# Opportunities for hydrogen production in connection with wind power in weak grids

Magnus Korpås [a],* Christopher J. Greiner [b]

[a] SINTEF Energy Research, NO-7465 Trondheim, Norway

[b] Dept. of Electrical Power Engineering, Norwegian University of Science and Technology, NO-7491, Trondheim, Norway

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## Abstract

This paper gives an overview of the opportunities that exist for combining wind power and hydrogen ($H_2$) production in weak grids. It is described how $H_2$ storage can be applied in both isolated and grid-connected systems, and how the produced $H_2$ can be utilized for stationary energy supply and/or as a fuel for transportation. The paper discusses the benefits and limitations of the different $H_2$ storage applications, and presents a logistic simulation model for performance evaluation of wind-$H_2$ plants. A case study simulating the use of excess wind power in a weak distribution grid to produce $H_2$ for vehicles has been presented. It is shown that the penetration of wind power can be significantly increased by introducing electrolytic $H_2$ production as a controllable load. The results also indicate that there are large benefits of using the grid as backup for $H_2$ production in periods with low wind speed, regarding the $H_2$ storage sizing and the electrolyser operating conditions.

*Key words:* wind power, hydrogen, weak grid, electrolysis, logistic simulation

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## 1 Introduction

Hydrogen ($H_2$) has for a long time been regarded as a promising energy carrier for renewable energy sources [1,2]. In isolated power systems based on wind energy, $H_2$ can be produced from water electrolysis when the power output exceeds the load. Usually, the gas is compressed and stored in pressurized storage tanks although other storage alternatives also exist (See Section 2.2). When the power output from the wind turbine is not sufficient to feed the isolated load, stored $H_2$ is utilized for power generation in a fuel cell or a combustion engine. $H_2$ storage could also play a role in grid-connected systems, especially in connection with wind power in weak distribution grids. As an example, the best wind resources in Norway are often found in sparsely populated areas along the coastline where the local grid typically consists of long radial distribution feeders. In this case, $H_2$ can be produced from excess wind power that otherwise would have been dissipated due to network constraints. This opens for the future possibility of using $H_2$ as a fuel for local transport, such as ferries and buses [3,4]. Similar wind-$H_2$ combinations have been proposed in in other areas as well, see e.g. [5–9].

In comparison with other energy storage systems, the $H_2$ alternative offers great flexibility in sizing because of the modularity of electrolysers, fuel cells and storage tanks. The link to pollution-free transport is also important. However, there are several technological issues that so far have hampered the commercialization of $H_2$ energy systems, such as:

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* Phone: +47 73597229. Fax: +47 73597250.
*Email address:* `magnus.korpas@sintef.no` (Magnus Korpås).

- Low round-trip storage efficiency (electricity - $H_2$ - electricity)
- Low reliability and lifetime of fuel cells
- Limited ability of electrolysers to operate with fluctuating power input
- High cost of $H_2$ system components

The idea of using $H_2$ storage to balance wind power is far from new. Although the field has received increasing attention especially as the share of wind power in power systems increases and as the development of $H_2$ energy technologies continues, there are few planning studies that have addressed the variation and uncertainty of the energy input in a general manner. In areas with large seasonal variations in generation and load, it is important to study the relation between the rated power of the wind power plant and the $H_2$ storage size, since this will be crucial for the supply reliability and the installation costs of the system. With present investment costs, it would generally be economically favourable to oversize the wind power plant in order to reduce the need for long-term storage. This would lead to more non-utilized wind energy which will reduce the system efficiency in isolated systems. On the other hand, and more important, oversizing of the wind power plant would reduce the energy costs [10].

It is also crucial to take into account yearly variations when designing the system. For Norway, as an example, the variations in yearly average wind energy can be up to 20 % [11]. These variations will strongly influence the performance of distributed power systems that are dependent on $H_2$ storage, especially because of the low round-trip efficiency and high installation costs. Because of inclusion of memory in the system (the $H_2$ storage level and auto-correlation of wind speed between time steps), the preferred analysis methods have so far been based on time-sequential simulation models.

Typically, techno-economical feasibility studies have been performed by choosing hourly time steps and one year of operation [10,12,13]. The uncertainties induced by making these assumptions should be further investigated, and there is clearly a need for studies that highlight the consequences of stochastic variations in energy input from year to year.

Another important aspect is how to deal with short-term uncertainty of generation and consumption during on-line operation. As wind power can fluctuate significantly from hour to hour, robust strategies for operating the electrolyser and fuel cell must be applied in order to prevent too frequent start-ups and shut-downs, especially for isolated systems. One way of improving the operation is to incorporate wind power forecasts in short-term planning tools. If good day-ahead weather forecasts are available, it could be possible to achieve optimal interaction with the electricity market as to when the electrolyser should be operated [14].

This paper gives an overview of the opportunities that exist for the combination of wind power and $H_2$ production, storage and end-use, with emphasis on new possibilites in grid-connected systems. The paper is an extension of the work which was presented at the 2005 PSCC and 2006 PMAPS conferences [15,16]. The studied wind-$H_2$ systems are limited to weak grids (isolated or interconnected) where thermal capacity, voltage quality or voltage stability puts a limit to the integration of wind power into the power system. The main hydrogen components with their most important characteristics are briefly described in Section 2 while Section 3 and 4 introduces the opportunities in isolated power systems and grid-connected power systems respectively. Section 5 presents a logistic simulation model for assessment of wind-$H_2$ plants in weak grids. The model is used on a case study of a Norwegian island, which is described in Section 6. Results from simulations of the application example are presented in Section 7. Section 8 summarizes the main findings of this work.

## 2 Hydrogen storage overview

This paper considers the use of $H_2$ storage both for isolated and grid-connected power systems. A general illustration of a $H_2$ storage system coupled with a wind power plant is shown in Fig. 1. The arrows show the component interaction, and the symbols are explained in Table 1. The illustration is generalized in the sense that not all components need to be present for a special application. For instance, it is obvious that the external grid is not a part of an isolated power system. The following sections will give a short overview of the main components related to $H_2$ storage.

### *2.1 Electrolysis plant*

Water is split into $H_2$ and $O_2$ in an electrolysis cell by supply of direct current to the electrodes. Although the electrolysis process has been known since before the 19th century, only a small fraction of the $H_2$ production today comes from electrolysis. It is at present significantly cheaper to produce $H_2$ from hydrocarbons. However, this situation is expected to change in the future, both due to limitations of fossil resources and due to the inherent $CO_2$-formation from the reforming of fossil fuels. The net reaction for splitting of water is

$$H_2O + \text{electrical energy} \rightarrow H_2 + O_2$$

Electrolysis plants with alkaline electrolytes are commercially available with modules up to 2-3 MW. The electrolyte is aqueous, usually with a 20-30 % KOH solution. In addition to the electrolysis cells, an alkaline electrolysis plant consists of additional equipment for the following functions [17]:

- direct-current supply
- feed-water supply
- electrolyte circulation
- gas separation and purification
- cooling
- inert gas supply
- process control
- power supply to auxiliary equipment

The specific power consumption for the entire system including rectifier, initial compression (e.g. up to 30 bar) and other auxiliaries is in the range 53-62 kWh/kg [18]. This corresponds to 64-74 % efficiency, based on the higher heating value (HHV) of $H_2$ (HHV = 39.41 kWh/kg). Traditionally, alkaline electrolysers have been designed for constant $H_2$ production rates. In conjunction with wind energy on the other hand, the electrolyser should be able to follow sudden changes of operating conditions. Intermittent operation may cause impurity of $H_2$ in $O_2$ and vice versa. Moreover, fast power fluctuations can lead to incomplete separation of the gases from the electrolyte so that $H_2$ and $O_2$ are mixed in the electrolyte.

Another issue is how to operate the electrolyser in periods of low energy input. Since the alkaline electrolyte is very corrosive, the electrode will corrode if the production is stopped. The electrodes should be polarized as long as they are in contact with the electrolyte to prevent corrosion. A polarization current (stand-by power) must be provided from an external power source. For long periods with no $H_2$ production, one can alternatively remove the electrolyte from the system. However, such shut-down procedures will increase the power consumption during start-up.

Electrolysers with solid polymer electrolyte, also denoted proton exchange membrane (PEM), have simpler process layout, since there is no circulating liquid electrolyte. Thus, the PEM electrolyser is easier to operate and provides fast start-up. Another advantage is their high power density. Today, PEM electrolysers are available with modules up to 60 kW. PEM electrolysers have not yet been competitive with alkaline electrolysers mainly because of high costs for noble metal catalysts and polymer membrane. However, recent publications show remarkable achievments in improving the performance and bringing down the material costs of PEM electrolysers [19,20]. New developments, such as Inergon® from Hydro has an HHV-efficiency of ca. 80 % from electricity to 30 bar $H_2$ [21].

### *2.2 Hydrogen storage*

$H_2$ can be stored as compressed gas, as cryogenic liquid, in solids (metal hydrides, carbon materials) and in liquid $H_2$ carriers (methanol, ammonia). Compressed gas storage is most relevant for large-scale stationary storage systems. Compression of $H_2$ is normally obtained by the use of piston compressors or centrifugal compressors. Depending on the pressure difference, several stages of compression are often required because of the low density of $H_2$. The electricity consumption of the compressor is dependent on the pressure ratio and not the absolute pressure difference which makes it interesting to consider pressurised electrolysers that can reduce the electricity consumption related to mechanical $H_2$ compression.

Conventional methods of above-ground $H_2$ storage range from small or medium sized (0.05-50 $m^3$) high-pressure gas cylinders ($\geq$200 bar) to large low-pressure 12-16 bar spherical gas containers with volumes up to 15000 $m^3$. For large-scale storage of $H_2$, underground storage could be a future option in areas where the bedrock consists of porous minerals. Underground storage is assumed to be about two orders of magnitude cheaper than traditional pressure cylinders [22].

### *2.3 Hydrogen fuelled power generator*

Combustion engines can be adjusted for operation with $H_2$ without large problems. $H_2$ engines are readily available today for both stationary and transport applications, and they are at present cheaper and more reliable than fuel cells. $H_2$ has good combustion properties with high flame velocity. The main issues are uncontrolled combustion and the possibility of back firing.

In a fuel cell powered by $H_2$, the reverse reaction of water electrolysis takes place:

$$\mathrm{H_2 + O_2 \rightarrow H_2O + electrical\ energy}$$

The chemical energy content of $H_2$ is directly converted to electrical energy in the fuel cell. Therefore, a fuel cell can obtain higher electrical efficiency than thermal engines that are limited by the efficiency of the Carnot-cycle. However, kinetic overvoltages at the electrodes and electrical resistance cause relatively high losses in practical systems.

In renewable $H_2$ applications and automobile applications, low-temperature fuel cells, and especially proton exchange membrane (PEM) fuel cells, are considered as most promising because of their operating flexibility regarding start-up and shut-down procedures as well as intermittent operation. Typically, the system efficiency of PEM fuel cells from $H_2$ to AC power lies in the range 40-50 % based on HHV, and modules are available up to a few hundred kW. Presently, the main drawbacks of PEM fuel cells are low operating lifetime and high costs.

## 3 Opportunities in isolated power systems

In this section, we regard two different applications for $H_2$ produced from wind power in an isolated power system; Stationary power supply and vehicle fuel supply. Table 2 gives an overview of the required and optional components for the two types of systems, and also for systems designed for both applications.

### *3.1 Electricity supply*

When considering $H_2$ storage in isolated power systems, it is necessary to divide between those that rely entirely on wind energy and those that also include other energy sources [23]. For the latter kinds of power systems, the wind generator supplies part of the electricity demand, and for instance a diesel generator can be continuously operated to ensure power balance and stability. Hybrid systems comprising wind turbines, diesel generators and battery storage have been developed for many years and can now be considered as relatively mature. At locations with good wind conditions, wind-diesel systems are shown to be cost-competitive with pure diesel systems [24,25]. $H_2$ storage could make it possible to increase the wind penetration compared to what is possible with conventional batteries. $H_2$ is attractive due to the decoupling of energy conversion and storage. This is in contrast to batteries, where electrochemical energy is stored in the electrode materials. On the other hand, $H_2$ storage adds complexity to system design and operation, and it is inevitable that the overall storage efficiency will be lower than for modern batteries. At present, $H_2$ storage solutions are also significantly more costly than batteries. It should be emphasized that for certain system designs, it is possible to utilize excess heat from the fuel cell to achieve a higher overall efficiency.

In 2004, the world's largest wind-$H_2$ plant was installed at the island Utsira in Norway [26]. The system is designed to provide power to 10 households when operated as an isolated power system. Compared with a power system that also includes a backup generator, there are several new and critical issues that must be addressed stand-alone power systems entirely based on wind as primary energy source. First, the start/stop operation of the electrolyser makes system operation especially difficult without backup generation. For periods with low wind speed, the electrolyser must either be set in stand-by mode or run at minimum power by drawing power from a battery [27–29]. Secondly, it is critical that there is always enough $H_2$ stored to supply the load in case of long periods with insufficient wind power generation. It is necessary to take into account the potentially large differences between average power output from year to year, the seasonal variations and the possibility for long and unpredicted periods with low wind speed.

### *3.2 Vehicle fuel supply*

In this case, wind power is merely used for $H_2$ production. The idea is to make use of the energy source in areas with no electrical infrastructure and no electricity consumption. It can also be regarded as a future solution in areas where grid-connection of wind turbines is not considered to be economically and/or technically viable. The $H_2$ storage system could e.g. be connected to a filling station for $H_2$-fuelled vehicles, or, in a large-scale system, a $H_2$-pipeline network for further distribution [5,30,31].

### *3.3 Electricity and vehicle fuel supply*

This alternative supplies both electricity to an isolated load and $H_2$ fuel for vehicles. It can e.g. represent a future possibility for remote islands with sufficient wind resources to cover the complete energy needs, i.e. both the stationary and transportation energy demand [10,32]. The operation of such systems becomes particularly complex if the $H_2$ storage is connected to both a filling station and a power generator / fuel cell because then the stored $H_2$ serves two different purposes. A decision must be made on which demand should be prioritized in critical periods with no wind power output and when the amount of stored $H_2$ is low.

## 4 Opportunities in distribution grids

This section considers the coupling between wind power and $H_2$ production in distribution grids. The motivation for introducing $H_2$ production and storage is not as obvious as for isolated systems, since the interconnected power system balances the mismatch between local generation and consumption. However, this section shows that there exist some interesting opportunities for $H_2$ production and storage in grid-connected systems as well. Table 3 gives an overview of the required and optional components for the two possible types of grid-connected systems.

### *4.1 Electricity supply*

In this case, the $H_2$ subsystem is merely used as a way of storing electricity. The ideas explained here are therefore also fully applicable to other energy storage systems, such as batteries and flow cells. In fact, the applications are better suited for other and more energy-efficient storage technologies than $H_2$ since the need for long-term storage is not as crucial as for isolated systems.

A possible application of energy storage would be in areas with high wind power potential where the local load is relatively low and the existing distribution grid is rather weak. Wind energy could then be stored when the power generation exceeds the sum of the load and the export capacity. A disadvantage with this application is the low usage of the storage in periods with high load and low wind power generation. By taking into account electricity market conditions and costs for grid losses from import and export of power, it is possible to achieve a more optimal use of the installed storage capacity, as discussed in refs. [33,34]. However, the loss of energy in the storage cycle and the added costs of the energy storage must be considered in the analysis.

### *4.2 Electricity and vehicle fuel supply*

With a possible increase in the use of $H_2$ as a vehicle fuel, new opportunities may arise for wind power in weak distribution grids. The utilization of the existing grid capacity can be optimized by installing an electrolysis plant in proximity to the wind farm, and operating the electrolyser according to the fluctuating wind power. $H_2$ could then be produced from excess wind power, and thus make it possible to install more turbines. A major issue with this concept is to match the production of $H_2$ with the demand, which will fluctuate e.g. if $H_2$ is used at a filling station for passenger cars. In periods with low wind speed, $H_2$ can be produced from grid power to increase the supply reliability of $H_2$. The logistic model in Section 5 and the application example in Section 6 and 7 presents this concept in more detail. Another scenario is of course that $H_2$ can be sold to a market, just as electricity. Then the market price of $H_2$ and electricity will influence strongly on when to operate the electrolyser.

If there is a demand for $H_2$ fuel near the potential wind farm location, and a $H_2$ system with an electrolysis plant and a filling station is constructed, it might be beneficial to install a stationary fuel cell or combustion engine as a part of the $H_2$ system. As the round-trip efficiency of $H_2$ storage is very low, it is unlikely that the device would be used frequently during normal grid conditions [14]. On the other hand, the fuel cell or engine could be installed as a backup generator that can supply the local loads in case of grid faults. For this purpose, high storage efficiency is not needed, as the total amount of power generated from $H_2$ is expected to be very low. On the other hand, this solution will demand rapid start-up and good dynamic load-following properties. Last but not least, this added cost should be compared to the costs of load disruptions.

## 5 Logistic simulation model

### *5.1 Balance equations*

The logistic model represents the system described in Section 4.2, where $H_2$ is produced from wind power in an area with limited power transfer capacity. The logistic model uses a simplified representation of the system as shown in Fig. 2. The electrolyser produces $H_2$ when the wind power output, $P_{wgen}$, exceeds the capacity of the grid. A controllable dump load is operated if the $H_2$ storage system is not capable of absorbing all the excess wind power.

The power balance at time step $t$ is

$$P_{ely}(t) + P_{grid}(t) + P_{dump}(t) = P_{wgen}(t) - P_{load}(t) \tag{1}$$

where $P_{ely}$ is the electrolyser power, $P_{grid}$ is the power exported to the main grid, $P_{dump}$ is dumped wind power and $P_{load}$ is the local load. The relation between electrolyser power and the mass flow rate of $H_2$, $\dot{m}_{h,ely}$ (kg/h), is given by

$$P_{ely}(t) = SPC_{ely} \cdot \dot{m}_{h,ely}(t) \tag{2}$$

where $SPC_{ely}$ (kWh/kg) is the specific power consumption of the electrolyser, taking into account rectifier losses, power required for water splitting, $H_2$ compression and auxiliary power. The electrolyser operation is limited by the restriction

$$P_{ely}^{min} \leq P_{ely}(t) \leq P_{ely}^{max} \text{ or } P_{ely}(t) = 0 \tag{3}$$

where $P_{ely}^{max}$ is the electrolyser capacity and $P_{ely}^{min}$ is the power consumption at minimum $H_2$ production. The restriction in (3) states that the electrolyser must either be operated at $P_{ely} \geq P_{ely}^{min}$ or be switched off. The procedure of on/off switching is important if the electrolyser is used for wind power smoothing. It could be better to maintain $H_2$ production, even when the wind power generation drops to zero, because of mechanical wear and possibly electrochemical degradation related to frequent on/off switching. With present technology, electrolysers have a minimum operating point ranging from 5% to 20% of nominal power, depending on the manufacturer.

The $H_2$ is compressed and stored in pressure vessels before it is extracted at a filling station for vehicles. The $H_2$ storage balance is

$$m_h(t) = m_h(t-1) + (\dot{m}_{h,ely}(t) - \dot{m}_{h,fill}(t)) \cdot \Delta t \tag{4}$$

where $m_h$ (kg) is the mass of stored $H_2$ and $\dot{m}_{h,fill}$ (kg/h) is the flow rate of $H_2$ from the pressure vessels to the filling station. The amount of $H_2$ that can be stored and extracted is limited by the minimum and maximum allowable storage levels:

$$m_h^{min} \leq m_h(t) \leq m_h^{max} \tag{5}$$

If there is not enough stored $H_2$ to cover the $H_2$ load at the filling station at time step $t$, there will be a deficit of $H_2$ represented by

$$\dot{m}_{h,def}(t) = \dot{m}_{h,load}(t) - \dot{m}_{h,fill}(t) \tag{6}$$

where $\dot{m}_{h,load}$ is the $H_2$ load and $\dot{m}_{h,def}$ is the amount of $H_2$ not supplied.

### *5.2 Control strategy*

For the system considered here, the objectives of the control strategy are to:

(1) Maximize the utilization of available wind energy
(2) Minimize the amount of $H_2$ not supplied

The first target is handled by adjusting the electrolyser power in periods with high wind power output so that the grid capacity is not violated. For each time step, it is possible to find the required electrolyser power $P_{ely}^{req}$ that reduces the power export to the highest acceptable level, $P_{grid}^{max}$. In the model, $P_{ely}^{req}$ is simply calculated from:

$$P_{ely}^{req} = \max(P_{wgen}(t) - P_{load}(t) - P_{grid}^{max}, 0) \tag{7}$$

Similarly, the maximum allowable wind power $P_{wgen}^{lim}$ is a simple function of $P_{load}$ and $P_{ely}$ at each time step:

$$P_{wgen}^{lim} = P_{ely}(t) + P_{load}(t) + P_{grid}^{max} \tag{8}$$

The power export limit $P_{grid}^{max}$ is for the sake of simplicity represented by a constant value. However, in practice the power export may be limited by voltage quality or voltage stability, and thus varies with the power flow situation. However, the modelling framework is not limited to constant power export limit. In [15], it is shown how $P_{ely}^{req}$ and $P_{wgen}^{lim}$ is determined for a case where steady-state voltage rise is the limiting factor for how much wind power that can be transferred to the main grid.

A $H_2$ supply security limit, ${m_h}^{lim}$, for the stored $H_2$ is introduced in the control strategy in order to minimize the amount of $H_2$ not supplied. If the stored $H_2$ drops below this level, the electrolyser is operated at full $H_2$ production by drawing power from the external grid. This ensures that the $H_2$ storage will not be empty during longer periods with low wind speed.

The algorithm for the control strategy is implemented as a MATLAB-function and is given in the 8 steps shown below. First, the set-point for the electrolyser power $P_{ely}^{set}$ is determined. A sub function is called, which seeks to minimize the difference between the actual electrolyser power and the set-point, based on the component models for the $H_2$ storage system. A check on the wind power limit is carried out to determine if it is necessary to operate the dump load. Finally, the exported power to the main grid is calculated and the simulated variables are returned from the function.

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1. Read $P_{wgen}(t), P_{load}(t), \dot{m}_{h,load}(t), m_h(t-1)$
2. Calculate $P_{ely}^{req}$ from Eq. (7)
3. If $m_h < {m_h}^{lim}$ then $P_{ely}^{set} = P_{ely}^{max}$
   elseif $P_{ely}^{req} > P_{ely}^{min}$ then $P_{ely}^{set} = P_{ely}^{req}$
   else $P_{ely}^{set} = P_{ely}^{min}$
4. Solve minimize[ $|P_{ely}(t) - P_{ely}^{set}|$ ]
     subject to $H_2$ Eqs. (2)-(6)
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5. Calculate $P_{wgen}^{lim}$ from Eq. (8)
6. If $P_{wgen}(t) > P_{wgen}^{lim}$ then $P_{dump}(t) = P_{wgen}(t) - P_{wgen}^{lim}$
   else $P_{dump}(t) = 0$
7. Calculate $P_{grid}(t)$ from power balance Eq. (1)
8. Return $P_{ely}(t), P_{grid}(t), P_{dump}(t), \dot{m}_{h,fill}(t), \dot{m}_{h,def}(t), m_h(t)$
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## 6 Application example

In this example, it is shown how $H_2$ production can be combined with wind power in areas with limited network capacity, as discussed in section 4.2. The idea is to use excess wind power (that otherwise would have been dissipated due to grid constraints) to produce $H_2$ for a local bus and ferry. The example system is shown in Fig. 3, and it represents an island at the Norwegian coastline. The maximum allowable wind power output is limited by voltage constraints and the thermal limits of the overhead lines and sea cable. To simplify the analysis, a constant export limit of 4 MW is chosen here, although this limit will vary with the load pattern and the ability of the wind farm to control reactive power. More detailed grid analyses of a similar example system are described in refs. [15,35]. The average load at the island is 800 kW, and it follows a typical Norwegian pattern with low load at summer and high load at winter. Based on estimated schedules for a fuel cell bus and a hypothetical $H_2$ fuelled ferry, the $H_2$ consumption is set to 835 kg/day on weekdays and 470 kg/day on weekends. This corresponds to an average power consumption of 1825 kW for the chosen electrolysis plant, including rectifier, auxiliary equipment and $H_2$ compression with a total specific power consumption of 60 kWh/kg. Due to operation restrictions, the electrolyser must always be operated at minimum 20 % of its nominal power.

A 30-year time series of hourly wind power output has been constructed from wind speed measurements and a general wind power curve. The year-to-year variations in the capacity factor (average power relative to rated power) are shown in Fig. 4. It is evident that basing feasibility studies on a single year of wind speed measurements may give too optimistic or pessimistic results when comparing with the long-term average wind speed. Fig. 5 shows the monthly variations of the capacity factor for the best year (year 11), worst year (year 20) and a year with average wind speed close to the 30-year average (year 19). All years follow the same trend with best wind conditions during the winter months, when also the electricity consumption is highest.

## 7 Results

### *7.1 Wind power only*

First, the possibilities of utilizing the wind resources without $H_2$ storage are studied. If the installed wind power capacity is above the grid capacity, wind power must be dumped in periods with high wind speed and low electricity consumption. This is illustrated in Fig. 6, where the distribution of the wind energy is plotted for different wind power capacities. The prioritisation of the generated wind power is: 1) Supply of local load 2) Export to external grid 3) Dump excess power. We clearly see that the fraction of dumped wind energy increases significantly at high penetration levels which reduces the income from operating in the electricity market. With an installed wind power capacity of 9 MW, as much as 27 % of the available wind energy will be dumped.

### *7.2 Wind power with constant $H_2$ production*

When introducing $H_2$ production, a choice must be made on how to operate the electrolyser. The required electrolyser capacity and $H_2$ storage capacity can be minimized by always operating the electrolyser at constant power. With this control strategy, it was found that an electrolyser rating of 2000 kW and a storage capacity of 1500 kg are sufficient. The distribution of the wind energy for different wind power capacities will in this case be as shown in Fig. 7, where supply of wind power to the electrolyser is prioritised above the local load. Because of the increased local power consumption, the need for dumping of wind energy is significantly reduced compared to the case with no $H_2$ production.

### *7.3 Wind power with variable $H_2$ production*

A disadvantage with operating the electrolyser at constant power is that this leads to frequent import and export of power from the external grid. By increasing the rating of the electrolyser and the $H_2$ storage capacity, it would be possible to utilize more wind power directly for $H_2$ production, and thus reducing grid losses and the impact of possible high power prices for import and low power prices for export. Therefore, an alternative configuration with electrolyser rating of 3 MW and $H_2$ storage capacity of 3000 kg has been studied for the case of 9 MW installed wind power capacity. With this configuration (CONFIG 2), it is possible for the electrolyser to follow the wind power generation to a higher degree. A comparison with the results for constant electrolyser power (CONFIG 1) is given in Table 4. The symbols used in Table 4 are as follows:

$E_{wgen}$ : Annual wind power generation
$E_{ely}$ : Annual electrolyser consumption
$E_{dump}$ : Annual dumped wind energy
$E_{ely,grid}$ : Annual electrolyser energy supplied from grid import

With varying electrolyser power (CONFIG 2), the dumped wind energy is significantly reduced, but a part of the annual electrolyser energy is still supplied from grid import. This is because the $H_2$ demand is constant, and the electrolyser must therefore be operated even in periods with zero wind speed. It would of course be possible to guarantee that all $H_2$ is produced directly from wind power, but this would require a very large $H_2$ storage capacity and thus much higher investment costs.

Fig. 8 shows the main issue arising when wind power is combined with a constant $H_2$ demand in an area with significant seasonal wind variations. During the winter months the amount of stored $H_2$ is high since the wind power output frequently exceeds the grid capacity. During summer in an average year (year 19) it is not possible to produce all the required $H_2$ directly from wind power. The electrolyser must draw much of its power from the grid, and the storage level is consequently kept at minimum. It is important to notice that this happens even in the year with the highest average wind speed (year 11). In the worst year (year 20), the utilization of the installed $H_2$ storage is very low all over the year. The results indicate that there is a need to develop more advanced control schemes for the electrolyser based on both short-term and long-term wind forecasts. This is to achieve an optimized use of the available wind energy.

## 8 Conclusions

$H_2$ storage may open for new opportunities for wind power. Traditionally, $H_2$ storage is considered to be an option in isolated power systems, but there will also be interesting possibilities in combination with grid-connected generators if $H_2$ is introduced in the transport sector. $H_2$ storage systems are at present not cost competitive, but is nevertheless a promising alternative as a carrier of renewable energy, especially due to the possible link to pollution-free transportation.

This paper has given an overview of the potential uses of $H_2$ energy storage in combination with wind power. Emphasis has been given to the possibility of using electrolytic $H_2$ production as a load management method for wind power in weak distribution grids. Given a local market for $H_2$ such as fuel for ferries or cars, $H_2$ production from wind power provides control options that allow increased utilization of the wind energy resources. $H_2$ production and storage may become a viable option in areas where reinforcements of existing grids are costly or controversial due to environmental concerns.

A logistic simulation model for performance evaluation of wind-$H_2$ systems has been described in the paper. It is emphasized that the seasonal and yearly variations in energy input must be taken into account when sizing the individual components, as this could lead to high storage costs. The results further indicate that there are large benefits of using the grid as backup for $H_2$ production, regarding the operating conditions for the electrolyser and in order to minimize the required $H_2$ storage size.

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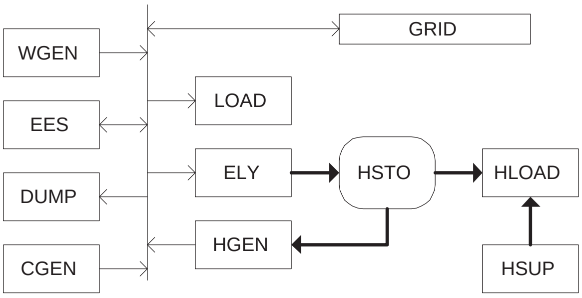

Fig. 1. Schematic illustration of the components in a general wind-$H_2$ energy system.

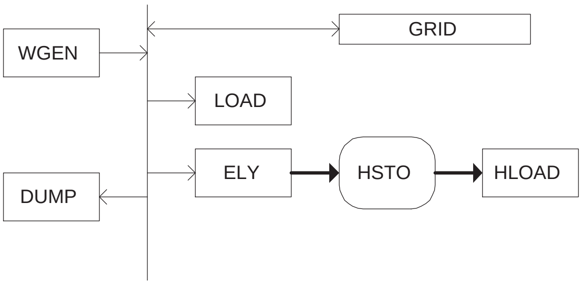

Fig. 2. Wind-$H_2$ plant connected to a weak distribution grid.

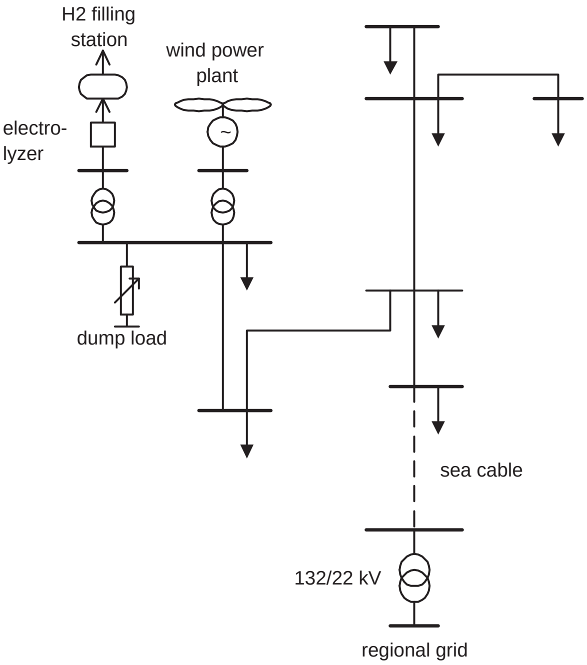

Fig. 3. Single line diagram of the example grid. The arrows refer to load points.

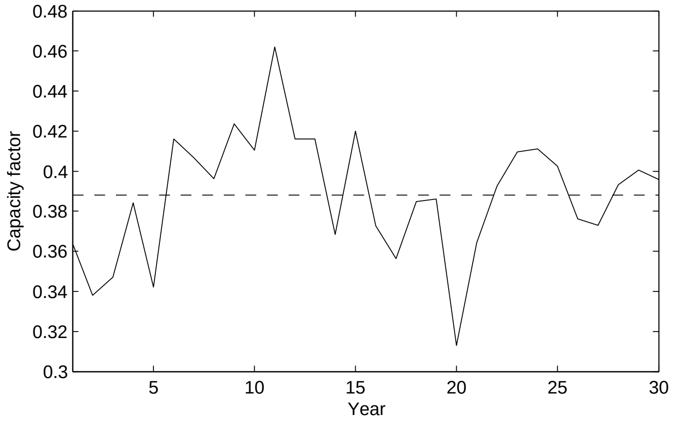

Fig. 4. Yearly variations in wind power generation. The dashed line is the average value.

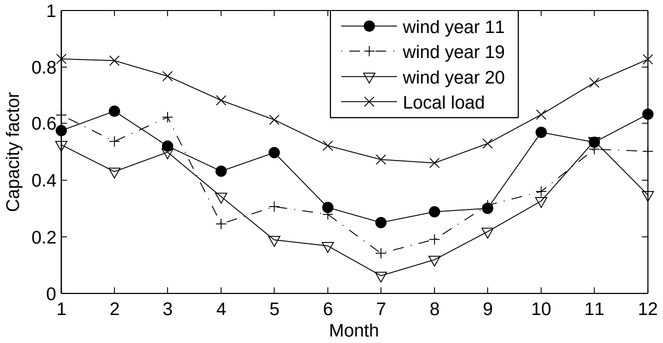

Fig. 5. Monthly variations in wind power generation and local load.

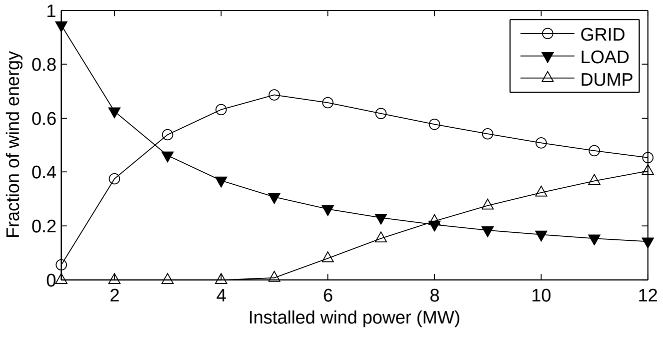

Fig. 6. Distribution of wind energy with no $H_2$ production.

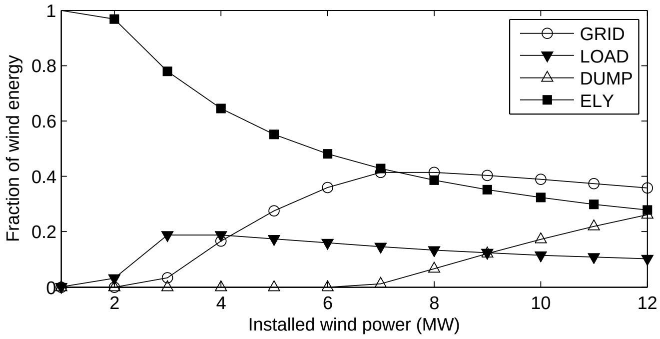

Fig. 7. Distribution of wind energy with constant $H_2$ production.

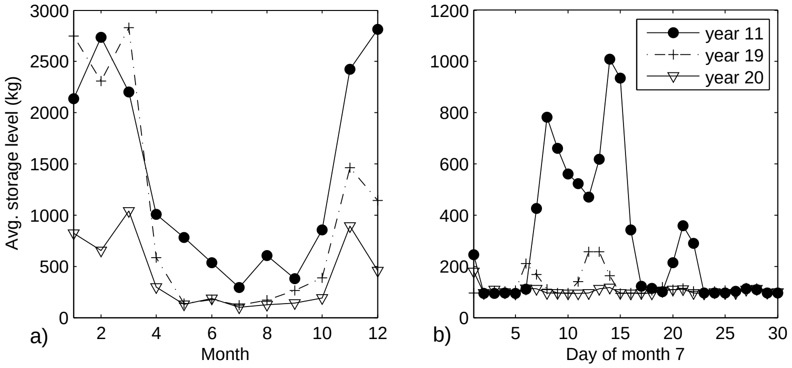

Fig. 8. $H_2$ storage level. a) Monthly variations. b) Daily variations within month 7.

Table 1

Component description

| Symbol | Description | Examples |
|---|---|---|
| WGEN | Wind generator | Induction generator (IG), Doubly-fed IG |
| DUMP | Controllable dump load | Resistive heating element |
| CGEN | Conventional generator | Diesel generator |
| EES | Electric energy storage | Lead-acid battery, flywheel |
| HGEN | $H_2$-fuelled generator | PEM fuel cell, combustion engine |
| LOAD | Electrical load | Households, weather station |
| ELY | Electrolysis plant | Alkaline electrolyser, PEM electrolyser |
| GRID | External grid | Weak radial, subsea cable |
| HSTO | $H_2$ storage | Pressurized tanks |
| HLOAD | $H_2$ load | $H_2$ vehicles |
| HSUP | Alternative $H_2$ supply | $H_2$ Pipelines, natural gas reformer |

Table 2

Applications in isolated power systems

| Purpose of the system | Required components | Optional components |
|---|---|---|
| Provide electricity | WGEN, ELY, HSTO<br>HGEN, LOAD | EES, DUMP<br>CGEN |
| Provide vehicle fuel | WGEN, ELY<br>HSTO, HLOAD | EES, DUMP<br>CGEN, HSUP |
| Provide electricity and vehicle fuel | WGEN, ELY, HSTO<br>LOAD, HLOAD | EES, DUMP, HGEN<br>CGEN, HSUP |

Table 3

Applications in distribution grids

| Purpose of the system | Required components | Optional components |
|---|---|---|
| Provide electricity | WGEN, ELY, HSTO<br>HGEN, GRID | LOAD, DUMP |
| Provide electricity and vehicle fuel | WGEN, ELY, HSTO<br>HLOAD, GRID | LOAD, DUMP<br>HGEN, HSUP |

Table 4

30-year simulation results for 9 MW installed wind power with 2 MW Electrolyser / 1500 kg $H_2$ storage (CONFIG 1) and 3 MW Electrolyser / 3000 kg $H_2$ storage (CONFIG 2)

| | | | CONFIG 1 | | CONFIG 2 | |
|---|---|---|---|---|---|---|
| | $E_{wgen}$ | $E_{ely}$ | $E_{dump}$ | $E_{ely,grid}$ | $E_{dump}$ | $E_{ely,grid}$ |
| avg (GWh/yr) | 30.6 | 16.0 | 3.5 | 4.8 | 1.6 | 3.4 |
| min (GWh/yr) | 24.7 | 16.0 | 2.1 | 3.8 | 0.8 | 2.1 |
| max (GWh/yr) | 36.4 | 16.0 | 4.7 | 5.9 | 2.4 | 4.9 |
| std (GWh/yr) | 2.4 | 0.0 | 0.5 | 0.5 | 0.4 | 0.6 |