A LOGISTIC MODEL FOR ASSESSMENT OF WIND POWER COMBINED WITH ELECTROLYTIC HYDROGEN PRODUCTION IN WEAK GRIDS

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Abstract - In this paper, electrolytic hydrogen (H_2) production is proposed as a control method for wind power in weak grids, allowing for a high penetration of wind power without violating network constraints. A logistical simulation model for performance evaluation of such wind-H_2 systems has been described in the paper. The simulation model utilizes results from power flow calculations, in order to take into account thermal limits and restrictions on slow voltage variations in the network. The model has been tested on an example study of a Norwegian island where H_2 is proposed to be used as a fuel for a local ferry. The analysis showed that both voltage constraints and thermal limits of the power lines influence the ability of using electrolysis for load management. With the chosen component sizing and control strategy, the required H_2 storage capacity was equivalent to 19 days of H_2 consumption in the ferry, while about 80% of the H_2 was produced from wind power. The results obtained here 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 electrolyzer operating conditions.

Keywords - wind power, hydrogen, weak grids, distributed generation, power systems operation, logistic models, renewable sources

1 INTRODUCTION

Integration of wind power into existing distribution grids is beneficial since power generation near points of consumption reduces electric losses and thereby makes more efficient use of the transmission system. However, the best wind resources are often found in sparsely populated areas where the local grid consists of long radial distribution feeders. In these cases, voltage variations and the thermal capacity of the network components put a significant limit on the wind power generation. Full exploitation of the wind resources by construction of new lines would in many cases be expensive or controversial due to environmental concerns or other planning restrictions. It is therefore a need to explore control concepts that can increase the wind power penetration in existing weak grids, such as reactive power control, dissipation of wind energy, load management, energy storage and coordinated generation control [1, 2]. This paper considers electrolytic production of hydrogen (H_2) as a load management method, where H_2 is utilized as a fuel for a local car ferry. By operating the electrolyzer as a controllable load it is possible to utilize excess wind power that otherwise would have been dissipated due to grid constraints.

The main advantage of using H_2 as a storage medium to smooth wind power fluctuations is the flexibility that the H_2 storage systems offer regarding sizing, operation and end-use. H_2 storage has previously received most attention in connection with stand-alone solar power plants, but in the later years the interest for wind-H_2 systems has grown substantially. Recently, the world's largest wind-H_2 plant was installed at the island Utsira in Norway, comprising 600 kW wind turbine, 48 kW electrolyzer, 55 kW H_2 combustion engine, 10 kW fuel cell and compressed H_2 storage capacity of about 215 kg. The system is designed to provide reliable power to 10 households [3]. The interest for stand-alone power systems with H_2 storage is high, but less attention has been given on the possibilities of using H_2 production as a method for reducing wind power fluctuations in constrained grids. It has been proposed in [4] to use excess wind energy in County Cork, Ireland, for large-scale production of H_2 to the transport sector. In Norway, the wind power potential is especially good at the coastline, where the existing distribution grids typically have weak connections to strong grid points. H_2 produced from excess wind energy in these regions could be used in public transport, such as buses and ferries, and thus replacing polluting fossil fuels. In addition, oxygen (O_2) is a by-product from water electrolysis that can be used locally in fish farms [5].

Different means of utilizing H_2 storage for exploitation of wind resources are proposed in [6]. A logistical simulation model was developed for assessment of different wind-H_2 configurations. Grid constraints were treated in a simple manner, by constant limitations for active power flow. In this work, the model is extended by introducing a control strategy based on voltage limitations in the grid. A similar simulation model is described in [1], where a battery energy storage system or a pumped hydro plant is operated for reducing the steady state voltage variations of wind power.

The purpose of the work presented in this paper is to develop and evaluate control strategies for electrolytic H_2 production that maximizes the utilization of wind power in weak grids and ensures a reliable supply of H_2 to a local market, such as fuel for ferries or cars. In this paper, the H_2 storage alternative is compared with dumping of excess wind energy. The presented simulation model is well suited to be used in conjunction with cost optimization to study how the component sizing and control strategy influences the cost of electricity and H_2 delivered from the wind-H_2 system. Such assessments, based on realistic case studies, are necessary to give an indication on how far away H_2 storage is from becoming a viable alternative for increasing the utilization of renewable energy sources.

The paper is organized as follows: Chapter 2 describes the mathematical models of the different components that comprise the wind-H_2 system, the control strategy for the electrolyzer and the structure of the logistic simulation model. The model is tested on a case study of a Norwegian island, which is described in chapter 3. Results from computer simulations are presented and discussed in chapter 4 and 5, respectively. Grid data for the case study is given in the appendix.

2 LOGISTIC MODEL

2.1 Balance equations

The logistic model uses a simplified representation of a distribution grid as shown in Figure 1. An electrolyzer produces H_2 when the wind power output, P_w, exceeds the capacity of the grid. The electrolyzer uses DC power for splitting water into H_2 and O_2. A controllable dump load is operated if the H_2 storage system is not capable of absorbing all the excess wind power. Alternatively, wind energy can be dissipated by blade pitching. The logistic model does not distinguish between these control mechanisms.

The power balance at time step t is

$$P_e(t) + P_g(t) + P_d(t) = P_w(t) - P_l(t) \quad (1)$$

where P_e is the electrolyzer power, P_g is the power exported to the main grid, P_d is dumped wind power and P_l is the local load. The relation between electrolyzer power and the mass flow rate of H_2, $\dot{m}_{h,e}$ (kg/h), is given by

$$P_e(t) = SPC_e \dot{m}_{h,e}(t) \quad (2)$$

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

$$P_e{}^{min} \leq P_e(t) \leq P_e{}^{max} \text{ or } P_e(t) = 0 \quad (3)$$

where $P_e{}^{max}$ is the electrolyzer capacity and $P_e{}^{min}$ is the power consumption at minimum H_2 production. The restriction in (3) states that the electrolyzer must either be operated at $P_e \geq P_e{}^{min}$ or be switched off. The procedure of on/off switching is important if the electrolyzer 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, electrolyzers have a minimum operating point ranging from 10% to 50% of nominal power depending on the manufacturer. The efficiency of actual electrolyzer plants approaches zero for low operating points because of the power consumption of auxiliary equipment. In addition, alkaline electrolyzers must maintain a minimum protection current [7].

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

$$m_h(t) = m_h(t-1) + (\dot{m}_{h,e}(t) - \dot{m}_{h,f}(t))\Delta t \quad (4)$$

where m_h is the mass of stored H_2 and $\dot{m}_{h,f}$ 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:

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

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

$$\dot{m}_{h,ns}(t) = \dot{m}_{h,d}(t) - \dot{m}_{h,f}(t) \quad (6)$$

where $\dot{m}_{h,d}$ is the H_2 demand and $\dot{m}_{h,ns}$ is the amount of H_2 not supplied.

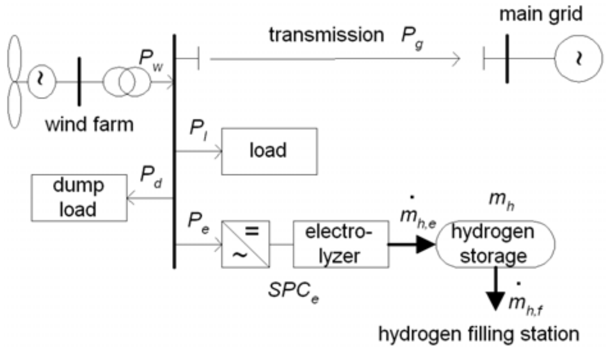

Figure 1: Schematic illustration of the components in the logistic model.

2.2 Control strategy

For the system considered here, the objective of the control strategy is 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 electrolyzer power so that the voltage levels in the grid are kept within acceptable limits. Wind generation leads to voltage increase, which is reduced by increasing the power consumption of the electrolyzer. For a specific wind generation and consumer load, it is possible to find the required electrolyzer power $P_{e,req}$ that reduces the voltage to the highest acceptable level, V_{max}. For low wind generation, when the voltage level is below V_{max}, $P_{e,req}$ will be zero. In the model, $P_{e,req}$ is represented as a function of P_w and P_l, which is established prior to running the logistic model, by the use of power flow calculations. Similarly, power flow calculations are used to find the maximum allowable wind generation $P_{w,lim}$ as a function of P_l and

P_e. Examples of these functions are provided in chapter 4.1. If the electrolyzer system is not able to reduce the voltage level sufficiently, the dump load is operated so that the net wind generation (wind generation - dump load) is equal to $P_{w,lim}$.

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

The algorithm for the control strategy is implemented as a MATLAB-function and is given in the 8 steps shown below. First, $P_{e,req}$ is calculated based on the wind power and consumer load at time step t. Then, the set-point for the electrolyzer power $P_{e,set}$ is determined. A sub function is called, which seeks to minimize the difference between the actual electrolyzer power and the set-point, based on the component models for the H_2 storage system. A check on the wind power limit is performed 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.

1. Read $P_w(t), P_l(t), \dot{m}_{h,d}(t), m_h(t-1)$
2. Calculate $P_{e,req}$
3. If $m_h < {m_h}^{lim}$ then $P_{e,set} = {P_e}^{max}$
   elseif $P_{e,req} > {P_e}^{min}$ then $P_{e,set} = P_{e,req}$
   else $P_{e,set} = {P_e}^{min}$
4. Solve $\min[\,|P_e(t) - P_{e,set}|\,]$
   subject to H_2 equations (2)-(6)
5. Calculate $P_{w,lim}$
6. If $P_w(t) > P_{w,lim}$ then $P_d(t) = P_w(t) - P_{w,lim}$
   else $P_d(t) = 0$
7. Calculate $P_g(t)$ from power balance (1)
8. Return $P_e(t), P_g(t), P_d(t), \dot{m}_{h,f}(t), \dot{m}_{h,ns}(t), m_h(t)$

2.3 Computer implementation

Power flow calculations are necessary to find how wind generation, consumer load and electrolyzer power influence the steady-state voltage level in the grid. The power flow toolbox MATPOWER [8] is employed for this purpose. The power flow results are used to establish equations for $P_{e,req}$ and $P_{w,lim}$ which are used in the control strategy of the logistic model as described in chapter 2.2. Thus, the power flow calculations are decoupled from the logistic simulation model.

The 5 steps shown below summarize the structure of the logistic model implemented in MATLAB. The simulation input file contains component model parameters, simulation parameters and parameters that determines the functions for $P_{e,req}$ and $P_{w,lim}$. Time series for wind generation, P_w, is generated from a time series for wind speed, v, and a power curve specified in the simulation input file. In step 4, the control strategy function described in chapter 2.2 is called, which returns the values of simulated variables for time step t. This is repeated until the final time step T is reached. In Step 5, the summary results are calculated. This includes utilization factors of the different components, total electrical energy generation and consumption in the simulation period and total H_2 production and consumption.

1. Read parameters from simulation input file
2. Read time series for $v, P_l, \dot{m}_{h,d}$ from text files
3. Construct time series for P_w
4. for $t = 1 : T$
   run control strategy
   store simulation variables for time step t
5. Calculate summary results and write to output file

3 EXAMPLE CASE STUDY

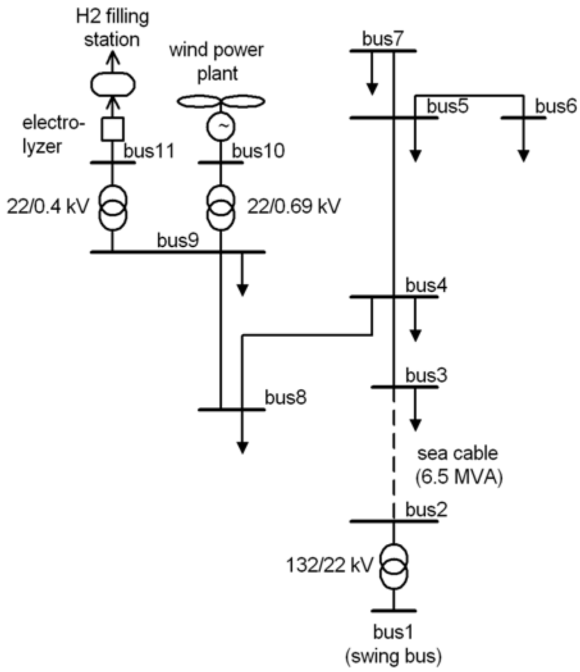

Figure 2: Single line diagram of the example grid.

The model has been applied to an example system, which represents an island at the Norwegian coastline with good wind conditions and limited grid capacity. A single line diagram of the example grid is shown in Figure 2. The local distribution grid is connected to the mainland grid by a subsea cable with 6.5 MVA capacity, and a potential location for a wind farm is chosen based on the best wind conditions at the island. Detailed grid data and load distribution data are given in the appendix. The main load centre is at another place of the island, where also a quay for a small car ferry is located. It is proposed here to examine the possibilities of running the ferry on H_2 produced locally from water electrolysis, as shown at bus11 in the single-line diagram. Based on present ferry schedules, the daily consumption of H_2 to the ferry is estimated to be approximately 560 kg, and it is assumed that the consumption is constant during the year and that filling occurs each day at 06:00. The specific power consumption of the electrolyzer, SPC_e, is set to 56 kWh/kg, based on the energy requirement of commercial electrolyzers [9].

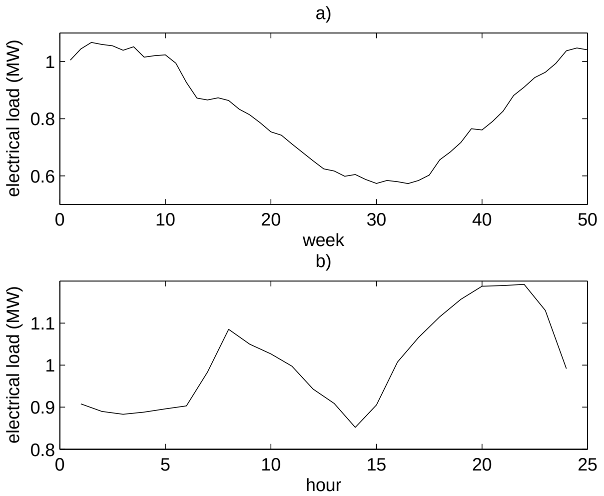

Figure 3: a) Electric load variations during the year. b) Electric load variations during a day.

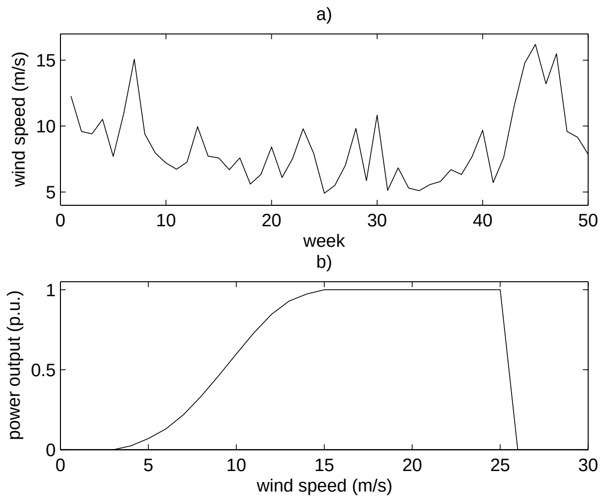

Figure 4: a) Wind speed variations during the year. b) Wind power curve.

Based on requirements for steady-state voltage variations in the region, the maximum voltage level, V_{max}, is chosen to be 1.06 p.u. referred to the 22 kV distribution grid. This is more restrictive than the European voltage quality standard [10], which states that the slow voltage variations shall be within $\pm$ 10% at 230V level during 95% of the week. At high wind generation, the voltage levels will be highest at the common connection point of the wind farm, which is bus9. The electrolyzer power is varied in order to keep the voltage at bus9 below V_{max}, and the rectifier is assumed to be operated at unity power factor. The minimum operating power, $P_{e,min}$, is set to 20% of the electrolyzer capacity.

The simulation period is set to one year with hourly time steps. Figure 3 shows the variations of the electricity consumption at the island during the year and the day, with high consumption in winter and low consumption in summer. This is typical for Norwegian conditions. The seasonal wind speed variations follow a similar pattern as the electrical load as observed from Figure 4, but with higher relative variations. Figure 4 also shows the power curve that has been used in the simulations. With the chosen wind power curve and wind speed series with average annual wind speed of 8.5 m/s, the utilization time of the wind power plant is about 3500 hours. The power factors of the electrical load and the wind power plant are set to 0.95 lagging and 0.96 lagging, respectively.

4 RESULTS

4.1 Power flow analysis

A power flow analysis has been performed to find the maximum wind power penetration that is possible without violating the voltage constraints. Table 1 displays the results for different combinations of wind power and electrical load. With no wind power, the voltage magnitude is close to 1 p.u., and the active power losses, P_{loss}, are only 0.3-1.2% of the total load. It is found that the wind power limit is 4.4 MW at minimum electrical load, since this gives a voltage magnitude of 1.06 p.u. at bus9. Due to the long distribution distances, the active power losses related to wind generation is relatively high (about 10%).

P_w (MW)	P_l (MW)	S_{3-2} (MVA)	P_{loss} (MW)	Q_{imp} (MVAR)	V_{bus9} (p.u.)
0	0.4	-0.41	0.001	0.03	0.996
0	0.8	-0.83	0.006	0.17	0.991
0	1.3	-1.37	0.016	0.34	0.985
4.4	0.4	4.01	0.475	1.78	1.060
4.4	0.8	3.73	0.461	1.90	1.056
4.4	1.3	3.42	0.447	2.06	1.050

Table 1: Power flow results. The values for total load, P_l, refers to minimum, average and maximum load.

As observed from Table 1, a load increase at the island reduces the voltage and thus makes it possible to generate more wind power. It is therefore proposed to use an electrolyzer plant at bus11 for load management. An iterative procedure has been applied to find the electrolyzer power that gives a voltage level of 1.06 p.u. at bus9 for a range of values for wind power generation, P_w, and consumer load, P_l. The result is plotted in Figure 5. It can be observed that the required electrolyzer power increases with increasing wind power and decreasing load. The data fits well to the second order multivariable function

$$P_{e,req} = -0.016{P_w}^2 + 0.80P_w - 0.52P_l - 3.05 \quad (7)$$

The corresponding function for maximum wind generation is

$$P_{w,lim} = 0.056{P_e}^2 + 1.60P_e + 1.06P_l + 3.89 \quad (8)$$

Equations (7) and (8) are used in the logistic simulation model, in order to represent the steady-state voltage limit in the network. The quality of the fitted data can be measured by the root-mean-squared error

$$RMSE = \sqrt{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2/(n-k-1)} \quad (9)$$

where y_i is the value obtained from power flow and $\hat{y}_i$ is the fitted value. The number of calculated data points is n

and the number of free variables is k. In this case, $n = 36$ and $k = 2$. It is found that $RMSE = 29$ kW for $P_{e,req}$ and $RMSE = 35$ kW for $P_{w,lim}$.

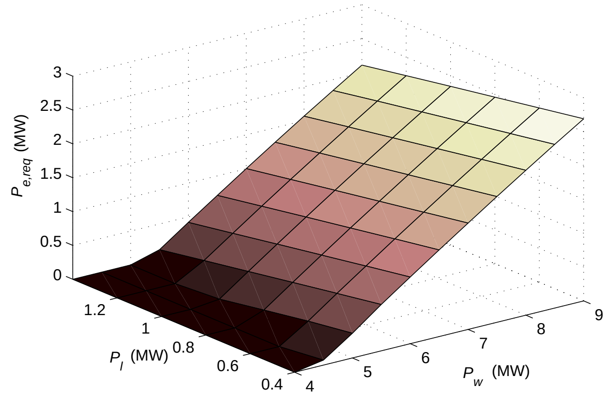

Figure 5: Required electrolyzer power as a function of wind generation and electrical load.

4.2 *Wind power only*

First, the possibilities of utilizing the wind resources without H_2 storage are studied. It was found from the power flow analysis that it is possible to install at least 4.4 MW wind power without violating the voltage constraints at any time. If the installed wind power capacity is above 4.4 MW, wind power must be dumped in periods with high wind speed and low electricity consumption. This is illustrated in Figure 6, where the average energy flow is plotted for different wind power capacities. We clearly see that the annual dumped energy, E_d, increases significantly for high penetration levels. The net wind generation is reduced analogously, which will affect the production cost of wind energy. With an installed wind power capacity of 8.2 MW, the dumped wind energy equals the total demand at the island.

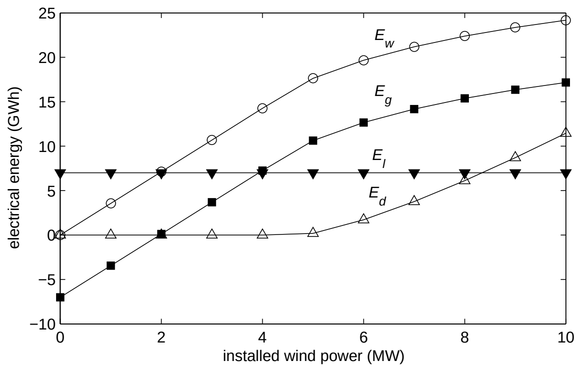

Figure 6: Yearly generation and consumption as a function of installed wind power capacity, in the case with no H_2 production. E_w: net wind generation (subtracted for dumped energy), E_d: dumped wind energy, E_l: electricity consumption, E_g: net export to the main grid.

4.3 *Wind power with H_2 production*

When water electrolysis is used as a controllable load for wind power, it is necessary to determine the sizing of the wind power plant, the electrolyzer and the H_2 storage plant that both satisfies the H_2 demand and does not cause violation of voltage constraints in the network. Moreover, the thermal capacity of the lines should not be exceeded. In addition to the already mentioned criteria, the component sizing is chosen so that the H_2 storage level at the last time step is approximately equal to the initial storage level. This ensures that there is balance between the production and consumption of H_2 over the year.

The logistic simulation model has been run for a range of values for electrolyzer capacity, H_2 storage capacity and wind power capacity. An optimal solution of the sizing problem has not been sought here, since it then would be necessary to take into account other factors such as investment costs, component lifetime and power market conditions [6]. It is found that ${P_w}^{max} = 9.5$ MW, ${P_e}^{max} = 3.0$ MW and ${m_h}^{max} = 10,700$ kg gives satisfactory results for the example system studied here. A single 3.0 MW electrolyzer is not available in the market today, but the plant could for instance be designed with two separate alkaline electrolyzers from Norsk Hydro [9]. The H_2 supply security limit, ${m_h}^{lim}$, which was introduced in chapter 2.2 is set to one day's H_2 consumption, i.e. 560 kg.

Figure 7 displays the average weekly H_2 storage level and electrolyzer power for a yearly simulation of the system. It is evident from the figure that the amount of stored H_2 is much higher during winter than summer. This is because the wind generation is highest in winter, and the electrolyzer power follows the wind power variations, according to the voltage magnitude requirements in the network. At summer, the wind generation is mostly below the level that causes unacceptable voltage rise. In this period, the electrolyzer power is drawn from the main grid. Regardless of the wind generation, the electrolyzer power is always kept at least at 20% of its capacity, i.e. 600 kW. Moreover, the electrolyzer power is set to ${P_e}^{max}$ when the H_2 storage level drops below ${m_h}^{lim}$. This causes the average electrolyzer power to be relatively high between week 30 and 40, even though the wind generation in these weeks are very low, according to Figure 4. The utilization time for maximum capacity of the electrolyzer and the subsea cable is 3380 hours and 4180 hours, respectively.

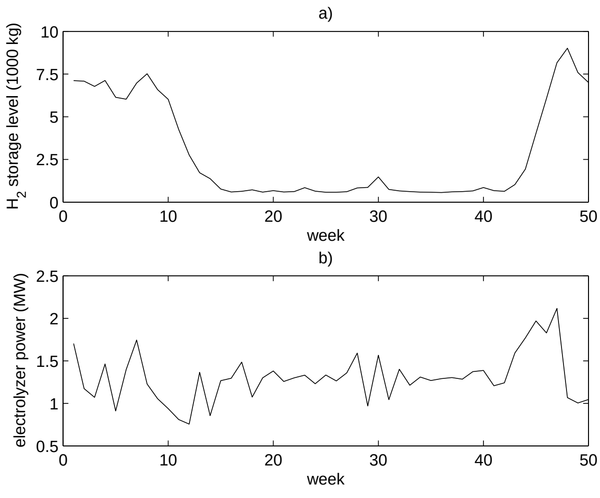

Figure 7: a) Average weekly H_2 storage content. b) Average weekly electrolyzer power.

A comparison between wind power only and wind power with H_2 production is given in Table 2 for 9.5 MW installed wind power. The symbols E_w, E_d, E_l and E_g

in the table are the same as explained in Figure 6. E_e is total electrolyzer energy and $E_{e,g}$ is electrolyzer energy imported from the main grid. The latter variable is used to distinguish between H_2 production from local wind power at the island and from other power plants.

With no H_2 production, as much as 30% of the available wind energy is dumped. There is also a considerable export of wind energy to the main grid. With H_2 production, there is no dumped wind energy, and the export of wind energy is reduced due to the electrolyzer load. Moreover, the energy import form the main grid to the electrolyzer is 2.4 GWh, or 21% of the total electrolyzer energy.

	E_w	E_d	E_l	E_g	E_e	$E_{e,g}$
WP only	23.8	10.1	7.0	16.8	0	0
WP+H_2	33.9	0	7.0	15.4	11.4	2.4

Table 2: Comparison of results for wind power only (WP only) and wind power with H_2 production (WP+H_2). Installed wind power capacity is 9.5 MW. All values are in GWh.

5 DISCUSSION

Since 21% of the electrolyzer power is drawn from the main grid, there is not sufficient excess wind energy available to ensure that all H_2 is produced from wind power. An evaluation of the power market is required to give any suggestions if it is beneficial to reduce the power import further. Due to the seasonal wind variations, very large H_2 storage would be required if all H_2 should be produced directly from wind power, since the fuel demand for the ferry is expected to be more or less constant during the year. Moreover, to reduce the amount of power drawn from the main grid, the electrolyzer could be set in standby-mode in periods with low wind generation, instead of producing H_2 at minimum power. Because of the fluctuations in wind generation, new control schemes should be adopted to avoid too frequent starts and stops of the electrolyzer, since this may have a negative impact both on the performance and the lifetime of the electrolyzer.

If the market price of power is low, it may be beneficial to increase the power import for H_2 production, and thus reduce the H_2 storage size. It is possible to supply the required amount of H_2 to the ferry (560 kg/day) by operating the electrolyzer continuously at 1.3 MW. In this case, the maximum voltage level in the grid is reached at 6.5 MW wind power generation. However, it is observed from Table 3 that the maximum wind power can be increased to 7.8 MW in this case by operating the rectifier at a lagging power factor of 0.9.

P_w (MW)	P_l (MW)	PF_e (-)	S_{3-2} (MVAR)	Q_{imp} (MVAR)	V_{bus9} (p.u.)
6.5	0.4	1.0	4.95	2.62	1.059
7.8	0.4	0.9	6.44	4.94	1.059

Table 3: Power flow results for 1.3 MW electrolyzer power. PF_e refers to the lagging power factor of the rectifier connected to the electrolyzer.

In Table 1 it was shown that the maximum voltage level was reached at 4.4 MW wind power for the case with no H_2 production. At this point, only 60% of the capacity of the sea cable (6.5 MVA) is utilized. By for instance installing an inductive load of 1.7 MVAR at bus5, it is possible to increase the wind power generation to 6 MW without violating the voltage limits and the thermal limit of the sea cable. On the other hand, the grid losses will then increase significantly due to the increased import of reactive power.

The voltage level of the swing bus has been chosen to constant for the simplified grid considered here. Preliminary load flow studies of the actual distribution grid have shown that the voltage level at this grid point will vary from 1.01 p.u. to 0.98 p.u., depending on the power consumption in the area. This will also have an impact on the maximum possible wind power generation. For example, if the swing bus voltage is 1.01 p.u. at minimum power consumption, the voltage limit at bus9 is reached already at 3.6 MW wind power.

With the present approach, a power flow analysis is performed before running the logistic simulation model. In order to further evaluate the possibilities for reactive power control, and to study issues such as the impact of voltage variations of the swing bus, it would be beneficial to integrate the power flow calculations in the logistic model, as described in [1]. This could be obtained by calling the power flow routine at each simulation time step, and modify the control strategy of the electrolyzer accordingly.

6 CONCLUSION

In this paper, electrolytic H_2 production is proposed as a load management method for wind power. 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 significant increased utilization of wind power resources in weak grids. H_2 production and storage may be a viable option in areas where reinforcements of existing grids are costly or controversial due to environmental concerns. A logistical simulation model for performance evaluation of such wind-H_2 systems has been described in the paper. The simulation model utilizes results from power flow calculations, in order to take into account limitations on slow voltage variations in the network.

The model has been tested on an example study of a Norwegian island with good wind conditions and the possibilities of using H_2 as a fuel for a local ferry. The analysis showed that both voltage constraints and thermal limits of the power lines influence the ability of using electrolysis for load management. Moreover, the results emphasize the consequences of seasonal wind variations regarding H_2 storage sizing and the amount of H_2 that is produced by drawing power from the main grid. With the chosen component sizing and control strategy, the required H_2 storage capacity was equivalent to 19 days of H_2 consumption in the ferry, while about 80% of the H_2 was produced from wind power. If this amount should be increased further, it would require a larger wind farm and a higher H_2 storage capacity, as well as improved control strategy for on/off switching of the electrolyzer. The results obtained here indicate that there are large benefits of using the grid as backup for H_2 production, regarding the required H_2 storage size and the operating conditions for the electrolyzer.

Further modelling work will focus on the electrolyzer operation, and the possibilities of using an active rectifier for reactive power control at the site of the electrolysis plant. The simulation model will also be used in conjunction with cost optimization to study how the component sizing and control strategy influences the cost of electricity and H_2 delivered from the wind-H_2 plant.

7 ACKNOWLEDGEMENTS

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A APPENDIX

bus	L [km]	Z [Ω/km]	B [μS/km]	S_{max} [MVA]
2-3	2.2	0.64+j0.13	53.4	6.5
3-4	3.9	0.36+j0.37	3.1	13.8
4-5	3.9	0.51+j0.38	3.0	10.9
5-6	4.6	0.72+j0.40	2.9	9.0
5-7	6.2	0.72+j0.40	2.9	9.0
4-8	5.4	0.72+j0.40	2.9	9.0
8-9	6.9	0.72+j0.40	2.9	9.0

Table 4: Line data.

bus	S_N [MVA]	U_{N1} [kV]	U_{N2} [kV]	e_r [p.u.]	e_x [p.u.]
1-2	12	132	22	0.004	0.086
9-10	*)	22	0.69	0.009	0.055
9-11	**)	22	0.40	0.011	0.047

Table 5: Transformer data. *) and **) Transformer rating is set to 1.1 times the value of wind power plant rating and the electrolyzer rating, respectively.

bus	3	4	5	6	7	8	9
f_l	0.01	0.1	0.54	0.1	0.06	0.14	0.05

Table 6: Load distribution on the buses. f_l is the fraction of the total load at the specified bus.

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