Geological hydrogen storage

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Abstract

The probably least expensive form of hydrogen storage would be geological storage in formations easy to excavate, such as salt dome intrusions near the surface (which can be excavated by water flushing) or vertically curved, capped aquifer layers not requiring excavation at all. Such geological formation are already in use for natural gas storage and have proven very stable. Consideration of hydrogen diffusion through the associated cap layers (typically clay) suggests that hydrogen can be stored at pressures somewhat lower than those used for natural gas. Estimates of cost and methods of store construction will be given.

The storage of hydrogen is of interest both in an energy system using hydrogen as an energy carrier (e.g. in connection with fuel cell vehicles) and also in an energy system with large contributions from renewable energy sources that cannot be stored, such as wind power or solar power. Scenarios for an energy system using either of these methods have been constructed and one will be presented. The scenario technique allows a calculation of the amount of storage needed for smoothing the effect of intermittent source flow out of phase with variations in energy demand. It will be shown that for wind power, the required store size for dealing with the variations in wind is only typically a few weeks of average electricity usage. In case hydrogen can also to be used directly, e.g. in the transportation sector, additional surplus power can be converted to hydrogen and thereby diminishing the requirement for centralised storage. If the primary source is solar power, the required storage period may be substantially larger, especially at high latitudes where the solar availability exhibits strong seasonality.

1. Introduction

For storage of intermittently produced power that is to be used later as electricity, geological hydrogen storage seems one of the lowest cost storage solutions, especially if reservoir-based hydro is not present in the region considered. Using alkaline fuel cells ("electrolysers") to produce the hydrogen and conventional gas turbines to regenerate power, the cycle efficiency would be under 40%, but it may increase to some 65%, if high-temperature reversible fuel cells (operated in electrolyser mode to produce hydrogen and in electricity generation mode to produce power) become available at reasonable prices. Competing technologies include batteries, which are currently as expensive as fuel cells, and compressed air storage, which is operational but has at least as low a round-trip efficiency as the hydrogen store without reversible fuel cells (Sørensen, 2004; 2007a).

The situation is different in case hydrogen becomes viable as a general energy carrier. This would entail a demand for hydrogen in several user sections, such as transportation or industry. Consequently, the hydrogen created from surplus renewable energy may have direct uses, implying that the system efficiency increases, because only a part of the hydrogen has to be converted back into electricity. Viable hydrogen vehicles will almost certainly be hybrids with a modest-size fuel cell (presumable of PEM-type) and an equally modestly rated store of advanced batteries (plus an electric motor with full power rating). These could be stand-alone hybrids, where the batteries are charged by the fuel cells operating at optimum efficiency (more or less full rated power), independent of traction requirements, and the vehicle is entirely operated on power from the batteries. Such vehicles would need only fuelling at hydrogen filling stations. The alternative would be plug-in hybrids, where the batteries may also be charged from the mains, when the vehicle is not in operation. The plug-in technology could, if charging can be managed to favour periods of surplus electricity production, further reduce the need for energy storage capable of regenerating electricity.

Simulations of future energy systems with 100% renewable energy inputs and hydrogen as a storage medium or a full-scale energy carrier have recently been performed for a group of countries in the North of Europe (Sørensen, 2007b,c,d,e,f). The conclusion of that investigation is that the Nordic countries could generate enough energy to cover both their own needs and the deficit found in Germany, and that very little hydrogen energy storage is required (one week of average consumption in Denmark, the other Nordic countries using the existing elevated water storage). Trade of energy between the countries considered will be substantial, but displacing the even larger current trade of fossil fuels with supply countries of dubious stability.

In the present paper, the discussion of geological storage options and conditions will be followed by a preliminary simulation study for the North American continent, offering new challenges and opportunities for the combination of renewable energy with hydrogen usage.

2. Geological hydrogen storage

Geological formations 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. (www.energinet.dk, 2007) 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 (Sørensen, 2005).

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. For leakage through the salt itself, modelling similar to the one for aquifers can be performed. 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 (Sørensen, 2007f).

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.

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 (www.energinet.dk, 2007).

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 (Sørensen, 2005; 2004).

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 (Ogden, 1999; Venter & Pucher, 1997), 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 (www.energinet.dk, 2007). The cost of producing the cavities by flushing is quoted as 15 euro/GJ by the company establishing the store (Petersen, 2006), and the rest would be overground 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.

3. Renewable energy scenarios for northern America

Figure 1 shows the wind power potential for North America, based on blended satellite scatterometer and reanalysis circulation model data (Sørensen, 2007c). The potential wind power that can be derived from very modest land of near-shore locations is given in Figure 2. Similarly, Figure 3 gives potential biomass production based on the model developed in Sørensen (2004), with consideration of irradiation, precipitation and soil nutrients. No artificial irrigation is assumed in Figure 3, but the model indicates about a doubling of yields with irrigation. Other renewable sources include solar power and heat, modelled as in a previous model for Europe (Sørensen, 2004; Sørensen, 2005; Sørensen, 2007d), hydro (taken at current level) and smaller sources such as geothermal, wave and tidal, which have not been included.

4. Simulation for a future carbon-free energy system for the United States

A few preliminary simulations have been carried out for the United States. Direct generation of electricity by hydro, sun and wind is insufficient for both covering power needs, possibly including high-temperature process heat and also generate hydrogen for a part of the vehicle fleet. However, the generation of liquid fuels from biomass resources derived from agricultural and forestry residues (all of which can be used and still serve most of their current functions in forestry management and nutrient recycling to fields), and possibly by additional aquaculture activities (e.g. using the waters between off-shore wind turbines) more than covers the need for such fuels and allows the USA to be self-sufficient, provided that the best available technology is used to achieve a high standard of energy conversion efficiency for all types of conversion. If hydrogen fuel-cell vehicles are considered more attractive that biofuel operated ones, an alternative would be to import the necessary electric power for electrolysis from neighbouring countries, notably Canada. The alternative of creating hydrogen from biomass residues is also available, albeit at a fairly low overall efficiency.

Figure 4 shows the essential energy demands, Figures 5 and 6 the insufficiency of geological stores (for hydrogen and for water) to improve the situation without assistance, because there is not enough energy of the types of interest for the stores and not because of insufficient storage capacity. Figures 7 and 8 shows how both power and heat can be supplied in full coverage of demand, drawing on a mix of resources and conversion methods, but with the surplus of biomass as the final agent to get the ends to meet, in the scenario illustrated, which is the one with only liquid fuels in the transportation sector and just a small number of (high-temperature) stationary fuel cells within the mix of technologies serving to make energy available as needed, despite the intermittency of some of the renewable resources.

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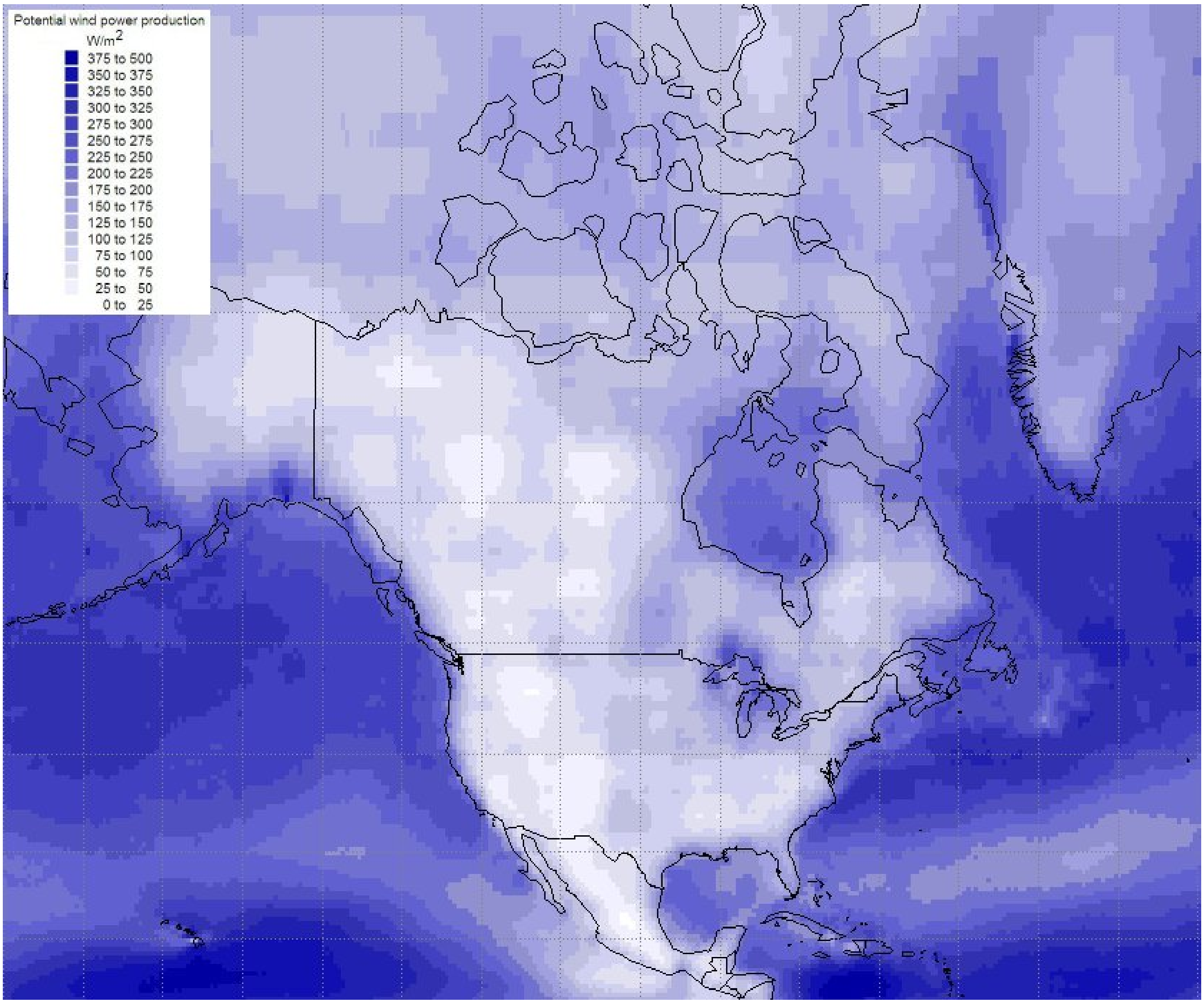

Figure 1. Potential wind power production in North America.

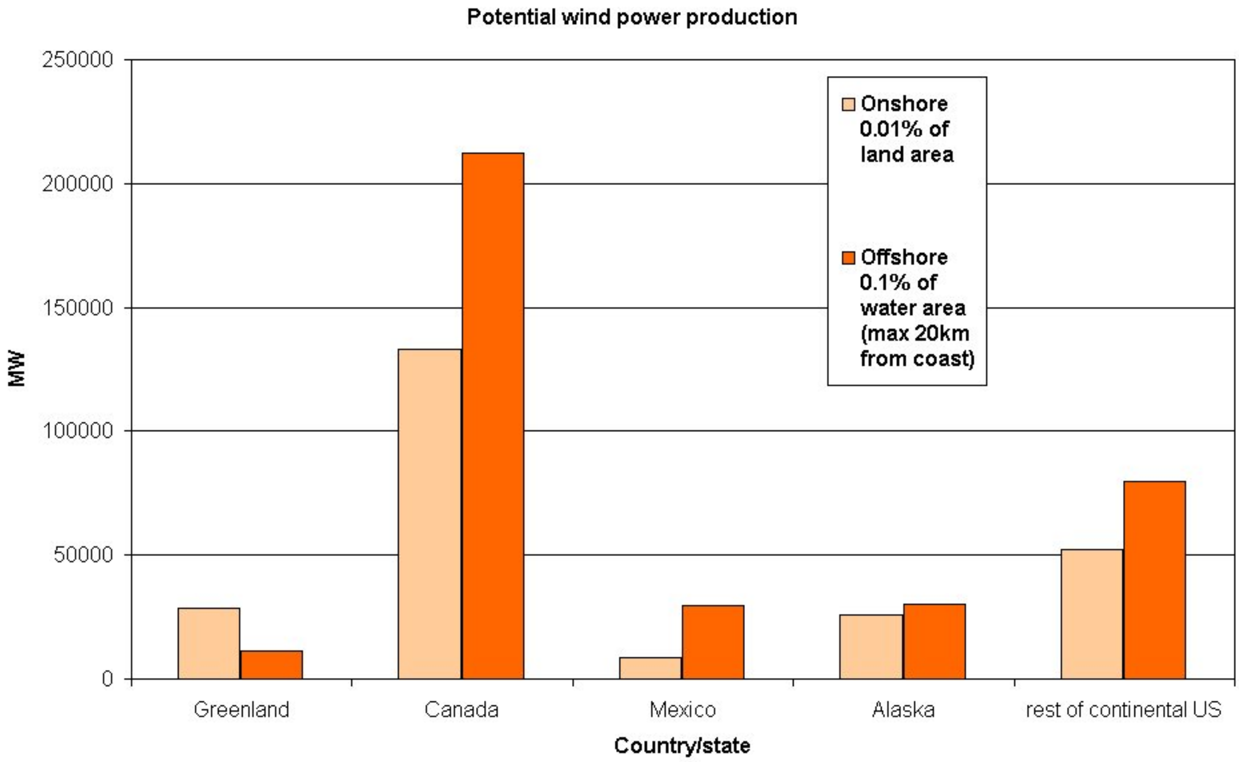

Figure 2. Power derived from a practical usage of wind resources in North America.

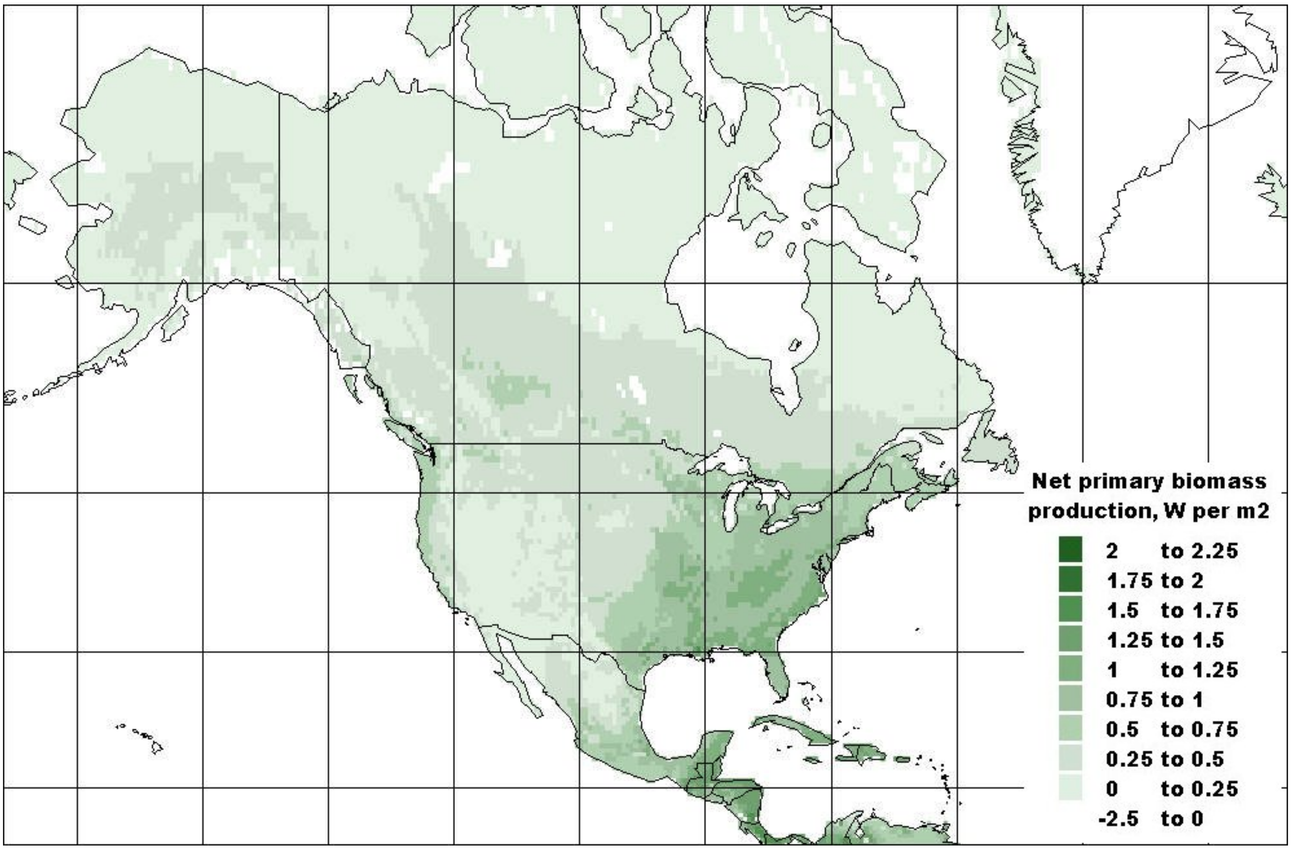

Figure 3. Potential biomass production in North America (without artificial irrigation).

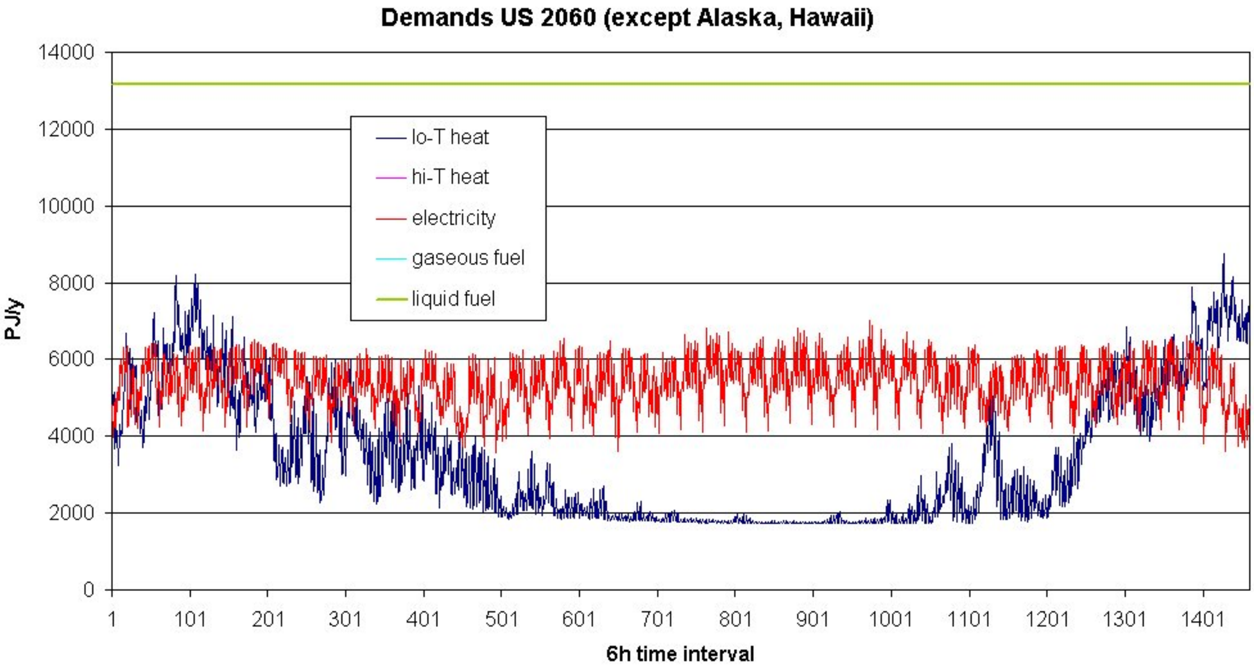

Figure 4. US (Alaska and Hawaii not included) energy demands in 2060 model with emphasis on efficient use of energy. In one scenario, the transportation sector is only demanding liquid fuels, while in a second scenario, half of the transport work is supplied by hydrogen fuel cell vehicles. Process heat is assumed to all-electric and is included as electricity, along with space cooling energy needs. Space heating and other uses of low-temperature heat has also been combined.

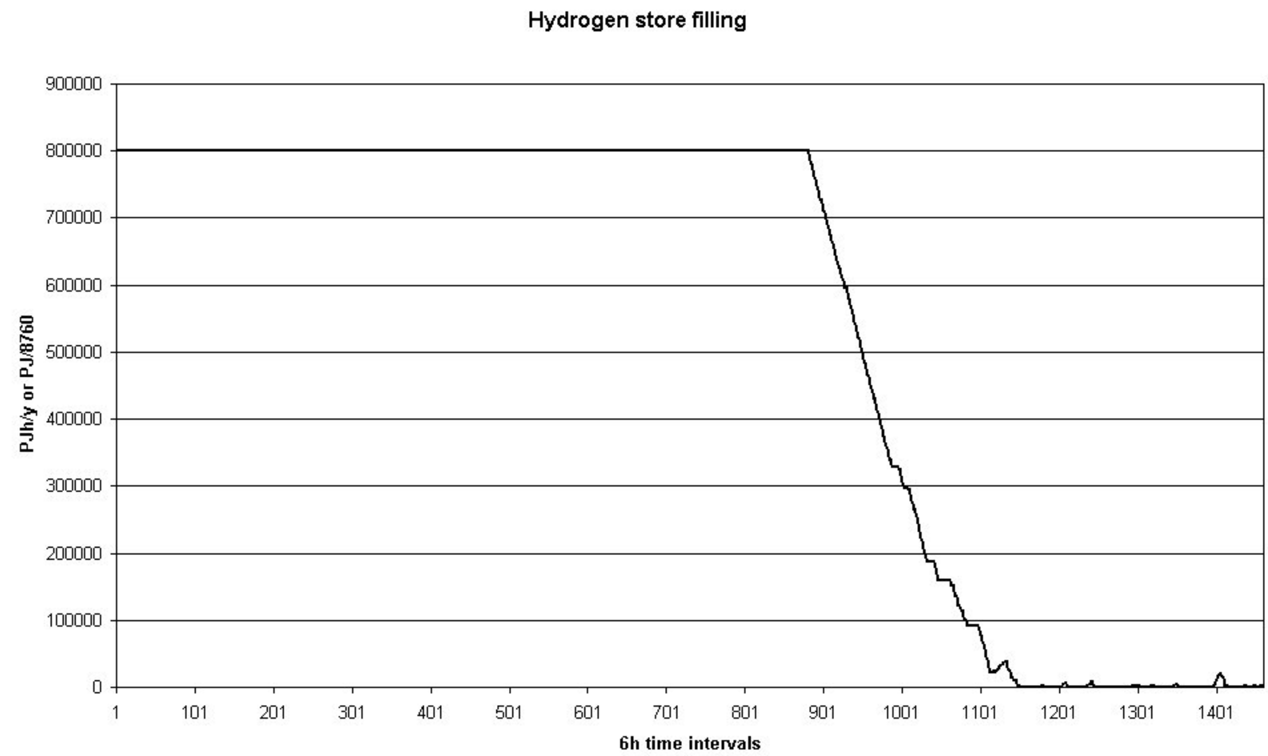

Figure 5. Filling of geological hydrogen store as function of time during a typical year.

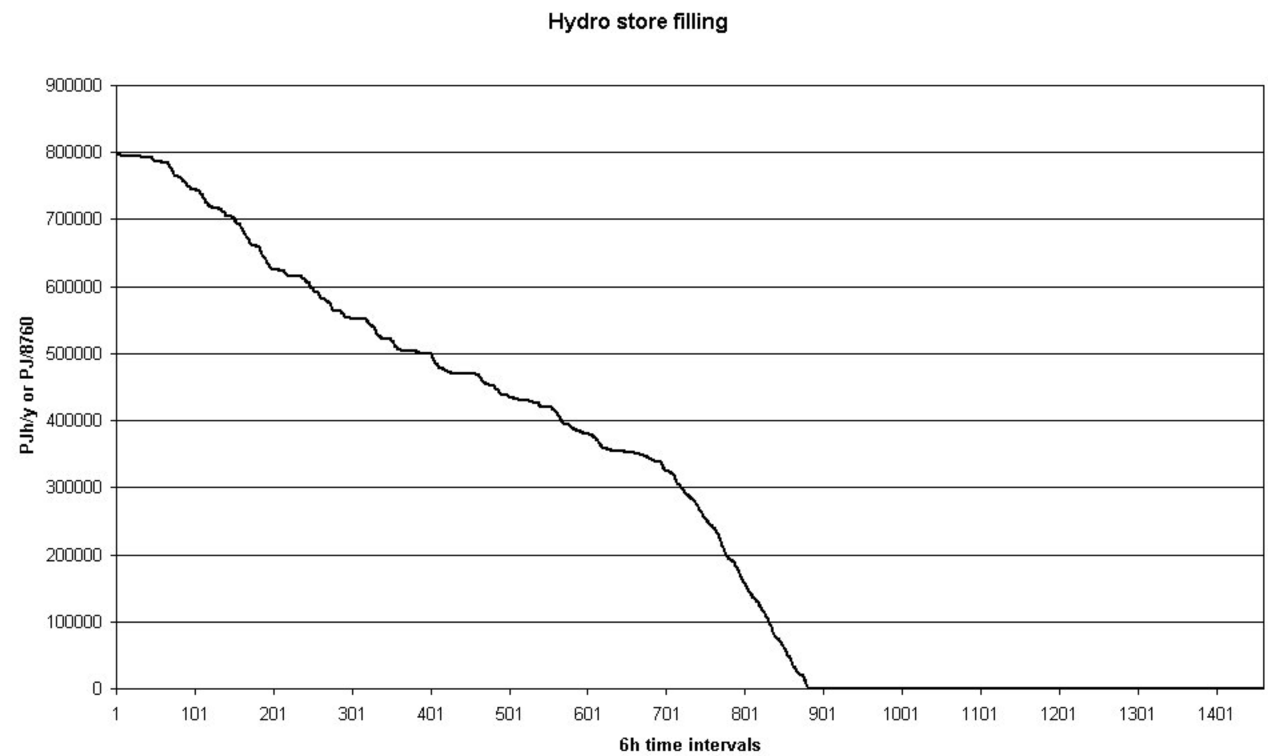

Figure 6. Filling of hydro reservoirs aas function of time.

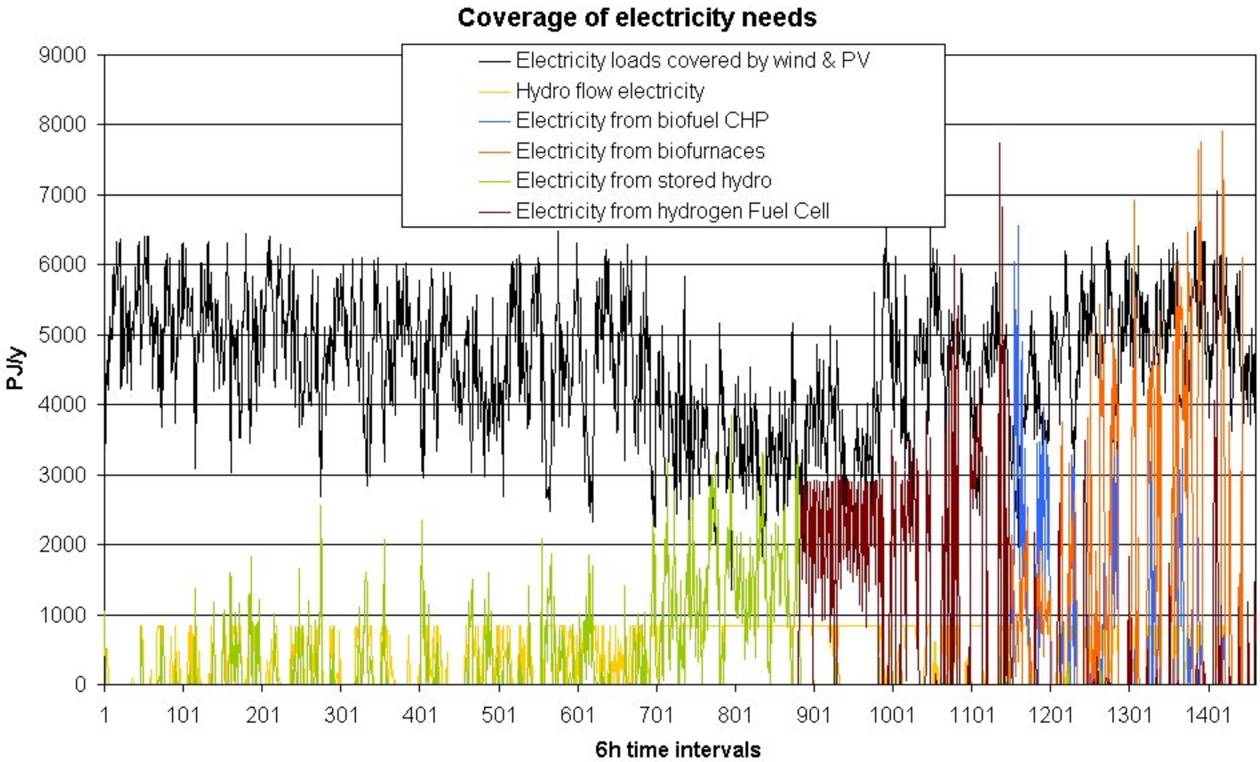

Figure 7. Contributions to fulfilling electricity needs in the year 2060 US scenario.

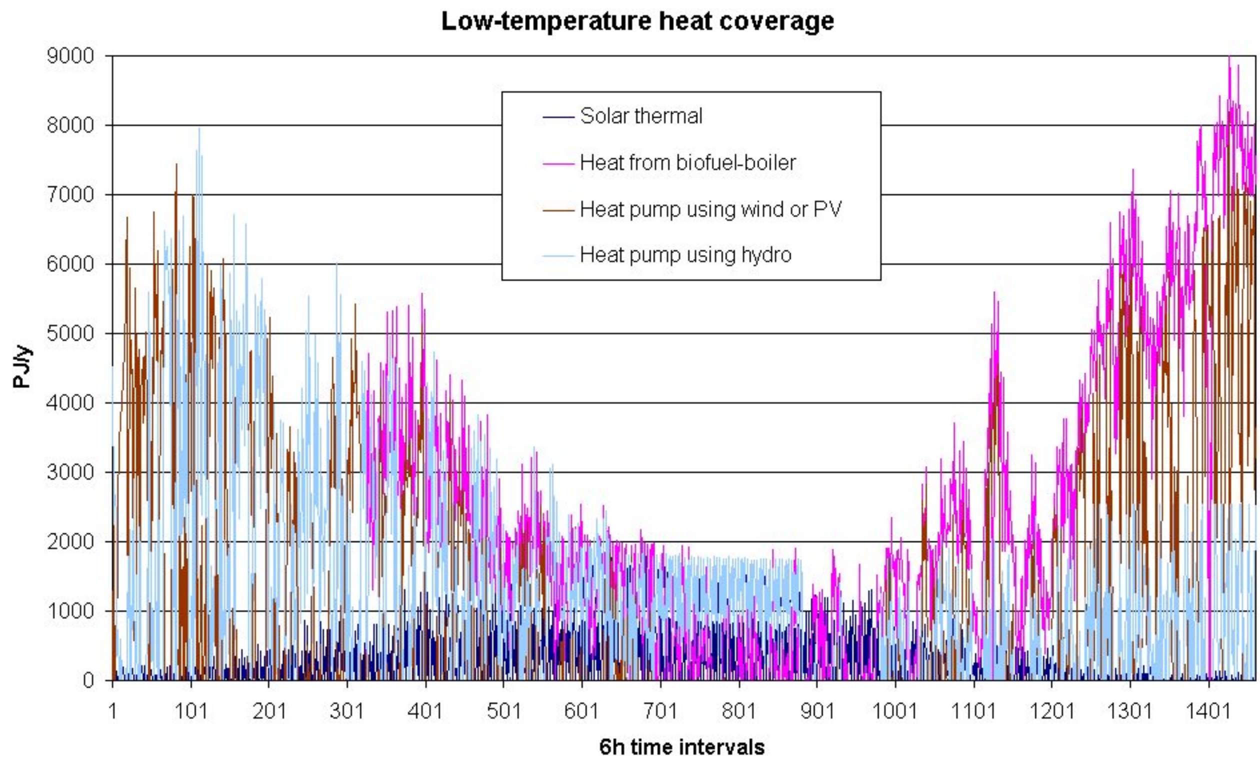

Figure 8. Contributions to fulfilling low-temperature heat needs in the year 2060 US scenario.