up.

Fig. 10. shows the geographical distribution of the primary renewable energy electricity input, based on wind turbines placed on land (on existing sites where smaller wind turbines are supposed replaced by current generation machines rated at 2-4 MW each), off shore on a fraction of the areas set aside (Fig. 1), plus photovoltaic panels assumed to be mounted on 25% of suitably south-facing roofs and facades. The power contribution is mainly during summer, where wind power is at a minimum.

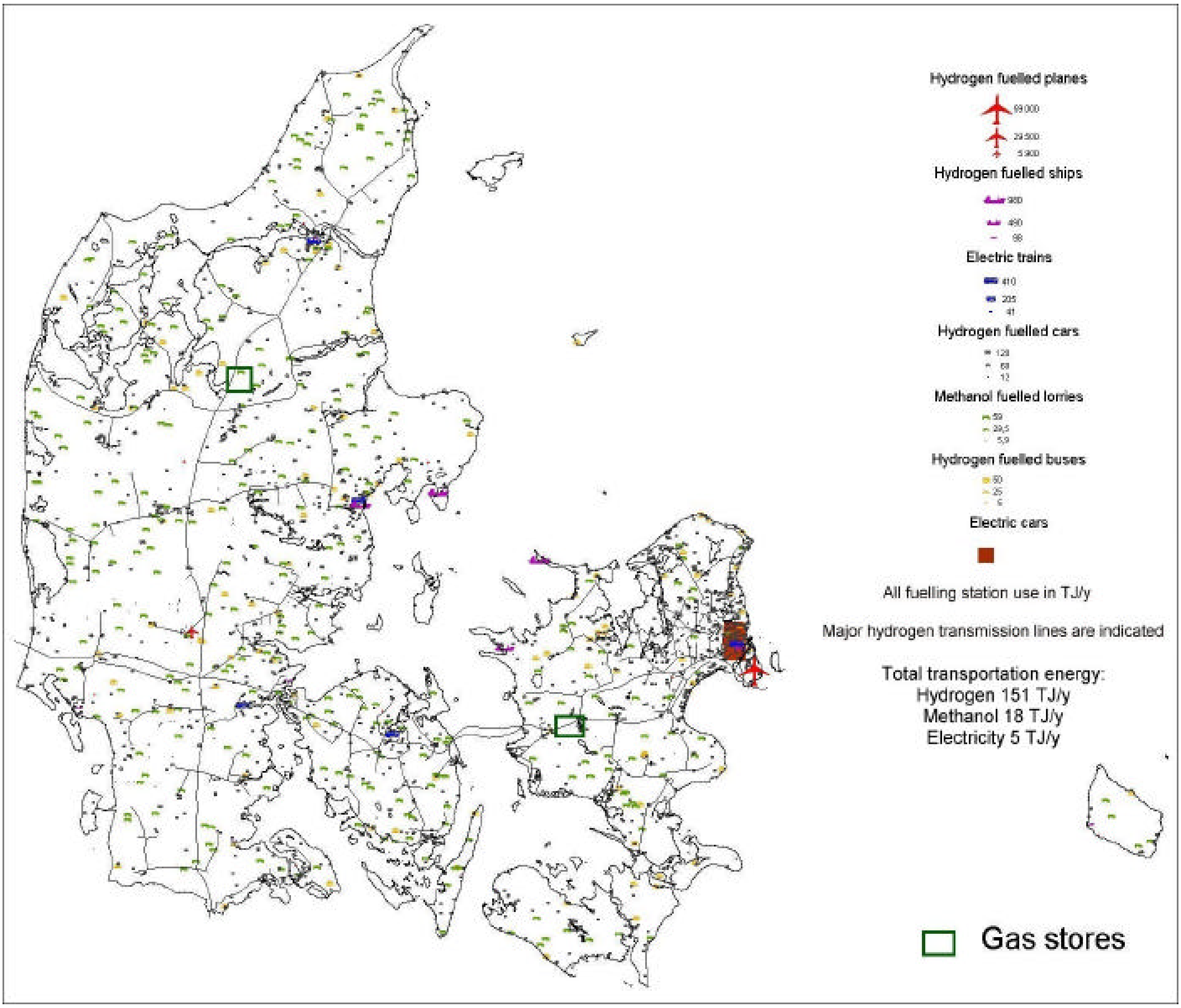


Figure 11. Coverage of transportation demands in the centralised scenario.

Figure 11 shows the locations in the centralised scenario of filling stations for private motorcars, buses, lorries (assumed to use not hydrogen but methanol), ships and planes. Also indicated are hydrogen gas lines and the two main hydrogen underground cavern sites. For trains and in the city of Copenhagen, electric vehicles are assumed to be in use. The totals indicate that hydrogen is the main fuel used for transport.

4. A decentralised hydrogen scenario.

In the decentralised 2050 scenario, each or nearly all buildings are assumed to be equipped with a reversible fuel cell capable of storing surplus electricity from renewable energy sources received through the grid, of using the hydrogen to fill the tank of any vehicles in garages attached to the building (the vehicle fuel tanks serving as an extension of any stationary hydrogen stores in the building), and finally of re-generating electricity from stored hydrogen when direct supply is insufficient (cf. Fig. 5).

The hydrogen stores in buildings, and possibly also in vehicles, may for increased safety be not compressed storage tanks but metal hydrides or carbon nanofibre stores. None of the latter is developed to the stage of industrial production yet. Should the reversible fuel cell technology presently under commercialisation turn out impractical for the stated reasons of efficiency or cost, there would have to be two fuel cell installations (optimised for opposite operation) in each building, or one fuel cell and one other kind of electrolyser. Current development makes it far more likely, that the winning fuel cell technology be PEM FC's rather than SOFC's or MOFC's, because if it becomes mass produced for automotive applications, its cost will likely diminish to a level where it can easily offset any possible in efficiency that the other types of fuel cells may have.

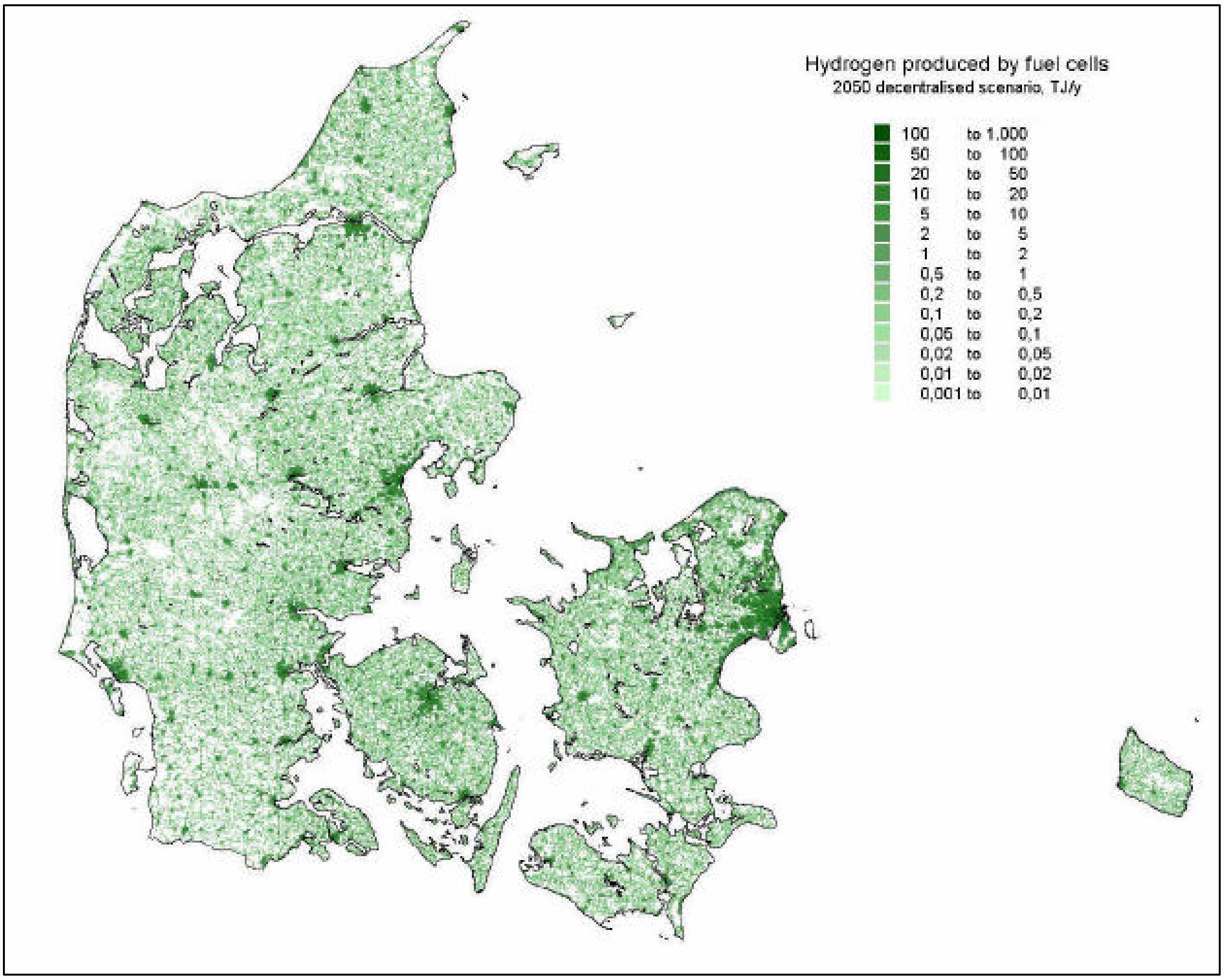


Figure 12. Hydrogen production from surplus wind power in the decentral 2050 scenario.

The hydrogen production geographical distribution, which is thus basically a map of building distribution, is shown in Fig. 12, notably different from Fig. 6 describing the corresponding locations of hydrogen production in the centralised scenario. The main primary renewable energy production is shown in Fig. 13, differing only slightly from that of Fig. 10, due to less energy being required in the decentralised scenario. Additional contributions from agricultural residues are not shown [2]. The hydrogen obtained from surplus renewable energy production (chiefly wind power) is either loaded into vehicles at the decentralised building premises, or stored into local hydrogen storage facilities. The annual simulations show, that the maximum storage required because of mismatch between surplus power and power demands is the equivalent of one half cubic metre of metal hydride storage, even disregarding the hydrogen that may be stored in vehicles in the garages of the buildings. This store size is quite manageable for nearly all buildings, being placed in basements or buried under or adjacent to the building.

The variation in filling of all the decentralised stores is illustrated in the time-simulation results depicted in Figs. 14 and 15. Fig. 14 shows the results for the amount of storage mentioned above, corresponding to 60 EJ total storage capacity. It is seen that there are a few hours during the year, where this storage is insufficient. Increasing store sizes does not solve the problem, but increasing the amount of installed offshore wind power so that the production increase from 99 to 180 PJ does, as shown in Fig. 15. It is seen that the store is now sufficient at all times during the year of data considered. However, wind power totals as well as distributions in time vary from year to year, and it is not assured that the store will be sufficient for all years. It is believed that this is also not required, for the following reason:

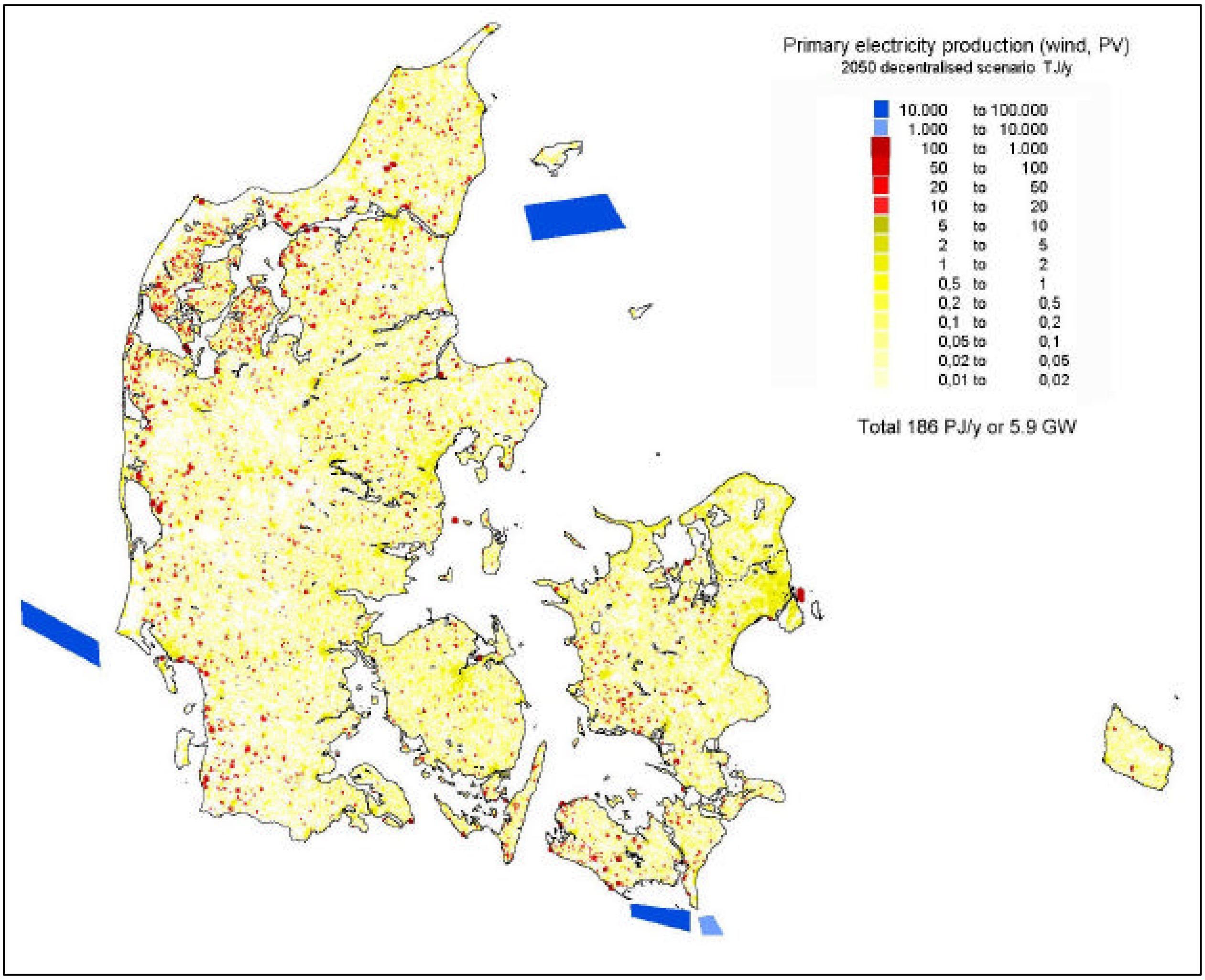


Figure 13. Renewable production of electricity in the decentral 2050 scenario, in analogy to that of the centralised scenario shown in Fig. 10. Due to smaller demand, the overall production is also smaller in the decentralised scenario.

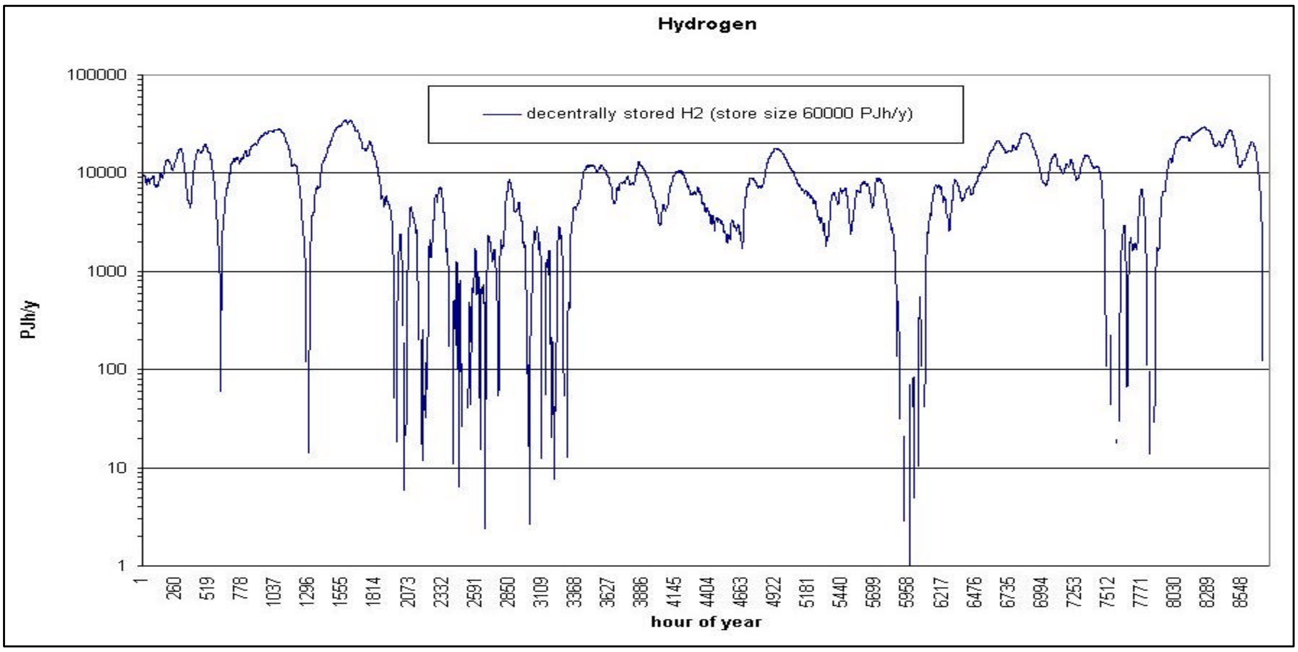


Figure 14. Decentralised scenario: Variations over the year 2050 in filling of all hydrogen stores combined, for reference case.

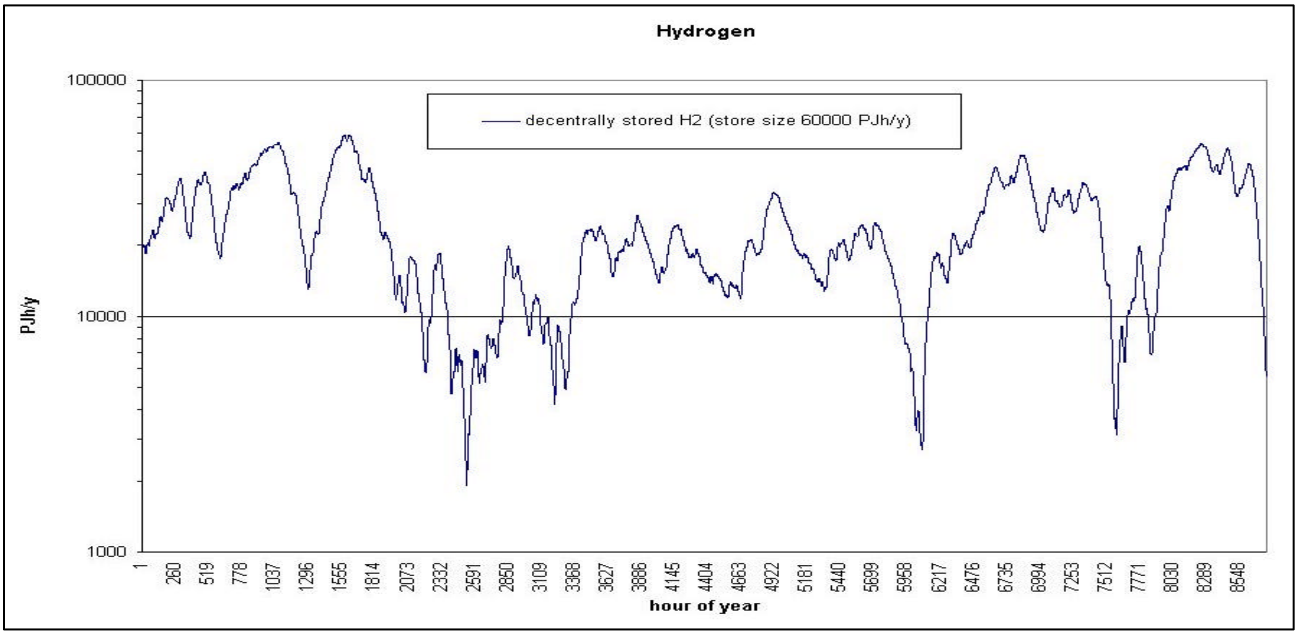


Figure 15. Modified decentralised scenario: Variations over the year 2050 in filling of all hydrogen stores combined, with offshore wind power production increased to 180 PJ.

The picture of the transport sector organisation is similar to Fig. 11, except that private cars are mainly filled in the garages of buildings. Further, the transportation energy totals are less in the decentralised scenario: 46 PJ/y hydrogen, 18 PJ methanol and 5 PJ electricity.

5. Discussion.

As noted the total energy production is the two scenarios is not identical. The higher end-use demand assumed in the centralised scenario (281 PJ/y) reflects the more conventional nature of this scenario, where a tendency has long been noticed: that many people are willing to pay the often higher price for new energy provision technology than they are for energy efficiency technology maintaining the same end-use service at a lower price. The decentralised scenario, on the other hand, assumes a rational social policy and consumer behaviour, in which energy efficiency measures are properly ranked relative to new supply options. This reduces the end-use energy demand to 186 PJ/y) and allows the system to work with a lower primary production. However, it is not necessarily cheaper, because the decentralised fuel cell and storage units may well be more expensive per kW of rated power than centralised ones. Still, they may be preferred because of the customer appeal of being your own energy producer, both as regards electricity, heat and motor fuels.

The critical items for the introduction of hydrogen in the future energy system are cost and inertia in infrastructure. The fuel cell costs have over the last 5 years changed from about 7 euro/W to 30 euro/W, with an expectation of a price fall the coming years, due to heavy research, development and commercialisation investments over the past couple of years. Yet, the fuel cell technology is not so different from that of e.g. lithium ion batteries (polymer membranes, catalysts at electrodes), which has not fulfilled the hope of price decline making such batteries of interest for applications other than small scale consumer electronics. The solutions to technical problems of stability and lifetime are likely to involve additional costs, and a cautious guess is that the price may drop by a factor of 5-10 over the next decade, provided that demand allows suitable mass production. This does not bring the price down to current alternatives, even including environmental externalities, and it would not seem that the conditions for accepting such prices could be established before actual fuel shortages increase the cost of fossil fuels. It is thus for good reasons that the scenario work described above looks at a 50-year period for a complete turnover of the energy system.

The question of infrastructure change will pose an initial barrier to introduction of centralised hydrogen, whereas the concept of decentral hydrogen utilisation may evolve naturally from an initial introduction of building-integrated fuel cells based on natural gas, to be later replaced by reversible fuel cells producing and using hydrogen and thus making the building ready for total energy supply including filling of hydrogen-based vehicles belonging to the owners, occupants or guests of each building.

References

[1] Danish Department of Energy (1999). *Energy 21* (plan scenario, action plan 1998 and update 1999). Government Press, Copenhagen.

[2] Sørensen, B., Petersen, A., Juhl, C., Petersen, T., Ravn, H., Søndergren, C., Jørgensen, K., Nielsen, H., Larsen, H., Morthorst, P., Schleisner, L., Sørensen, F. (2001). Scenarier for samlet udnyttelse af brint som energibærer i Danmarks fremtidige energisystem. IMFUFA Texts No. 390 from Roskilde University, Institute 2.

[3] Kuemmel, B., Nielsen, S., Sørensen, B. (1997). *Life.cycle assessment of energy systems.* Roskilde University Press, Copenhagen.

[4] Sørensen, B. (2000). *Renewable Energy, 2nd ed.*, Academic Press, London and San Diego. (3rd. ed. expected in 2004 by Elsevier Science)

[5] Sørensen, B. (2004). *Hydrogen and Fuel Cells.* Academic Press/Elsevier (expected late 2004 or 2005).

[6] DONG (2003). Naturgaslagrene i Ll. Thorup og Stenlille, http://www.dong.dk/dk/publikationer

[7] Zittel, W., Würster, R: (1998). Hydrogen in the energy sector. Hyweb knowledge report at website http://www.hyweb.de/knowledge/w-i-energiew-eng.html

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