Available online at www.sciencedirect.com

ScienceDirect

International Journal of Hydrogen Energy 32 (2007) 1500–1507

International Journal of HYDROGEN ENERGY

www.elsevier.com/locate/ijhydene

A Norwegian case study on the production of hydrogen from wind power

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

[a]*Department of Electric Power Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway*
[b]*Energy Systems Department, SINTEF Energy Research, 7465 Trondheim, Norway*

Abstract

A method for assessment of wind–hydrogen (H_2) energy systems is presented. The method includes chronological simulations and economic calculations, enabling optimised component sizing and calculation of H_2 cost. System components include a wind turbine, electrolyser, compressor, storage tank and power converter. A case study on a Norwegian island is presented. The commuting ferry is modelled as a H_2 ferry, representing the H_2 demand. The evaluation includes a grid-connected system and an isolated system with a backup power generator. Simulation results show that much larger components are needed for the isolated system. H_2 cost amounted to 2.8 €/kg and 6.2 €/kg for the grid-connected and isolated system, respectively. Sensitivity analyses show that a marginal decrease in wind turbine and electrolyser cost will reduce the H_2 cost substantially. Rate of return is also important due to high investment costs. The grid-connected system is by far the most economical, but the system involves frequent grid interaction.

Keywords: Wind power; Electrolysis; Modelling; Chronological simulation; Hydrogen economy; Distributed generation; Renewable energy

---

1. Introduction

The Norwegian coastline hosts a great wind power potential. Only 281 MW is currently in operation (2005), but licences have been given for the construction of a further 844 MW and applications are being considered for a total of around 4000 MW [1]. If all projects were to be approved, a total wind power installation of 5000 MW would generate around 15 TWh annually. However, the total technical potential is estimated to be about 250 TWh/year with generation costs within 0.033–0.05 €/kWh, excluding grid expansion costs [2]. Grid integration of wind power plants is, however, accompanied with substantial technical challenges such as keeping voltage and frequency levels satisfactory while dealing with highly variable power generation. In addition, the best wind resources are often found far from areas with high electricity consumption, resulting in long-distance transmission and high power losses. It is, therefore, a need to explore options to increase the local utilisation of wind energy in remote areas, e.g. by electrolytic hydrogen (H_2) production.

The transport sector represents one of the largest contributors to air pollution in the industrialised countries. Even though improved engine technology reduces the specific emissions, the increase in use and demand will most likely keep emissions at present levels or higher. Changing to H_2 as an alternative energy carrier is a promising way of reducing local emissions from vehicles. Moreover, the Norwegian marine sector contributes to 10% of the national CO_2 emissions and 40% of the NO_x emissions due to its use of fossil fuels, mostly diesel [3]. Since the best (onshore) wind energy resources in Norway are located along the coastline, the combination of wind power and local H_2 production for use in ships and ferries should be considered in order to increase the exploitation of remote wind resources and reduce emissions to air.

In this paper, we present a simulation study of a combined Wind–H_2 plant on a small Norwegian island. Today, a local diesel ferry connects the 650 inhabitants with the mainland, and the island is supplied by power from the main grid by a submarine cable. Due to the good wind conditions and the low power transmission capacity, the combination of wind power with local H_2 production and enduse is evaluated in this paper. The H_2 is to be consumed by a fuel cell driven ferry equal in specifications to the existing diesel driven ferry. The case study

---

* Corresponding author. Tel.: +47 73550401; fax: +47 73594279.
E-mail address: Christopher.Greiner@elkraft.ntnu.no (C.J. Greiner).

0360-3199/$ - see front matter © 2006 International Association for Hydrogen Energy. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijhydene.2006.10.030

should be considered an evaluation of a near future scenario, as H_2-driven ferries are not yet available. Costs and specifications of some system components are optimistic regarding present status but they are regarded plausible in a future perspective.

Many feasibility studies of full-scale renewable H_2 systems have been published, but the main focus has so far been on isolated power supply, see, e.g. [4–6]. The option of using H_2 produced from renewable energy sources as a transportation fuel is also receiving increased attention. In [7], a feasibility study of an autonomous solar-H_2 system connected to a filling station for fuel cell buses is presented. Furthermore, it has earlier been proposed to use excess wind energy for large-scale production of H_2 to the transport sector [8]. In the present work, we employ a new methodology for assessment of both grid-connected and isolated Wind–H_2 systems. The method is based on a chronological simulation model and includes both technical and economic calculations, enabling system costs and production cost of H_2 to be calculated. This makes it possible to give recommendations on optimised sizing of the individual components for both grid-connected and isolated Wind–H_2 systems.

2. System description

The system to be evaluated is a combined wind power and H_2 production facility, which is denoted the Wind–H_2 system. The wind power plant and the H_2 production plant need not necessarily be in proximity to each other. The Wind–H_2 system is evaluated with two different configurations; grid-connected and isolated. With grid connection the system is connected to the nearby distribution grid and can exchange power at any time. The system is in this case also connected to local power consumption. The grid capacity should be sufficient to provide the maximum electric load at times of zero wind power generation. Excess wind power is exported to the grid. In the case of an isolated system on the other hand, the system has no ability to interact with the surroundings, including local power consumption. In this case, a diesel power generator is included as backup. The backup generator should be sufficient to provide the minimum necessary electrolyser power at long periods of zero wind power generation. In periods with high wind speeds, any excess wind power is dumped. The two system configurations are displayed in Fig. 1.

In both cases, H_2 will be supplied to a filling station where local vehicles can fill at demand. Other system alternatives might include a fuel cell or a H_2-fuelled combustion engine, where H_2 can be reused to generate electricity for the local grid. This possibility is not included, and it would also be unnecessary for the isolated system.

3. Methodology

3.1. Technical and economical evaluation of Wind–H_2 systems

A chronological simulation model has been developed for assessment of Wind–H_2 energy systems. The simulation model is implemented in Matlab with Excel interface and is structured as follows:

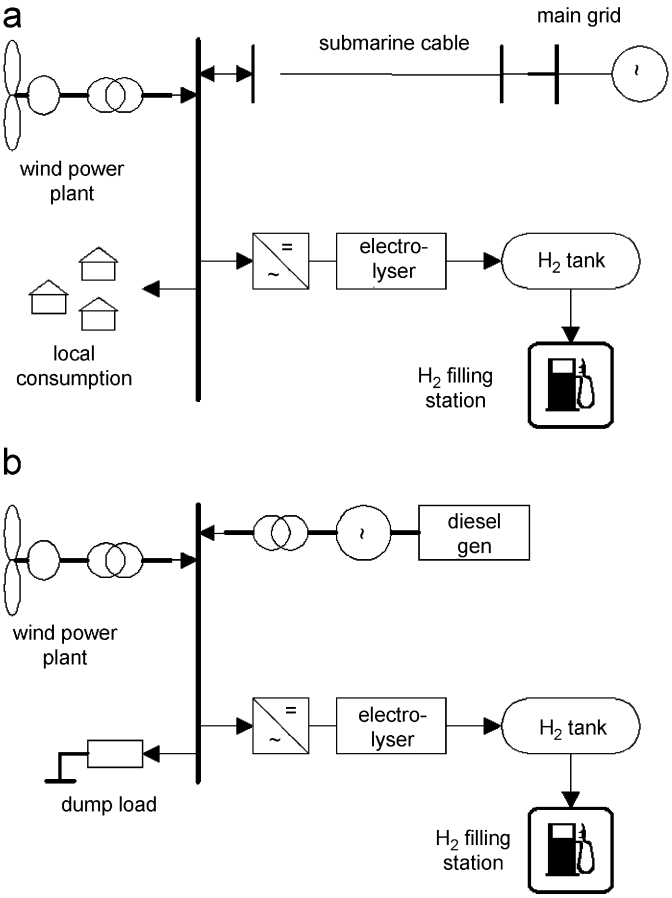

Fig. 1. Remote Wind–H_2 systems with supply of hydrogen to vehicles. (a) Grid-connected system. (b) Isolated system. The arrows show the direction of power flow and hydrogen flow.

1. Read parameters from Excel;
2. Read time series for wind speed, electric load, market power price and H_2 demand from text files;
3. Construct time series for wind generation;
4. For $t = 1: T$

   Run control strategy,

   Store simulation variables for time step t,

5. Calculate summary results and write to Excel.

The core of the simulation model is the control strategy in Step 4. The objectives of the control strategy are to maximise the utilisation of available wind energy and to minimise the amount of H_2 not supplied [9]. Based on the chosen control strategy and component parameters, the model calculates the electrical energy balance and the H_2 balance for each time step of the simulation. Step 4 is repeated until the final time step T is reached. In Step 5, the summary results are calculated. This includes utilisation factors of the different components, total power generation and consumption in the time period and total H_2 production and consumption.

In addition to the technical calculations conducted in the simulation model, an economic model has been developed within the Excel interface. The economic model uses result data from the simulation model to conduct an economic analysis of the chosen system. The basic formulas used in the economic calculations are described below.

Based on a component lifetime of N_l years and a rate of return of r, the annuities of each component is calculated with the following equation;

$$A = I \times \frac{r/100}{1-(1+r/100)^{-N_l}}, \tag{1}$$

where I is the investment cost and A is the annuity of the investment.

Given a fixed period of analysis of N_{ap} years and a rate of return of r, the capitalised cost of a component is calculated with the following equation;

$$K = A \times \frac{1-(1+r/100)^{-N_{ap}}}{r/100}, \tag{2}$$

where A is the annuity of the investment cost given in Eq. (1) and K is the capitalised cost (total cost) in the period of analysis. Hence, K ensures that remaining costs of components outside the period of analysis are not included in the system cost calculation.

H_2 cost is calculated by dividing the total annual cost of the system including sale/purchase of power from the grid by the total annual H_2 production;

$$C_{H_2} = \frac{A_I + A_{OM} + C_{imp} - S_{exp}}{m_{H_2}^{tot}}, \tag{3}$$

where A_I and A_{OM} are the annuities of investment costs and operation & maintenance costs (O&M costs), respectively, C_{imp} and S_{exp} are the annual power import cost and the annual power sales profit, respectively, and $m_{H_2}^{tot}$ is the total annual production of H_2. The import cost and sales profit of electricity is the product of the amount imported/exported and the market power price at time of transaction.

3.2. Dimensioning the Wind–H_2 system

The dimensioning of both the grid-connected and the isolated system is based on a constant daily H_2 demand. The rationale for this is that public transport operates with fairly constant running patterns every day all year around. In addition, the volume of maximum accumulated H_2 not supplied per year should be set. This value should be very close to or equal to 0% unless H_2 fuel can be provided elsewhere on short notice. The methodology takes into account idealised components with 100% availability. Including unavailabilities (downtime) would increase component sizes, however, the method presented yields as a best case scenario, or an ideal system with which a more realistic system could be compared.

3.2.1. Grid-connected system

Dimensioning the grid-connected system is done by reducing the component sizes to a minimum without exceeding the maximum value for H_2 not supplied. In that way, system cost and, therefore, the production cost of H_2 will be as low as possible. Minimum electrolyser power is found by the following formula;

$$P_{ELY,min} = SPC_e \times d_{H_2}, \tag{4}$$

where $P_{ELY,min}$ (kW) is the minimum electrolyser power, SPC_e (kWh/kg) is the specific power consumption of the electrolyser and d_{H_2} (kg/h) is the *average hourly* H_2 demand. The same approach as for the electrolyser is used when dimensioning the compressor;

$$P_{C,min} = SPC_c \times d_{H_2}, \tag{5}$$

where $P_{C,min}$ (kW) is the minimum compressor power, SPC_c (kWh/kg) is the specific power consumption of the compressor and d_{H_2} is the H_2 demand. The power converter should be dimensioned to deliver the maximum amount of power required by the actual electrolyser and compressor when in 100% operation;

$$P_{PC,min} = \frac{(P_{ELY} + P_C)}{\eta_{PC}}, \tag{6}$$

where η_{PC} is the power converter efficiency.

To dimension the storage tank, four steps are conducted:

1. Define the minimum storage level of the tank.
2. Define the time spent for continuous filling of the vehicle.
3. Calculate the minimum supply security limit of the tank. The supply security limit prevents the tank from being emptied (falling below the minimum storage level) while filling occurs and accounts for the maximum hourly H_2 production and time required for continuous filling. The shorter the filling time, the higher the net decrease in tank volume and, therefore, the higher the limit for security of supply.
4. Conduct system simulations including the supply security limit and choose the minimum tank volume necessary not to violate the maximum volume of H_2 not supplied.

To dimension the wind turbine, five steps are conducted in an iterative procedure:

1. Calculate the annual power requirement of the H_2 facility.
2. Estimate total power import from the grid and account for power losses in grid transmission (percentage of total import).
3. Simulate total system with multiple wind turbine sizes.
4. Choose minimum sized turbine sufficient to generate the same amount of power as is consumed by the H_2 facility and lost in grid transmission.
5. Compare actual power import to the system of choice (wind turbine $+H_2$ facility) with the value estimated in Step 2. If value is satisfying choose wind turbine. If not, repeat Steps 2–5.

The grid capacity should be equal to or higher than the average power requirement of the H_2-plant, enabling the plant to draw power from the grid whenever the wind turbine fails to provide the necessary power. If grid capacity at the specified location is not sufficient, some type of additional backup power should be available, e.g. a diesel power generator.

3.2.2. Isolated system

With an isolated system, the diesel power generator plays the role of the grid connection in the previous evaluation. Thus, the diesel power generator should be sufficient to provide power to the electrolyser and the compressor and account for losses in the power converter:

$$P_{\text{diesel}} = \frac{(P_{\text{ELY,min}} + P_{\text{C,min}})}{\eta_{\text{PC}}}. \tag{7}$$

By dimensioning the backup power generator to provide all the electricity needed by the H_2 facility the security of supply of H_2 can be maintained independent of the wind power generation. The dimensioning of the isolated system will be very dependent on the specifications of the diesel power plant and the diesel fuel cost. Diesel power generation in small or medium sized generators is very expensive. Compared to wind power the cost is several times higher per kWh. The optimal dimensioning of the isolated Wind–H_2 system is conducted with the diesel power generator being in operation whenever grid power would be required in the grid-connected system. The annual diesel consumption and the investment and O&M costs of the diesel power generator of choice is added to the H_2 cost, and the optimal system is chosen based on total H_2 production cost and fraction of total annual H_2 production from diesel power. As no clear restrictions on acceptable consumption of diesel fuel is set, the decision on system configuration will depend on the person evaluating it. It is important to compare the diesel fuel consumption of the backup power generator to the fossil fuel consumption of the vehicle that is replaced. In this study, the focus is to maximise the utilisation of the Wind–H_2 system and minimise the backup power. Therefore, a more costly system could be chosen due to higher renewable fraction.

An alternative backup system could be a hydrocarbon reformer. The reformer would generate H_2 directly using, e.g. natural gas, naphtha or methanol. Energy efficiency would be far greater and, therefore, also the environmental benefit, but a reformer system would add more components and add to the complexity and cost of the system (the electrolyser is already installed and has zero marginal cost). It is also questionable whether a reformer system could handle the highly varying output needed when the wind turbines fail to supply parts of the necessary power for the electrolyser system. Including a reformer is still an interesting alternative and is clearly worth analysing, however, it is outside the scope of this study.

3.3. Calculating H_2 demand

H_2 demand is calculated for a vehicle that would consume an equal amount of H_2 each day of the year, which in term would yield an *average hourly* H_2 demand. This assumption should be adequate for public transport vehicles. For the case of a remote island community, a commuting ferry would represent a potential constant demand of H_2 each day and this is the case to be evaluated. Calculation of the daily H_2 demand for the vehicle should be conducted based on data for the existing fossil fuelled vehicle as to average fuel demand and engine efficiency:

$$D_{H_2} = \frac{D_{\text{ff}} \times \text{LHV}_{\text{ff}} \times \eta_{\text{ff}}}{\text{LHV}_{H_2} \times \eta_{H_2}}, \tag{8}$$

where D_{ff} (kg/day) is the demand for fossil fuel, LHV_{ff} (MJ/kg) is the lower heating value of the fossil fuel, η_{ff} is the efficiency of the fossil fuelled engine, LHV_{H_2} (MJ/kg) is the lower heating value of H_2, η_{H_2} is the efficiency of the H_2 engine/fuel cell and D_{H_2} (kg/day) is the demand for H_2. The value of D_{H_2} should be increased by a factor of choice accounting for possible losses during filling and storage.

3.4. Calculating environmental benefits

When H_2 replaces a fossil fuel, the local emissions of CO_2 will be virtually zero. If H_2 is produced from electrolysis, with power supplied by non-fossil sources, the emissions will be virtually zero over the whole chain from production to end use. Formation of CO_2 during combustion of fossil fuels is linearly dependent on the amount of fuel used, when assuming complete combustion. A basic formula for the emission of CO_2 from complete combustion[2] of a fossil fuel is given below:

$$e_{CO_2} = 3.67 \cdot m_F \cdot mf_C, \tag{9}$$

where e_{CO_2} (kg) is the CO_2 emission, m_F (kg) is the mass of fuel, mf_C is the mass-fraction of carbon (C) in the fuel and 3.67 is the ratio between molar mass of CO_2 and pure C. Emissions of NO_x on the other hand are dependent on the thermodynamical properties in the combustion chamber and must, therefore, be evaluated based on the specific engine of choice.

4. Case study

A case study was conducted with wind and grid data for a Norwegian island with 650 inhabitants and a commuting ferry running on diesel. The local grid holds 22 kV and the island is connected to the mainland by a submarine cable. The wind data shows a great potential for wind power with an annual average wind speed of 8.5 m/s at 70 m above ground level (agl). However, the distance to the nearest regional grid (132 kV) is over 20 km and the relatively weak 22 kV grid between the island and the regional grid prevents more than a few MW of power input. In addition, the inclusion of one or more wind turbines in the local grid could be unwanted from the grid owner's point of view. Therefore, the island was considered a good case for evaluating both a grid-connected system and an isolated system. The island of choice is considered to be representative for many island communities along the Norwegian coastline.

A time series of wind speeds (hour values) for one whole year adjusted to 70 m agl was the basis for the wind power

---

[2] All carbon reacts with oxygen to form carbon dioxide: $C + O_2 \rightarrow CO_2$.

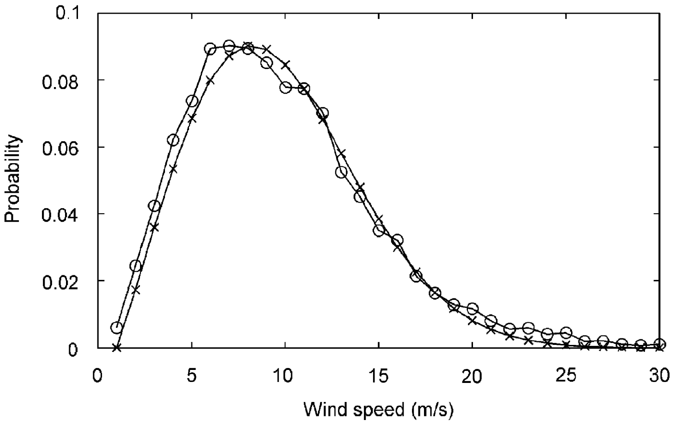

Fig. 2. Distribution of actual wind speed (○) compared to the Weibull distribution (×).

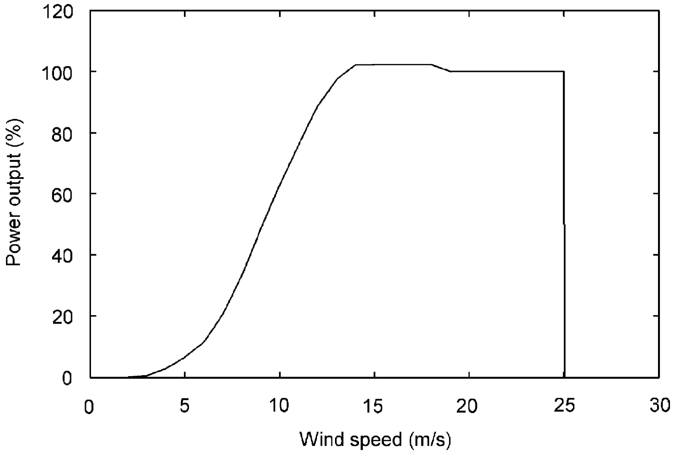

Fig. 3. Power curve for bonus 2.0 MW wind turbine.

Table 1
Component cost data

Component	Investment cost	O&M cost (%)	Lifetime (yr)
Wind turbine	€900/kW	2	20
Alkaline Electrolyser	€1300/kW	4	15
H_2 storage tank	Variable[a]	2	30
Compressor	€700/kW	4	10
Power converter	€130/kW	2	10
Diesel power plant	€630/kW	2	25

[a] $I = €80 * 2500 * (V_H^{max}/2500)^{0.75}$ [10]. V_H^{max} is the tank capacity in N m^3.

generation. Calculations were conducted with the power curve of a 2.0 MW bonus turbine. The wind distribution and power curve are displayed in Figs. 2 and 3, respectively. For the grid-connected system a time series of local load (month average values) was included. A time series for Norwegian power prices based on the years 1997–2003 was also added. Before inclusion, the prices were normalised and multiplied with a base price of 0.025 €/kWh. Prices were obtained from Nord Pool, the Nordic power exchange. The parameters used in the case study are:

- specific power consumption of electrolyser (SPC_e): 42 kWh/kg H_2[3];
- specific power consumption of compressor (SPC_c): 2.2 kWh/kg H_2;
- power converter efficiency: 95%;
- specific diesel consumption in diesel power generator: 0.278 l/kWh;
- diesel cost: 0.5 €/l;
- mass fraction of carbon in diesel: 86.5%;
- maximum grid import/export capacity: 5 MW;
- period of analysis: 25 years;
- rate of return: 8% pa.

The economic parameters used to calculate component costs are given in Table 1.

To calculate the H_2 demand, the following parameters were used for the existing diesel driven ferry:

- average diesel consumption: 1680 kg/day;
- diesel engine efficiency: 42% [11];
- mass fraction of carbon: 86.5%;
- LHV_{diesel}: 43.1 MJ/kg;
- emissions of NO_x: 4.7 kg/MWh AC [11].

The H_2 ferry is modelled as a hypothetical fuel cell driven ferry running on pure H_2. Hydrogen is to be stored onboard with a capacity of serving one day of operation. The ferry is set to be at dock during night time, where filling of H_2 is to occur within a time span of 4 hours. For the H_2 ferry, the following parameters were set:

- fuel cell efficiency: 60%;
- LHV_{H_2}: 120.0 MJ/kg;
- H_2 losses during filling and storage: 5%;
- maximum level of H_2 not supplied: 0%.

Following the method presented in Section 3.3, the average daily H_2 demand is found to be 450 kg/day.

5. Results

5.1. Grid-connected system

The derivation of the proposed configuration of the grid-connected system is fairly straightforward given the methodology presented in Section 3 and the input parameters listed in Section 4. When evaluating the grid-connected system, grid losses accompanying power import/export were set to 10% of active power, given the long distance from the regional grid. Results are displayed in Table 2. Fig. 4 shows average wind power, local load and electrolyser load on a monthly basis. The grid-connected system imports power from the grid mainly during late spring and late summer, when power prices are generally low. Subsequently, the system exports power during the

---

[3] The low power consumption can be justified regarding future industrial goals [12].

Table 2
Main results

	Grid-con. system	Isolated system
Avg. wind speed (m/s)	8.5	8.5
H_2 demand (kg/day)	450	450
Wind turbine (MW)	2.3	3.0
Electrolyser (MW)	1.0	2.0
H_2 tank (capacity in kg)	680	3400
Compressor (kW)	60	120
Power converter (MW)	1.1	2.2
Diesel power backup (MW)		0.9
Wind generation (GWh)	8.4	11.0
H_2 from wind power (%)	69[a]	96[b]
Excess wind power (%)	40[c]	36[d]
Red. of CO_2 emissions (t/yr)	1940	1700
Red. of NO_x emissions (t/yr)	14.6	< 14.6[e]
Wind–H_2 system cost (M€)	5.1	11.1
H_2 cost (€/kg)	2.8[f]	6.2
Break even diesel cost (€/l)	0.7	1.5

[a] From grid power import, 31%.
[b] From diesel backup power, 4%.
[c] Exported.
[d] Dumped.
[e] Due to lack of data for backup power generator.
[f] Including sale/purchase of market priced electricity.

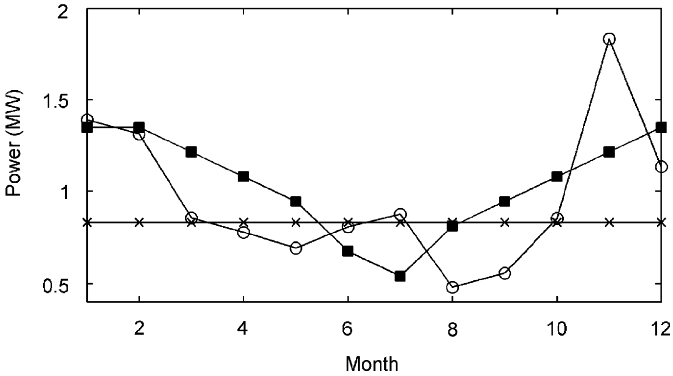

Fig. 4. Monthly variations in wind power (○), electrolyser load (×) and local load (□) for the grid-connected system.

winter when power prices are greater. The economical benefit of the seasonal difference in import and export reduces the H_2 cost. The reason for this is that the market price of electricity during periods of high import is lower than the cost of generating power from wind. A simulation with a system excluding this economic benefit showed that the H_2 cost increased by 8%. This effect is of course dependent on the time series for market power prices and the cost of producing electricity from wind.

The electrolyser is dimensioned to produce H_2 at near constant rate all year around. This reduces investment costs to a minimum and, therefore, also the H_2 cost. A larger electrolyser would be able to consume more wind power at any given time, but this also calls for the ability to store more H_2 which again would increase the H_2 storage and, therefore, also the total system costs. The low Norwegian power prices make it economical to utilise the grid backup frequently.

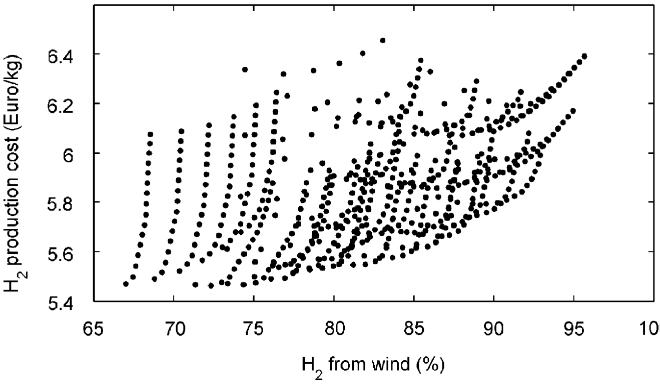

Fig. 5. H_2 production cost as function of H_2 production from wind with various configurations for the isolated system.

5.2. Isolated system

The dimensioning of the isolated system is more complicated, due to the cost of diesel fuel for the backup system. Based on the results for the grid-connected system, a set of different system configurations for the isolated system were chosen. The simulation of the isolated system comprised 576 different system configurations, with the following variable parameters:

- wind turbine: 2.0–3.0 MW ($\Delta = 0.2$ MW);
- electrolyser: 1.0–2.0 MW ($\Delta = 0.2$ MW);
- onsite storage capacity (H_2 at 200 bar): 10 000–40 000 N m^3 ($\Delta = 2000$ N m^3).

The simulation results are displayed in Fig. 5. The general trend is that production cost of H_2 increases with increased amount of H_2 produced from wind power (increased renewable fraction). However, the cheapest system is not the system with the lowest renewable fraction (leftmost marker). The leftmost 16 vertical markers represents systems with a wind turbine of 2.0 MW, an electrolyser of 1.0 MW and storage tank ranging from 10 000 N m^3 (lowest marker) to 40000 N m^3 (highest marker). The uppermost “horizontal” six markers represent systems with an electrolyser of 2.0 MW, a storage tank of 10 000 N m^3 and wind turbines ranging from 2.0 to 3.0 MW. The rightmost of these markers is the system with the highest H_2-cost, but it should be emphasised that the renewable fraction of this system is far from the highest obtained in the calculation. The six horizontal markers below represent the same system but with a tank of 12 000 N m^3 (next tank level). This indicates that when the electrolyser is relatively large compared to the wind turbine, having a larger tank is more significant in reducing the H_2-cost. The system of choice is represented by the rightmost marker due to the highest renewable fraction (lowest diesel consumption). Details for this system is represented in Table 2 and compared to the grid-connected system.

Another general trend is that the higher the diesel fuel cost, the more economical is the construction of a larger system, thus enabling more H_2 to be produced from wind power. This analysis is presented in Fig. 6.

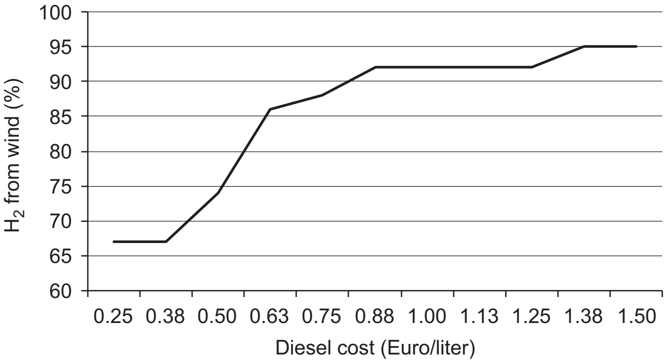

Fig. 6. Cheapest Wind–H_2 system (in terms of H_2 production from wind) versus diesel cost.

5.3. Main results

For the chosen systems with 0% H_2 not supplied, the main results are listed in Table 2. The system of choice for the isolated case is the system with the highest renewable fraction (% of H_2 generated by wind power). This system is more costly in terms of H_2 production cost but considered more favourable in terms of low consumption of backup power, refer to discussion in Section 3.2.2. The break-even diesel cost is the cost of diesel fuel for the existing ferry necessary to make the H_2 alternative economical. For the isolated system the break-even diesel cost also yields for the diesel power generator. This would make the H_2 cost even higher. H_2 production from diesel power corresponds to an average daily diesel consumption of about 200 kg (refer to diesel consumption of existing ferry). This also cuts the total reduction of CO_2 emissions by 12%. If $\frac{1}{3}$ or more of the H_2 is produced from diesel power, the backup generator would in fact consume more diesel than the existing ferry. A requirement for the grid-connected system is that the total annual power generation should equal or exceed the total annual power requirement of the H_2 production facility and losses in power import. Given this requirement, one could claim that the system is a zero-emission system even though it imports a large quantity of power that originally could descend from, e.g. fossil fuels.

5.4. Sensitivity analysis

Fig. 6 shows the impact on H_2 cost by changing the rate of return and the specific investment costs of different system components. Due to the small relative size and specific cost of the compressor and power converter, respectively, these were not included in the analysis. The graph yields for the grid-connected system. Fig. 6 shows that a marginal decrease in the cost of the wind turbine and the electrolyser is essential in reducing the production cost of H_2. The effect of changing the wind turbine cost displays the importance of electricity cost in electrolytic H_2 production. Another important factor is the rate of return, since the system is characterised by high investment costs and low operational costs. Changing the period of analysis would have no effect, since the annuity cost is the basis for the H_2 cost calculation (Fig. 7).

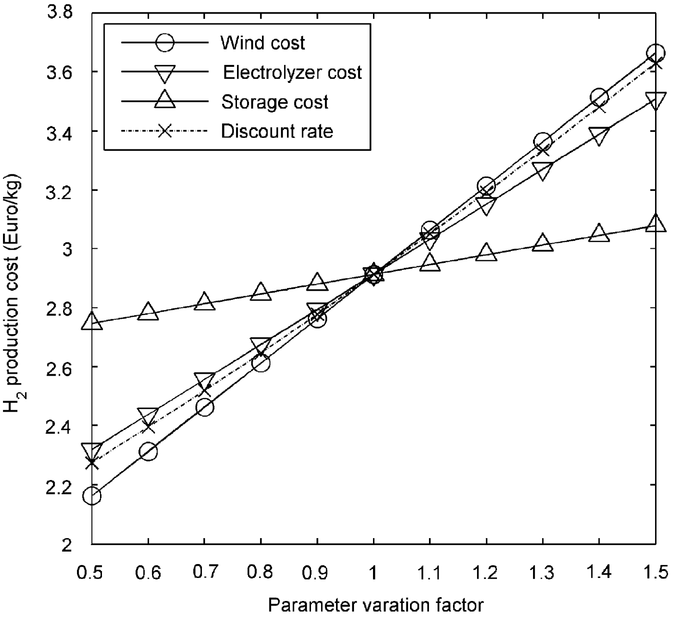

Fig. 7. Impact on H_2 cost by altering economic parameters (specific investment cost and rate of return) for the grid-connected system.

6. Conclusions

Profitability of the Wind–H_2 system is highly dependent on the original fuel costs of the ferry. For the grid-connected system to be economical, the existing ferry needs to pay a diesel cost of 0.7 €/l or more. This is not taking into account the expenditures for a fuel cell driven ferry, a technology which is currently on the research stage and not yet commercially available. The grid-connected system is dimensioned with the lowest possible realistic component sizes, meaning that the electrolyser runs on almost constant power all year. Tank volume is cut to a minimum, meaning that the tank is almost emptied during filling and quickly filled up during the day. Utilisation factors for the components will be high, but the system relies on considerable power exchange with the grid. The grid-connected system comprises a wind turbine of 2.3 MW, an electrolyser of 1.0 MW and a H_2 storage tank capacity of 680 kg, accounting for 1.5 days of demand. Production cost of H_2 would be 2.8 €/kg.

In case of the stand-alone system, the diesel cost is significant both in calculating the H_2 cost and the fuel cost of the ferry. For this system there is a need for a substantial increase in diesel fuel costs to make the H_2 alternative profitable. The system is dimensioned to produce larger amounts of H_2 in a short time and store near eight days of H_2 demand. The system would experience extensive power dumping and periods where diesel power produces much or all of the H_2 (especially during late summer with low wind speeds). Due to existing grid capacity, an isolated system is considered a poor alternative, both in regards of H_2 cost, which was found to be over two times higher with a diesel cost of 0.5 €/l, and in an environmental point of view, where the zero emission system stands forward as the ideal system. The isolated system comprised a wind turbine of 3.0 MW, an electrolyser of 2.0 MW and a H_2 storage tank capacity of 3400 kg. Production cost of H_2 would be 6.2 €/kg. Due to the optimisation of the Wind–H_2 system, the isolated system of choice is not the cheapest (being a system with a H_2 cost of 5.5 €/kg), however, the system of choice has the highest renewable fraction (production of H_2 from wind power) reaching 96%. The cheaper system would have a renewable fraction of only 74%.

The analyses are based on a one-year time series of wind speeds, close to a long term yearly average. In order to evaluate both systems in a long-time perspective, data from multiple years, with extremity years of low and high wind speeds should be obtained. However, the grid-connected system will have sufficient power supply from the grid at all times, so dimensioning the system based on wind speed data from a year average would be a good simplification. In case of the isolated system, this would probably be insufficient. It is concluded that if grid power is available, and interaction with the grid does not lead to unwanted disturbances in the power flow, the grid should be connected. This would make possible a smaller system with optimised configuration. Sufficient grid connection would also prevent dumping of excess wind power. Another beneficial outcome of grid connection is the fact that excess wind power is mostly generated during winter when market power prices are high, while the main deficit of wind power is found during late summer when prices are generally lower. To conclude, the highly varying power generation from the exploitation of wind resources is problematic in dealing with a constant H_2 demand. Dimensioning a Wind–H_2 system for this purpose only, is especially challenging.

References

[1] Norwegian Water Resources and Energy Directorate; 2005. ⟨http://www.nve.no⟩.

[2] Hofstad K, Mølmann K, Tallhaug L. Vindkraftpotensialet i Norge (Eng.: Wind power potential in Norway). Report 17, Norwegian Water Resources and Energy Directorate, Oslo, Norway, 2005.

[3] Norwegian Statistics; 2004. ⟨www.ssb.no⟩.

[4] Santarelli M, Calí M, Macagno S. Design and analysis of stand-alone hydrogen energy systems with different renewable sources. Int J Hydrogen Energy 2004;29:1571–86.

[5] Ulleberg Ø. Stand-alone power systems for the future: optimal design, operation and control of solar-hydrogen energy systems. PhD thesis, Norwegian University of Science and Technology, Trondheim, Norway; 1998.

[6] Ghosh PC, Emonts B, Stolten D. Comparison of hydrogen storage with diesel-generator system in a PV–WEC hybrid system. Sol Energy 2003;75:187–98.

[7] Vidueira JM, Contreras A. PV autonomous installation to produce hydrogen via electrolysis, and its use in FC buses. Int J Hydrogen Energy 2003;28:927–37.

[8] González A, McKeogh E, Gallachóir BO. The role of hydrogen in high wind energy penetration electricity systems. Renew Energy 2003;29: 471–89.

[9] Korpä M. Distributed energy systems with wind power and energy storage. PhD thesis, Norwegian University of Science and Technology, Trondheim, Norway; 2004.

[10] Amos WA. Costs of storing and transporting hydrogen. NREL/TP-570-25106, National Renewable Energy Laboratory, Golden, Colorado; 1998.

[11] Jordanger E, Møller-Holst S, Maurstad O, Brevik DA. Hydrogen som energibærer, Energi og utslippsregnskap for utvalgte energikjeder (Eng.: Hydrogen as an energy carrier, energy and emission calculations for selected energy chains). Technical Report TR A5713, SINTEF Energy Research, Trondheim, Norway; 2002.

[12] Ivy J. Summary of electrolytic hydrogen production. NREL/MP-560-36734, National Renewable Energy Laboratory, Golden, Colorado; 2004.