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Sørensen, Bent

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UNDERGROUND HYDROGEN STORAGE IN GEOLOGICAL FORMATIONS, AND COMPARISON WITH OTHER STORAGE SOLUTIONS

BENT SØRENSEN

Roskilde University
Department of Environmental, Social and Spatial Change
Energy, Environment and Climate Group, bld. 27.2
Universitetsvej 1, DK-4000 Roskilde Denmark
boson@ruc.dk http://mmf.ruc.dk/energy

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Abstract: Storage of hydrogen in geological formations has been considered in connection with large-scale use of hydrogen, as well as for storage and regeneration of electric power from intermittent renewable sources such as wind energy. Candidates are salt domes, aquifers and rock cavities. The two first ones are in use for natural gas storage, e.g. in Denmark. The present study looks at the conditions for storing hydrogen in such formations, rather than methane. Key questions are permeability of surrounding layers (typically cap rock or in the Danish case clay) and integrity of the formation. It is concluded that hydrogen storage with minimal losses can be achieved by lowering the pressure relative to that used for natural gas storage. Energy modelling and determination of balances for storage with regeneration of electric power and with direct use of hydrogen e.g. in the transportation sector is discussed.

1. Introduction

Geological hydrogen storage is one of the most promising technologies for large-scale storage at low cost. Other possibilities comprise storage in canisters, incorporation into metals or advanced hydrides, possibly in the form of ammonia. If alternatives are taken to include all ways of storing excess electric power for use at a later time where production is insufficient to cover demand, comparison must be made also with storage options such as (advanced) batteries, compressed air and pumped hydro, to mention just a few [1-3]. The merit of underground hydrogen storage relative to several of these other options is a central theme to this study. The following sections discusses the stability of geological hydrogen storage, the practical set-up of operation and, by use of simulation models, the performance that may be expected from such storage facilities if incorporated into specific energy systems. The concluding section then sums up the status of the underground storage options relative to other possibilities.

2. Geological hydrogen storage: description of technologies and general appraisal

Two technologies are currently in use for storage of large amounts of gases. One is storage in aquifers, i.e. water carrying layers capped with impermeable layers above and preferably also below the layer into which hydrogen may be pumped so as to replace water. Typically, there would be clay layers with a sand layer in between. The geometry of the sand layer and its contained water would have the form of a waving structure, with some bends that curve upward. These are the locations where a gas such as hydrogen may be pumped into the geological structure, thereby displacing water but still be confined due to the pressure of the water below, when the curvature is such that the gas cannot “run” away to the sides. Decisive parameters are the permeability of the water-carrying layer and of the enclosing clay layers, where the latter determines the leakage rate of the gas. Further, the integrity of the structure, e.g. in terms of forming an unbroken upward bend, would determine the rate of losses to the sides. Finally, adsorption or other penetration of the gas, here hydrogen, into the water will have to be considered generally, in order to determine the maximum length of time, that the gas can be expected to remain in the store.

Models of aquifer performance have been proposed, including all the variants mentioned above with complete or partial confinement (see, e.g. [3] for confined volumes, [5] for semi-confined aquifers, and [6] for side-wise incompletely confined ones). All the modes of loss mentioned above have been observed [7]. Stability of the store is influenced by the pressure used (which must at least equal the hydraulic pressure at the depth of storage) and by variations in pressure during charge or discharge, as well as by temperature variations such as increases during compression and injection, which in most installations have to be reduced by use of cooling devices [1].

The other technology in use at present (for natural gas storage) is deposit in cavities created in salt domes, i.e. intrusions of geological salt layers towards the atmospheric surface. Such cavities can be formed by the inexpensive method of flushing with water, following which it may be necessary to seal the inside walls, depending on the integrity of the salt structure [8]. For leakage through the salt itself, modelling similar to the one for aquifers can be performed [9]. If the integrity of the salt formation is low, canisters lowered into the flushed holes may be used, in order to completely eliminate the leakage problem, albeit at a cost. For most installations, the salt itself constitutes a sufficient barrier to avoid leakage.

Other options for avoiding excavation of cavities for storage are to use abandoned mines or oil/gas wells and proceed as for salt domes, with or without lining. Finally, if no inexpensive cavity formation is possible, one may create artificial cavities in whatever geological formation is present, e.g. by fracturing rock formations. This option has the highest cost.

3. Modes of using geological hydrogen stores

Diurnal capacity natural gas stores have been used to avoid adjusting production to demand, and more substantial underground stores to insure against pipe disruption, e.g. in Denmark that presently derives its natural gas from fields some 300 km out in the North Sea. It is estimated that repairing a severed sea-floor gas pipe could in the worst case take two months, and it is therefore required that gas is stored in an amount of minimum two months of average demand. One of the two Danish stores, in Lille Thorup, is based on 7 cylindrical holes flushed out of a salt deposition at a depth of 1270-1690 m. It operates at a pressure of 16-23 MPa, a temperature of 40-50°C, and has a storage capacity of 445×10^6 Nm^3, i.e. the volume in m^3 that the gas would have at standard temperature and pressure. The actual cavern volume is 57% larger then the operating volume, because a minimum of gas is required to push gas up to the surface for use. The other Danish gas store is an aquifer facility at Stenlille, with an operational volume of 360 Nm^3 but a total volume as large as 1160 Nm^3 [10].

In the future, storage of gases such as hydrogen in similar facilities are expected to be required primarily when intermittent renewable energy sources constitute a large fraction of a country's energy supply. To be on the safe side with the smaller hydrogen molecule, the storage pressure should be lowered compared with that used for natural gas, but 5-10 MPa should be feasible. For example, the Danish installations securing two month of natural gas supply would be more than sufficient as backup for similar or even larger amounts of wind energy, the intermittency of which rarely requires more that 10 days of storage [1, 2].

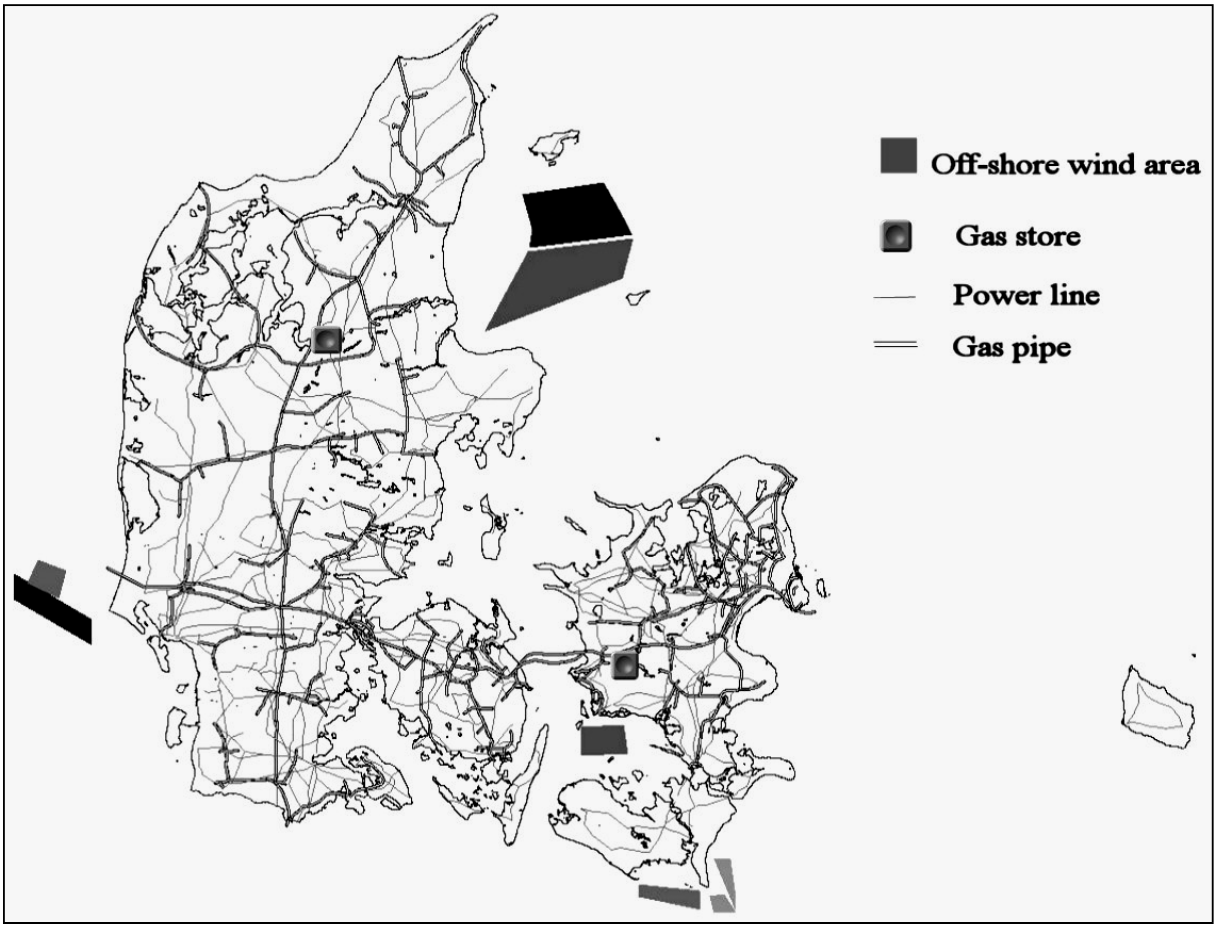

Figure 1. Location of areas designated for off-shore wind parks in Denmark. Existing gas stores and transmission lines for gas and electricity are also indicated.

The set-up of a primarily wind-based power supply system in a country such as Denmark would imply constructing wind turbine parks particularly at the off-shore sites already assigned for such use (the first two such parks are operating and two more decided). Transmission lines between the off-shore locations and the locations where excess power would be transformed into hydrogen for underground stores (by electrolysers, e.g. of alkali, PEM or SOFC type [1]; the stores could be the two existing ones currently used for natural gas, or other ones established in one of several salt dome intrusions and aquifers available) would have to be reinforced, which is a minor cost in the overall picture. Figure 1 shows the locations of wind turbine sites (on- and off-shore) as well as the two existing stores and transmission lines for power and gas.

4. Simulation of the performance of future energy systems with hydrogen storage

Several scenario simulations have looked at various options for meeting all energy demands by renewable energy, both on a global level [2], on a European Union level [11] and on a national level (for Denmark, [1]). The results presented here are from a new, ongoing simulation study of hydrogen storage and energy trade in a regional system comprising Germany and the Nordic countries (except Iceland, because it is not part of the current power exchange scheme) [12]. The scenarios consider various demand developments, all of which, however, assumes economic rationality in the sense that most energy efficiency measures costing less than the energy use they avoid will be implemented before the scenario year 2060. The reservation "most" pertains to equipment with a natural lifetime over 50 years, which in practice means a percentage of buildings, and where some retrofitting is assumed to take place, but not achieving the efficiency that could be achieved in a new building. Generally, efficiency improvements are made when equipment has to be replaced anyway. The energy demand assumptions of the middle Danish scenario for 2060, which will be used here, are shown in Figure 2, for energy delivered to end-users in the energy form specified. The transportation energy is divided equally between fuel cell and biofuel vehicles, but the contributions differ due to the assumed efficiency difference, 36% for fuel cell vehicles and 26% for biofuel vehicles.

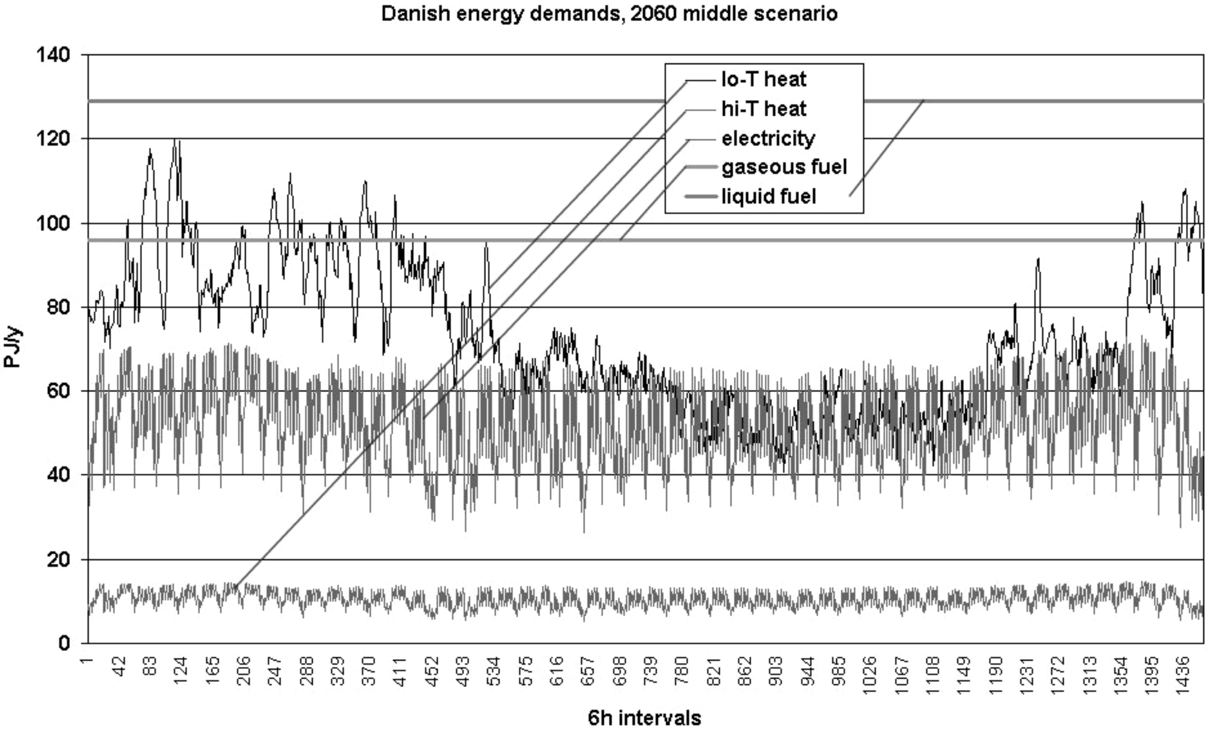

Figure 2. Danish energy demands assumed in the 2060 scenario.

To cover the 2060 demands, 245 PJ/y of wind power is assumed to be produced, on- and mostly off-shore (at the locations shown in Figure 1). This is considerably below the potential identified but still 10 times more than the current production. Further, 82 PJ/y of biofuels are produced based upon residues from agriculture, forestry and some aquaculture. The potential is here far greater (322 PJ/y, thus constituting an export potential), because Denmark is a large exporter of agricultural products produced is quantities far above the indigenous needs. Biofuels are primarily covering needs in the transportation sector, while electricity from wind is covering direct electricity demands, hydrogen production, high-temperature process heat (by electric furnaces) as well as low-temperature heat (by heat pumps). During hours of insufficient wind production, biofuels are burned, preferably in combined power and heat plants or else in boilers, to provide the electricity and heat deficits. The disposition of wind power is shown in Figures 3 and 4, while that of the produced hydrogen and of biofuels is shown in Figures 5 and 6.

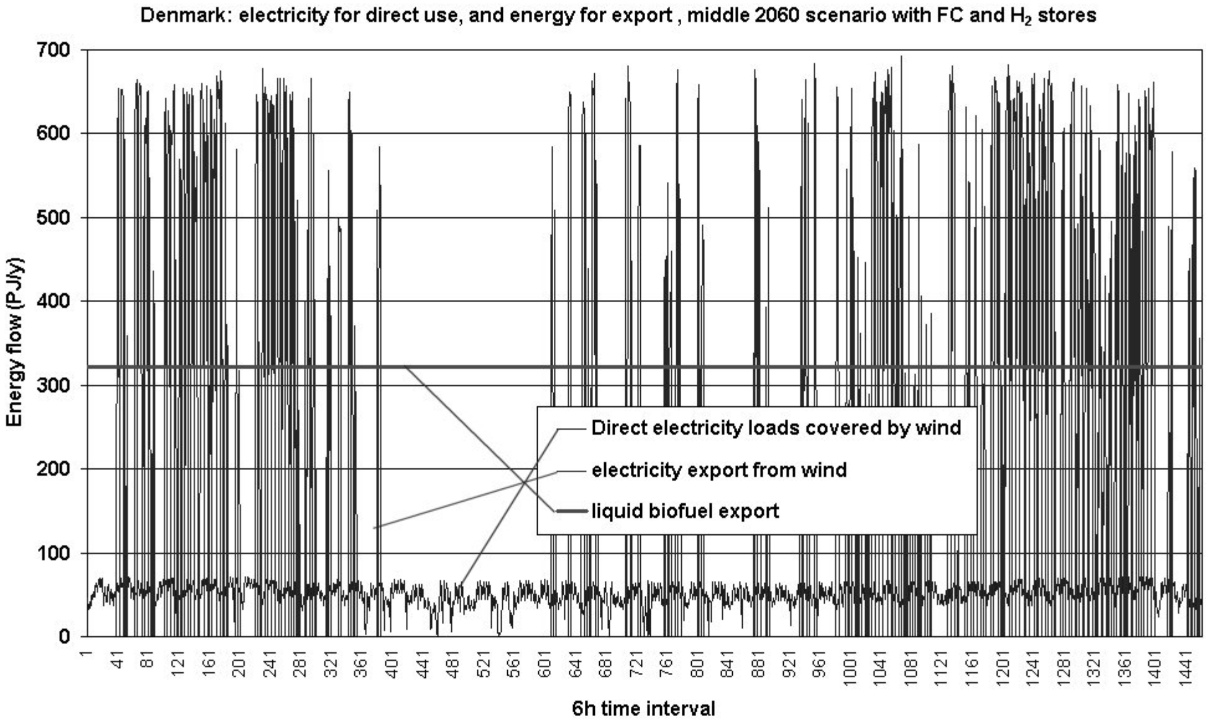

Figure 3. Danish wind power used to cover dedicated electricity demands, and amounts available for export after coverage of the indirect needs shown in Figure 4. Further the potential production of biofuels beyond what is required to satisfy Danish demands is shown.

It is seen from Figure 3, that wind power production (as given by the data taken for the year 2000 [13]) is low during a period in April and May, where even the direct electricity demand cannot always be met (dips to zero in the otherwise load-following curve). During other parts of the year, there is a surplus of wind power production, which may be exported to neighbouring countries connected to Denmark by transmission grids (notably Germany, which is less well endowed with renewable power than the Nordic countries).

The indirect uses of wind power for covering heat demands and for producing hydrogen, mainly for the transportation sector, is shown in Figure 4. The occasional dips in low- or high-temperature heat production indicate hours where additional sources are required. These demands are covered by use of biofuels or stored hydrogen (Figure 5). The hydrogen production is irregular because of the irregularity of the high-wind periods that provide surpluses for such transformation, and a hydrogen storage system is required. This will be discussed below in connection with Figure 7.

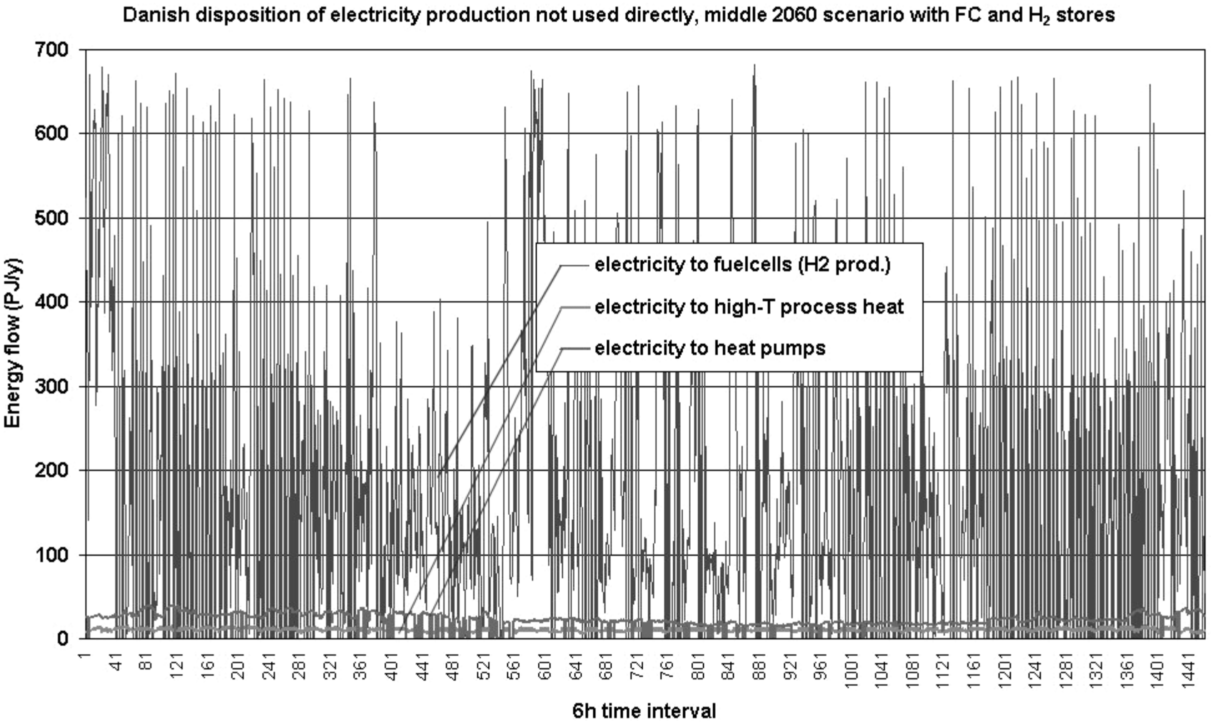

Figure 4. Non-direct uses of electric power in the 2060 Danish scenario. A large and irregularly available surplus is used to produce hydrogen by electrolysis, while a more stable production is taken place of high- temperature heat in electric furnaces and low-temperature heat by use of heat pumps with their environmental reservoir taken as soil or water streams.

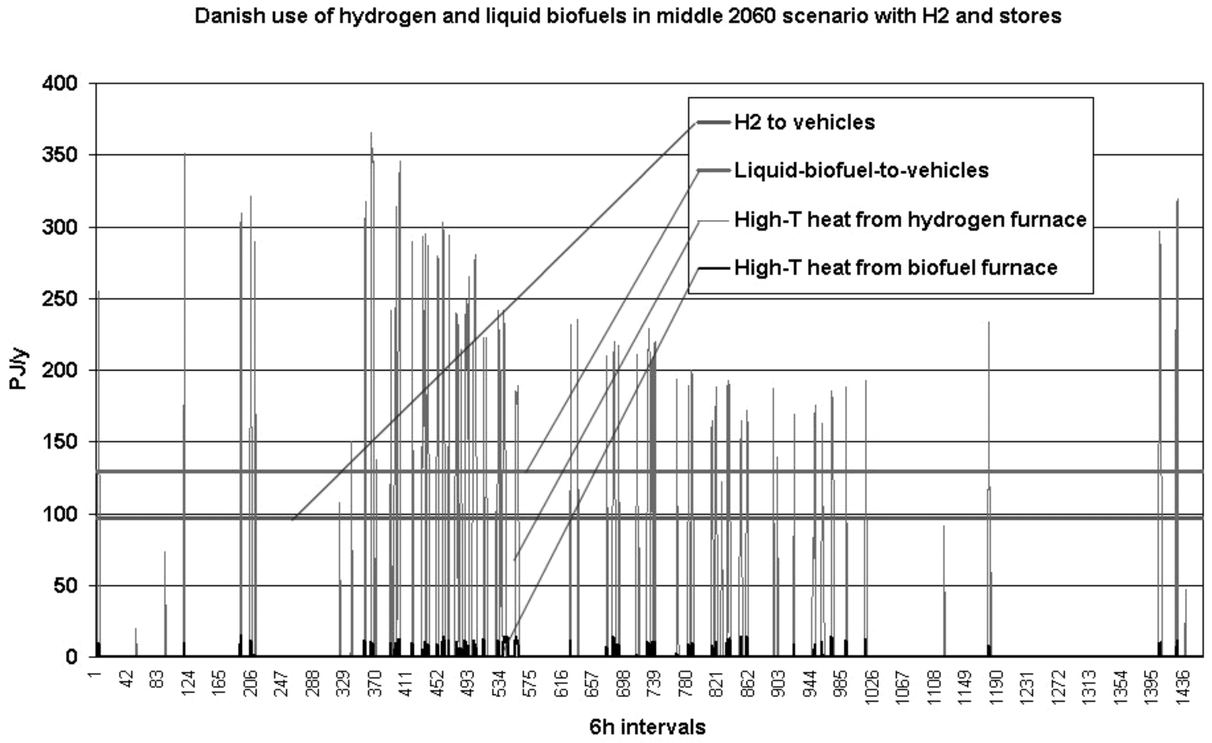

Figure 5. Disposition of hydrogen produced by excess Danish wind power, and biofuels.

In Figure 5, the demand for hydrogen and liquid biofuels from the transportation sector is indicated, along with the mentioned uses of such fuels for covering deficits in heat demand. Biofuels are derived from agricultural residues, i.e. the energy use is not in competition with food production, from forestry management (again only sustainable practices of removing residues are included), and from aquaculture such as algal growth in fenced ocean segments.

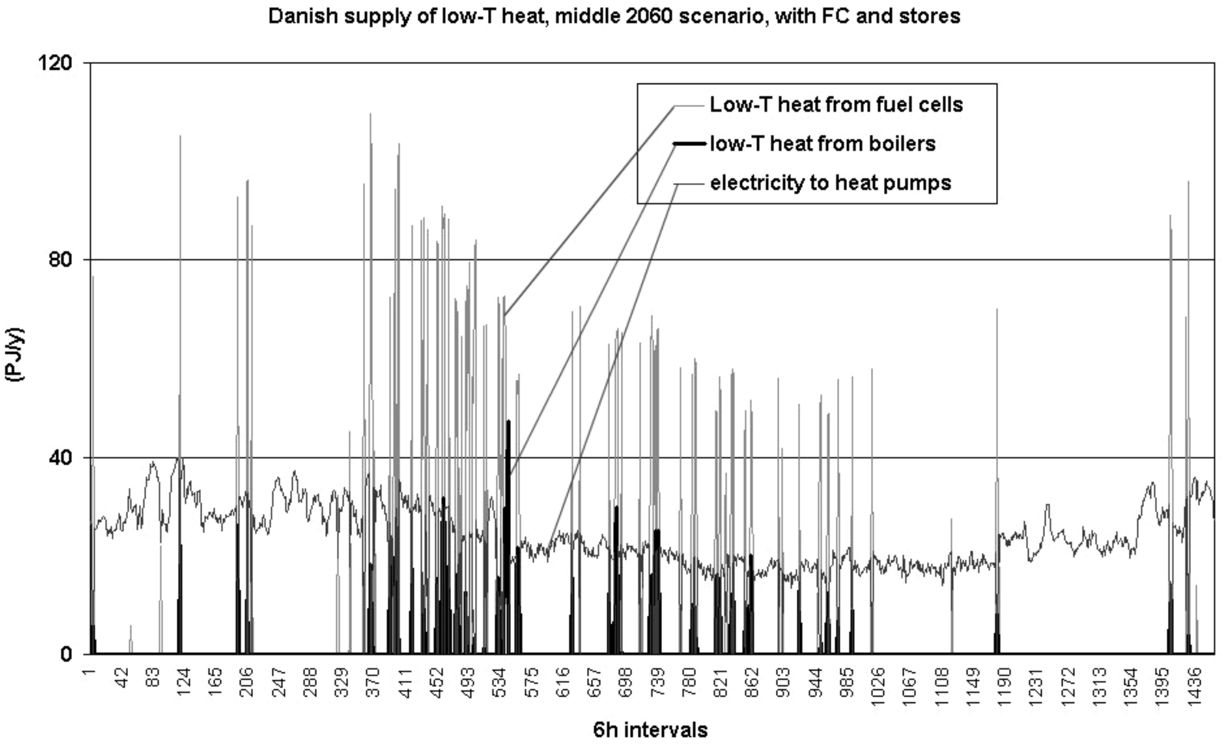

Figure 6. Supply of low-temperature heat in Danish 2060 scenario.

The Danish supply of low-temperature heat is further detailed in Figure 6. A fairly stable heat supply is derived from the heat pumps (better visible in Figure 6 than at the scale used in Figure 4), using a very moderate amount of electricity due to the high coefficient of performance COP (the ratio between heat output and power input), exceeding 4 for systems with soil or water as the environmental reservoir. Low-cost technologies for establishing the pipe-system e.g. below garden lawns (without digging or interfering with vegetation at the surface) have become available, and even for the less efficient air-to-air heat pumps, COP-efficiencies of the best current equipment are reaching values of about 4. Figure 6 also indicates a number of hours, where it is necessary to produce high-temperature heat (e.g. for industry) by furnaces using hydrogen (produced earlier by wind in fuel cells and stored). Even that fails during a few hours, where industrial boilers using biofuels are used, due to the limitations placed on the amount of installed hydrogen storage.

The variations in filling of the hydrogen stores are shown in Figure 7. It is seen that the unusually long period in April-May with low winds empties the storage caverns and necessitates the use of backup from biofuels as described above. Alternatively, store sizes could of course be increased, but it was decided that the additional cost would not be warranted due to the rare occurrence of wind lulls of duration more than 3 weeks. During the rest of the year, store filling is close to maximum and closest in winter.

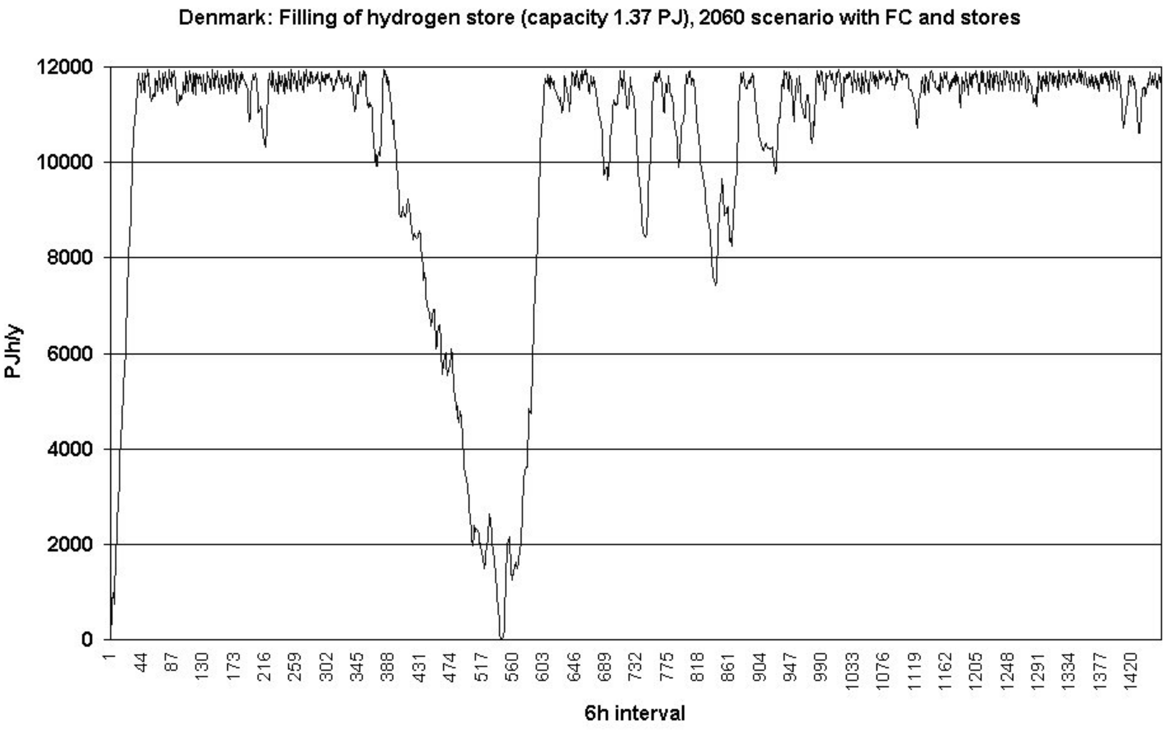

Figure 7. Variations in filling of Danish hydrogen stores, assumed to have a maximum combined capacity of 1.37 PJ (or 12000 PJh/y as indicated).

5. Conclusions and comparison with other storage solutions

Options other than geological storage in consideration for hydrogen include compressed gas storage in standard canisters made of steel or composites. These are more expensive and mostly suited for automotive storage. Storage in liquefied form (at low temperatures) is further expensive and lossy because of the required energy supply for liquefaction and the need to boil off hydrogen due to pressure variations associated with the orto-to-para molecular structure transitions in low-temperature hydrogen [1]. Finally, a number of high-density storage options are associated with incorporation of hydrogen in metal lattices (as hydrides) or into more complex chemical structures. Although promising, several of the schemes considered today have problems of stability or of getting the hydrogen into and out of the confining structure at the rates required (particularly for automotive applications).

For these reasons, alternatives to geological storage of hydrogen are often rather seen as alternative ways of transforming electric power and regaining it, without the use of hydrogen. These methods are at a disadvantage, if hydrogen is a necessary fuel in the future energy system, but would otherwise be attractive. The issue if therefore basically, if hydrogen-fuelled fuel cell vehicles are a must in emerging sustainable energy systems, or if hydrogen just could perform the more limited role of serving as a store for excess electricity that needs to be available at a later time, but still in the form of electricity. In the latter case, pumped hydro (into high-lying reservoirs) or compressed air stores may be of interest, especially in geographical regions with natural reservoir-based hydropower. Flywheels and batteries have so far been restricted to short-time storage and small-scale applications, but there are developments in progress that could bring advanced batteries such as lithium-ion batteries into use in the power supply sector [2].

The conclusion that geological storage appears as one of the most viable hydrogen storage options should of course be backed by actual cost estimates. Some such estimates based on US installations have been made at a while ago [14, 15], indicating an added cost to hydrogen having gone through an underground store in the range of 2-6 US$/GJ for storage times up to about a month (precisely what is required for wind power). One of the Danish natural gas stores (salt dome based) were recently sold to the net-operating company at the request of the European Commission, prompted by its anti-monopoly legislation, at a price of 60 euro per GJ of storage capacity [10]. The cost of producing the cavities by flushing is quoted as 15 euro/GJ by the company establishing the store [16], and the rest would be over-ground installations, the cost of the 300 Nm^3 non-extractable natural gas-filling and probably some market mark-up. Levelised over a lifetime of 30-50 years this agrees well with the US figures.

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