A MODEL FOR TECHNO-ECONOMIC OPTIMIZATION OF WIND POWER COMBINED WITH HYDROGEN PRODUCTION IN WEAK GRIDS

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Abstract – This paper presents a two-step method for dimensioning and time-sequential operation of Wind-hydrogen (H_2) plants operating in power markets. Step 1 involves identification of grid constraints and marginal power losses through load flow simulations. Step 2 involves solving a model for optimization of the component sizes (wind turbine, electrolyser, H_2 storage, fuel cell) and the corresponding time-sequential operation of each component. Results are presented through a case study of a Norwegian island with good wind resources, a weak connection to the main transmission grid and a commuting ferry, constituting the H_2 load. Main results show that if H_2 consumers are willing to pay at least 0.31-0.34 € per Nm^3, the wind power penetration could be cost-effectively increased by 1.8-1.9 MW by including an average H_2 load of 1.36 MW. The H_2 plant is very dependent on power import and H_2 storage capacity is only 1.5 - 2 days of average demand. The operational flexibility of the H_2 plant opens for a more optimal power exchange with the grid. It is concluded that H_2 produced from wind power could be competitive with fossil fuels. H_2 is however not cost-effective as *electric energy storage* for wind power plants operating in power markets.

Keywords: Wind power, hydrogen, weak grids, distributed generation, renewable energy, quadratic optimization

1 INTRODUCTION

The best wind power resources are often found far from the main transmission grid and possible connection points could be at the end of long radial distribution feeders. A small penetration of wind power would be beneficial regarding reduction of marginal power losses. However voltage levels and thermal capacities form a significant upper limit on the technical and cost-effective penetration. Reinforcing the grid might be too costly. Options to increase the wind power penetration could be energy storage in the form of conventional batteries or flywheels but these technologies show both low energy capacity and high cost. Lower cost options such as pumped hydro or compressed air are only available at specific sites.

Another possibility to increase wind power penetration is electrolytic hydrogen (H_2) production. Electrolysers use direct current to split water molecules into pure H_2 and oxygen (O_2). H_2 is then compressed and stored in high pressure tanks, while the O_2 is either vented to air or redistributed. Many different technologies for production and storage of H_2 exist, see e.g. [1] for a review of H_2 technology and discussions on wind power combined with H_2 production. H_2 has been an important industrial product for decades. However the main interest world-wide today is dedicated to the potential of using H_2 as a clean energy carrier in the transportation sector and stationary power and heat supply. Numerous demo-projects with H_2 fuelled buses, cars and ferries are planned or operational world wide[1]. H_2 produced with indigenous renewable energy will both reduce energy imports (e.g. oil and gas) and lower emissions of CO_2.

The high operational flexibility and the modularity of electrolysers and H_2 storage tanks makes H_2 technology well suited for combination with renewable power generation. Electrolyser capacities range from tens of kW to several MW. An increasing attention has been given to the production of H_2 from grid connected wind power in the literature, see e.g. [2] - [6]. The main advantage of grid connected systems over isolated systems is the ability to use the grid as power backup, which reduces the required H_2 storage capacity and thus investment costs. A drawback of H_2 as *electric energy storage* is the low round-trip efficiency. Combined with high costs of electrolysers and fuel cells this makes H_2 unsuitable for short-term energy storage in operation with a power market. However, the significantly lower energy storage costs (about 10 times cheaper than conventional lead-acid batteries) makes H_2 a good candidate for long-term electric energy storage in *isolated* power systems.

Techno-economic studies of combined Wind-H_2 plants in the literature have often used pre-determined component sizes and simple estimates of the electric grid capacity. Complex relations in time between wind power, energy demand, component costs and grid constraints determine the optimal size of the system components (wind power plant, electrolyser, H_2 storage, fuel cell). This paper presents a model that can assess at the same time the techno-economic dimensioning and time-sequential operation of a Wind-H_2 plant. The model is based on deterministic quadratic programming and the grid restriction inputs to the model are derived through load flow simulations. The model is solved for one year of operation with hourly values.

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[1] http://www.h2stations.org/

The paper is organized as follows: Chapter 2 presents the model and derives the relations between the components in terms of power and energy flow. Chapter 3 presents the case study and the following results are presented in Chapter 4. Conclusions are drawn in Chapter 5, followed by references and an appendix with more details on the economical data for the components.

Nomenclature

Nm^3	Normal cubic metre (1 atm, 0°C)
LHV	H_2 Lower Heating Value (3.0 kWh/Nm^3)
AC	Annual Cost
NI	Net Income
$ELYC$	Electrolyser&compressor system
FC	Fuel cell system
C_w	Specific annual cost of wind turbine (€/kW·yr)
C_e	Specific annual cost of ELYC (€/kW·yr)
C_H	Specific annual cost of H_2 storage (€/Nm^3·yr)
C_f	Specific annual cost of FC (€/kW·yr)
e_{tar}	Power import tariff (€/kWh)
e_H	Sales price of H_2 (€/Nm^3)
e_{Hi}	Cost of imported H_2 (€/Nm^3)
η_{ec}	ELYC efficiency (%)
η_f	FC efficiency (%)
P_w^{max}	Optimal Wind turbine capacity (kW)
P_e^{max}	Optimal ELYC capacity (kW)
H^{max}	Optimal H_2 storage capacity (Nm^3)
P_f^{max}	Optimal FC capacity (kW)
nP_e^{min}	Minimum ELYC operating power (%)
nH^{min}	Minimum H_2 storage volume (%)
nP_f^{min}	Minimum FC operating power (%)
P_e^{min}	Minimum ELYC operating power (kW)
H^{min}	Minimum H_2 storage volume (Nm^3)
P_f^{min}	Minimum FC operating power (kW)
H_{ns}^{max}	Maximum H_2 not supplied (annual %)
H_i^{max}	Maximum H_2 import capacity (Nm^3/h)
$nP_w(t)$	Timeseries of normalized wind power (p.u.)
$H_d(t)$	Timeseries of H_2 load/demand (Nm^3/h)
$e_{spot}(t)$	Timeseries of electricity spot prices (€/kWh)
$P_l(t)$	Timeseries of local electric load (kW)
$P_l^{est}(t)$	Timeseries of estimated local electric load (kW)
$H(t)$	H_2 storage level (Nm^3)
$H_p(t)$	H_2 production from ELYC (Nm^3/h)
$H_s(t)$	H_2 supplied by the Wind-H_2 plant (Nm^3/h)
$H_f(t)$	H_2 consumed by FC
$H_i(t)$	H_2 import (Nm^3/h)
$H_{ns}(t)$	H_2 not supplied (Nm^3/h)
$P_w(t)$	Absolute wind power generation (kW)
$P_{ew}(t)$	ELYC power from wind turbine (kW)
$P_{ei}(t)$	ELYC power imported from grid (kW)
$P_e(t)$	Total ELYC power (kW)
$P_f(t)$	FC power (kW)
$P_d(t)$	Dumped wind power (kW)
$P_{exp}(t)$	Power export (kW)
$P_g(t)$	Power exchange (export/import) (kW)
$P_g^{max}(t)$	Maximum power export capacity (kW)
$P_g^{min}(t)$	Maximum power import capacity (kW)
$ml(t)$	Marginal power losses in the electric grid (%)

2 WIND-H_2 PLANT MODEL

2.1 Plant model

Fig. 1 displays the model of the Wind-H_2 plant connected to the electric grid.

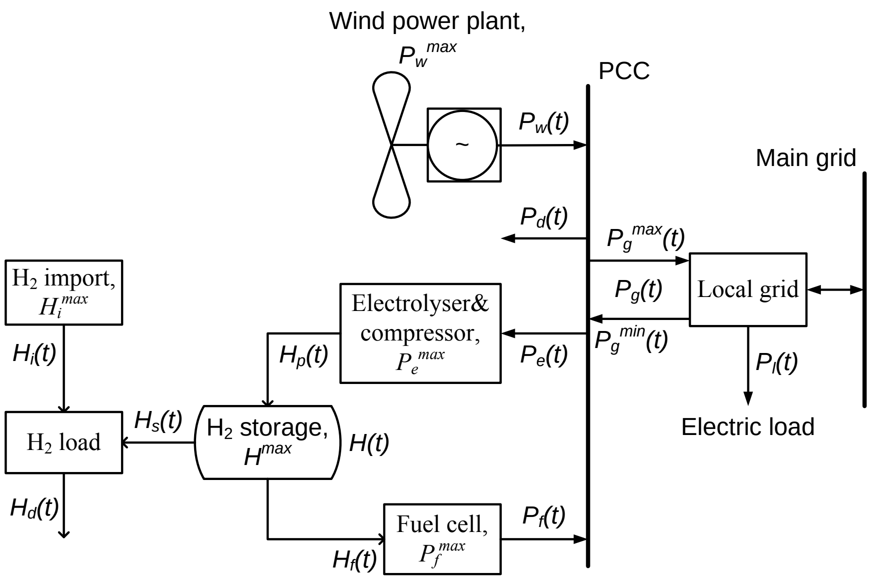

Fig. 1 : Model of the Wind-H_2 plant connected to an electric grid. Arrows show directions of power and H_2 flow.

The components included in the Wind-H_2 system and their corresponding installed capacities to be optimized are:

- Wind power plant, P_w^{max}
- Electrolyser&compressor system (ELYC), P_e^{max}
- H_2 storage tanks, H^{max}
- Fuel cell system (FC), P_f^{max}

Determining P_w^{max}, P_e^{max}, H^{max} and P_f^{max} is the main objective. The model is solved for a given time span (e.g. 1 year) and the corresponding time step variables for each component and the interaction with the grid will be derived throughout this chapter. The optimization formulation is given in section 2.3.

The ELYC and FC have minimum operating limits, given here by nP_e^{min} and nP_f^{min} respectively, below which both units must be shut down or put in stand by mode. Modern electrolyser systems can have nP_e^{min} as low as 5%[2]. Similarly H_2 storage tanks have a minimum operating pressure, which can be translated to a minimum storage level, nH^{min}, typically in the range of 10% for high pressure storage vessels. The minimum operating levels are expressed as

$$P_e^{\min} = nP_e^{\min} \cdot P_e^{\max} \quad (1)$$

$$P_f^{\min} = nP_f^{\min} \cdot P_f^{\max} \quad (2)$$

$$H^{\min} = nH^{\min} \cdot H^{\max} \quad (3)$$

To avoid binary operational variabels for the ELYC and FC, the two units are restricted to operate between the minimum and maximum limits at all times. The error of this simplification is expected to be small.

It is uncertain what the effect will be on modern electrolyser technology due to rapid start ups and shut downs. Degradation of the cells leading to higher maintenance costs have been observed for older technology, but these units were not constructed for intermittent operation. Electrolysers suitable for intermittent power input are still in the early stage of development and it is unknown how the effects will be. The same is true for FC technology. Experimental data and discussions relating to operation of a PEM (Proton Exchange Membrane) electrolyser with intermittent renewable energy can be found in e.g. [7].

2.2 Power and H_2 flow relations

[2] Inergon PEM, http://www.hydro.com/

The relations between power and H_2 flow in the ELYC system and the FC have been linearized. It is shown in [8] and [9] that under normal operating conditions the ELYC and FC system efficiencies are close to constant.

The H_2 storage balance is expressed as

$$H(t) - H(t-1) = H_p(t) - H_s(t) - H_f(t) \quad t \in \{1,...,T\} \qquad (4)$$

where *H(t)* and *H(t-1)* are the storage level at the end and the beginning of time step t respectively, $H_p(t)$ is the H_2 output from the ELYC, $H_s(t)$ is the H_2 supplied to the H_2 load and $H_f(t)$ is the H_2 consumed by the FC.

H(t) is limited by the upper and lower tank capacity

$$H^{\min} \le H(t) \le H^{\max} \quad t \in \{0,...,T\} \qquad (5)$$

To avoid emptying the H_2 tank at the end of the period the initial and resulting H_2 levels are restricted to

$$H(0) \le H(T) \qquad (6)$$

where H(0) and H(T) is the H_2 tank level at the beginning and the end of the period respectively.

The H_2 load balance for time step t is expressed as

$$H_d(t) - H_{ns}(t) = H_s(t) + H_i(t) \quad t \in \{1,...,T\} \qquad (7)$$

where $H_d(t)$ is the H_2 demand, $H_{ns}(t)$ is the H_2 not supplied, $H_s(t)$ is the H_2 supplied and $H_i(t)$ is the H_2 import.

H_2 import could be physically restricted and H_2 export is not considered, so

$$0 \le H_i(t) \le H_i^{\max} \qquad (8)$$

The H_2 not supplied should be restricted on an annual basis. It is expressed as follows

$$\sum_{t=1}^{T} H_{ns}(t) \le H_{ns}^{\max} \sum_{t=1}^{T} H_d(t) \qquad (9)$$

where $\sum H_{ns}(t)$ is the total H_2 not supplied and H_{ns}^{max} is the maximum level of H_2 not supplied.

The relation between H_2 production $H_p(t)$ and power input to the ELYC $P_e(t)$ can be expressed as

$$H_p(t) = P_e(t) \frac{\eta_e}{LHV} \quad t \in \{1,...,T\} \qquad (10)$$

where η_e is the ELYC efficiency based on the lower heating value (LHV) of H_2 (3.0 kWh/Nm^3).

$P_e(t)$ is restricted by the upper and lower bounds

$$P_e^{\min} \le P_e(t) \le P_e^{\max} \quad t \in \{1,...,T\} \qquad (11)$$

Due to an added grid tariff on power import, the electrolyser power for time step t is divided into power directly from wind $P_{ew}(t)$, and power import $P_{ei}(t)$

$$P_e(t) = P_{ew}(t) + P_{ei}(t) \quad t \in \{1,...,T\} \qquad (12)$$

It follows that $P_{ew}(t)$ is restricted by

$$P_{ew}(t) \le P_w(t) \quad t \in \{1,...,T\} \qquad (13)$$

where $P_w(t)$ is the wind power generation at time step t.

The FC power output $P_f(t)$ is expressed as

$$P_f(t) = H_f(t) \cdot \eta_f \cdot LHV \quad t \in \{1,...,T\} \qquad (14)$$

where $H_f(t)$ is the H_2 consumption and η_f is the FC system efficiency based on H_2 LHV.

$P_f(t)$ is limited by the upper and lower bounds

$$P_f^{\min} \le P_f(t) \le P_f^{\max} \quad t \in \{1,...,T\} \qquad (15)$$

Wind power generation at time step t is expressed as

$$P_w(t) = nP_w(t) \cdot P_w^{\max} \quad t \in \{1,...,T\} \qquad (16)$$

where $P_w(t)$ is the absolute wind power generation, $nP_w(t)$ is a normalized time series for wind power and P_w^{max} is the optimal installed wind power capacity.

The power balance at the point of common connection (PCC in Fig. 1) is expressed as

$$P_g(t) = P_w(t) + P_f(t) - P_e(t) - P_d(t) \quad t \in \{1,...,T\} \qquad (17)$$

where $P_g(t)$ is the net power exchange with the grid and $P_d(t)$ is dumped wind power due to grid constraints.

Due to different tariffs on power import and export the grid *export* is expressed as

$$P_{\exp}(t) = P_w(t) + P_f(t) - P_{ew}(t) - P_d(t) \quad t \in \{1,...,T\} \qquad (18)$$

which will always be ≥ 0, due to equation (13) and the fact that power dumping will never occur unless the maximum *export* level is reached.

The restrictions on power exchange with the grid can be expressed as

$$P_g^{\max}(t) = \zeta_1\left(P_l(t)\right) \quad t \in \{1,...,T\} \qquad (19)$$

$$P_g^{\min}(t) = \zeta_2\left(P_l(t)\right) \quad t \in \{1,...,T\} \qquad (20)$$

where P_g^{max} and P_g^{min} are the grid export limits and $P_l(t)$ is the electric load in the local distribution grid. P_g^{min} represents maximum *import* capacity and is therefore negative. ζ_1 and ζ_2 will depend on the grid layout and is therefore not generalized here. Equations (19) and (20) are derived in the case study.

$P_g(t)$ is thus limited by the upper and lower bounds

$$P_g^{\min}(t) \le P_g(t) \le P_g^{\max}(t) \quad t \in \{1,...,T\} \qquad (21)$$

The marginal power losses in the local distribution grid can be either positive or negative, dependent on the level of power export and the current load situation. The marginal losses are expressed as

$$ml(t) = \zeta_3\left(P_{\exp}(t), P_l^{est}(t)\right) \quad t \in \{1,...,T\} \qquad (22)$$

where $P_l^{est}(t)$ is a timeseries of estimated electric load based on a timeseries of actual load $P_l(t)$. The marginal losses are also dependent on the grid layout and are not generalized here. Equation (22) will be derived in the case study.

2.3 Optimization formulation

The objective function seeks to find the optimal combination of component sizes, and their respective time-sequential operation, that maximizes the total revenue of the combined Wind-H_2 plant

Maximize

$$\mathbf{c_1} \times \mathbf{x_1} + \sum_{t=1}^{T}\left(\mathbf{c_2}(t) \times \mathbf{x_2}(t) - \frac{1}{2}\mathbf{x_2}^{\mathbf{T}}(t) Q \mathbf{x_2}(t)\right) \qquad (23)$$

Subject to

Equations (1) - (22)

$\mathbf{x_1}$, $H_s(t)$, $H_{ns}(t)$, $P_d(t)$, $P_{ew}(t)$, $P_{ei}(t) \ge 0$

where; $\mathbf{x_1}$ and $\mathbf{c_1}$ represent the component installed capacity variables and their corresponding specific annual cost (AC) parameters respectively. $\mathbf{x_2}$ and $\mathbf{c_2}$ represent the relevant time step variables and their corresponding cost/income parameters respectively. In addition, the 5x5 matrix **Q**, consisting of only zeros except for element (5,1) and (1,5), enables the calculation of the quadratic terms of the objective function. These are the marginal power losses multiplied with the power export and the electricity spot price $e_{spot}(t)$. The model has purely linear constraints.

$$\mathbf{x}_1 = \left[P_w^{\max} \quad P_e^{\max} \quad P_f^{\max} \quad H^{\max}\right]^T \qquad (24)$$

$$\mathbf{x}_2 = \left[P_{\exp}(t) \quad P_{ei}(t) \quad H_s(t) \quad H_i(t) \quad ml(t)\right]^T \qquad (25)$$

$$\mathbf{c}_1 = \left[-C_w \quad -C_e \quad -C_f \quad -C_H\right] \qquad (26)$$

$$\mathbf{c_2} = \left[e_{spot}(t) \quad -\left(e_{spot}(t) + e_{tar}\right) \quad e_H \quad \left(e_H - e_{Hi}\right) \quad 0\right] \qquad (27)$$

$$\mathbf{Q} = \begin{bmatrix} 0 & \cdots & \mathrm{e_{spot}(t)} \\ \vdots & & \vdots \\ \mathrm{e_{spot}(t)} & \cdots & 0 \end{bmatrix} \qquad (28)$$

where e_{tar} is the power import tariff, e_H is the H_2 sales price and e_{Hi} is the cost of imported H_2.
The model is implemented in AMPL and solved with CPLEX 8.1 using the barrier algorithm (interior point).

2.4 Net income

Net income (NI) represents the annual income from sale of power on the spot market deducted the total AC.

2.5 H_2 production cost

The production cost of H_2 will be the difference in NI between the optimal wind power plant and the optimal Wind-H_2 system, divided by the annual H_2 production, with the H_2 sales price (e_H) set to zero. The production cost reflects the break-even sales price.

2.6 H_2 self supply

The level of self supply of H_2 is understood as the fraction of the annual H_2 demand served onsite by the Wind-H_2 plant. A self supply of e.g. 90% equals fixing H_{ns}^{max} to 0.1 in equation (9).

3 CASE STUDY

The case study comprises a wind power plant to be situated on a Norwegian island at the end of a 40 km long radial 22 kV distribution grid. The plant is combined with an onsite H_2 load represented by a commuting ferry. Two distinct power markets are represented by the Nordpool market in Norway (NO) and the European Energy Exchange in Germany (DE), both for the year 2006. The DE spot prices are highly variable on a daily basis, compared to NO prices. The DE spot prices are included because it is expected that future increased transmission capacity between Norway and Northern Europe will lead to a harmonization of NO spot prices to continental prices.

3.1 Input data

Hourly wind speed data have been collected for a nearby location from the National Meteorological Institute[3]. The wind speeds have been interpolated with a wind turbine power curve obtained from a manufacturers website[4], and normalized. The average annual capacity factor is 0.4. Fig. 3 displays the monthly average normalized wind power generation.

The *base case* annual H_2 demand is $2.5 \cdot 10^6$ Nm^3/yr. This corresponds to 1.36 MW of average ELYC power with the ELYC efficiency figure given in Table 1. The periodic H_2 demand pattern is displayed in Fig. 2 together with estimated demand patterns of other H_2 vehicles for comparison.

Hourly values for electric load have been obtained from the regional electricity utility. Maximum, minimum and annual load is 2.30 MW, 0.64 MW and 13.64 GWh respectively. Fig. 3 displays the normalized annual load series. The timeseries of estimated load, needed for marginal loss calculations, is divided into weekdays (hours 7-22), weeknights (hours 23-6) and weekends (equal to weeknights), for every week. The procedure is similar to the one used by the Norwegian system operator Statnett, in their calculation of marginal power losses in the transmission grid.

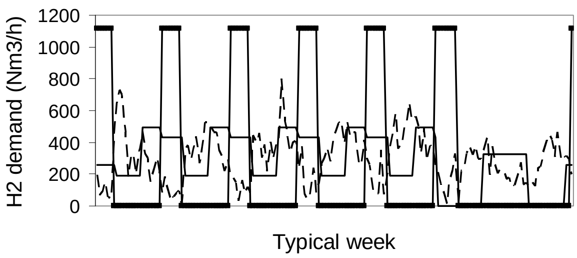

Fig. 2 : Estimated weekly H_2 load for 3 different types of transportation, all totalling $2.5 \cdot 10^6$ Nm^3/yr. 1 ferry (–■–) as used in the case study, 60 buses (––) and 2000 cars (– –).

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[3] http://www.eklima.no
[4] http://www.enercon.de/

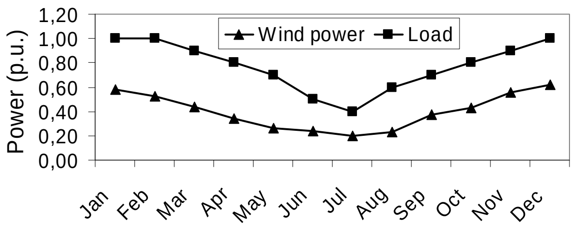


Fig. 3 : Normalized monthly avg wind power and electric load.

Table 1 displays the component input data. The AC is a socio-economic cost figure with 8% rate of return and a payback time equal to the component lifetime. More detailed cost figures are given in the Appendix.

COMPONENT (UNIT)	**SPEC. AC (€/UNIT·YR)**	**EFF (%)**	**MIN (%)**
Wind turbine (kW)	152	n/a	0
ELYC (kW)	115	63[a]	0
H_2 storage (Nm^3)	2.5	100	10
FC (kW)	109	45	0

[a] 4.75 kWh/Nm^3: Representative for large alkaline ELYC.

Table 1 : Component inputs. SPEC.AC: Specific annual cost. EFF: Efficiency, MIN: Minimum operational level.

The annual average spot price is 0.051 €/kWh (DE) and 0.049 €/kWh (NO). The power import tariff (e_{tar}) is fixed at 0.025 €/kWh.

3.2 Electric grid model

Fig. 4 displays the grid model. The Wind-H_2 plant is connected to bus 7, which is the point of common connection (PCC). The grid model was implemented in Matlab using Matpower[5]. Criteria for acceptable power flows are the steady state bus voltages, which must lie in the range 0.93-1.07 p.u. and the thermal capacities of all lines. For simplicity, the Wind-H_2 plant was given a power factor equal to 1.0. The reactive power generation from the capacitor bank at bus 5 is fixed at zero MVAr for maximum export capacity and 0.8 MVAr (installed capacity) for maximum import capacity.

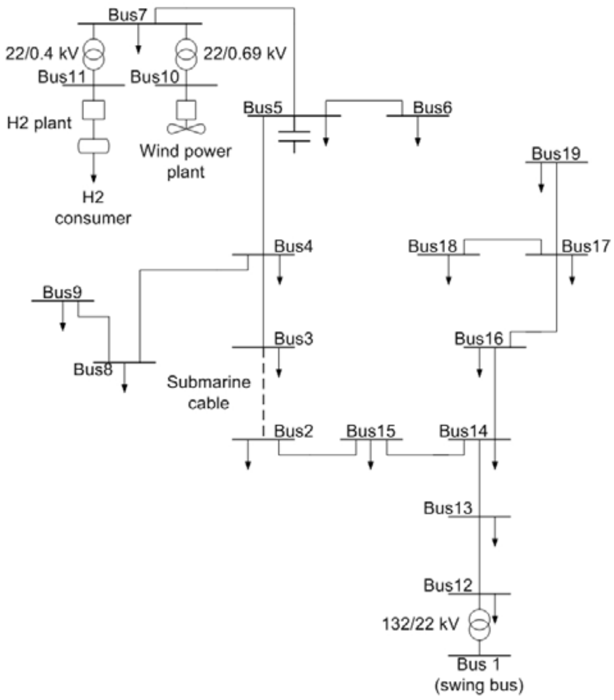


Fig. 4 : 22 kV distribution grid layout. Technical details on lines and bus loads can be found in [10].

[5] Package of Matlab M-files for solving power flow problems. http://www.pserc.cornell.edu/matpower/

4 RESULTS

4.1 Grid constraints and marginal power losses

Results from load flow simulations show that the grid constraints on power export and import from/to bus 7 can be linearized as

$$P_g^{\max}(t) = 2.45 + 0.674 * P_l(t) \quad t \in \{1,...,T\} \tag{29}$$

$$P_g^{\min}(t) = -2.5 + 0.522 * P_l(t) \quad t \in \{1,...,T\} \tag{30}$$

The voltage at bus 7 was the limiting parameter in all cases. The equations are plotted in Fig. 5.

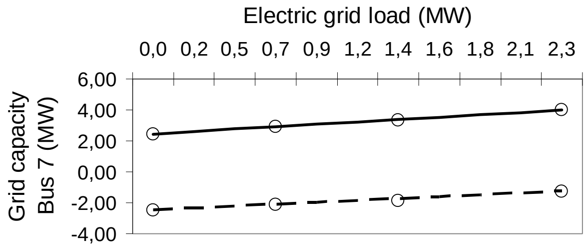


Fig. 5 : Grid capacity at bus 7 (ref. Fig. 4) as function of electric load. P_g^{max} (——) and P_g^{min} (— —). Symbols O are results from underlying load flow simulations.

The marginal grid losses are approximated by

$$ml(t) = 0.013 + 2.7 \cdot 10^{-5} \left(P_{\exp}(t) - P_l^{est}(t) \right) \quad t \in \{1,...,T\} \tag{31}$$

4.2 Wind power only

Table 2 displays the results with wind power only. The optimal installed capacities are higher than a conservative technical limit given by the capacity at minimum load (about 3 MW, ref Fig. 5). The seasonal correlation between wind power and load (Fig. 3) leads to insignificant levels of power dumping. Lower installed cost would lead to higher installed capacity and higher income, but also higher dumping and grid losses.

SPOT MARKET	NO	DE
Wind power (MW)	3.2	3.5
Wind power dumping (%)	0.0	0.4
Net income (k€/yr)	35.6	63.3

Table 2 : Optimal wind power capacity with wind power only.

4.3 Wind power and H_2 load

The base case H_2 demand is included and the Wind-H_2 system is set to be 100% self supplied with H_2. Table 3 displays the results.

SPOT MARKET	NO	DE
Wind power (MW)	5.0	5.4
Wind power export (%)	51.3	52.7
Wind power dumping (%)	0.2	0.3
ELYC (MW)	1.53	1.85
ELYC power from wind (%)	72.0	75.3
H_2 storage (Nm^3)	11644	15757
FC (MW)	0	0
Net income (k€/yr)	-807	-720
H_2 prod. cost (€/Nm^3)	**0.34**	**0.31**
Electricity cost contrib.[a] (%)	78.9	73.4

[a] Electricity costs (wind + import) as fraction of prod. cost.

Table 3 : Optimal Wind-H_2 system configuration.

Compared to Table 2, the optimal installed wind power capacity has increased by 1.8 and 1.9 MW for NO and DE respectively. All H_2 plant components are larger for DE. The reason for this is the high variations in daily spot prices, which makes it beneficial to install more wind power for export at high prices and more ELYC power for H_2 production at low prices, which also results in more H_2 storage. The optimal storage capacity is nevertheless not more than 1.5 days (NO) and 2.1 days (DE) of average demand, which points out the importance of having the grid as backup. Another important result is the cost fraction of electricity on the H_2 production cost, which is in the order of 73-79%. The H_2 production cost equals about 1.0 €/litre of gasoline energy equivalent. Combined with the high efficiency of fuel cells for mobile applications this indicates that H_2 produced from wind power could be competitive with fossil fuels.

Fig. 6 shows the annual power duration curves for the wind power plant and the ELYC. ELYC capacity factor is 0.73 for DE and 0.89 for NO. In NO the ELYC operates almost all hours of the year. In DE the ELYC would be out of operation in almost 1000 hours. Due to periodic high spot market prices in DE it would be beneficial to export relatively large amounts of electricity rather than use it for H_2 production. This is indicated by the area between $P_w(t)$, $P_e(t)$ and $P_{ew}(t)$.

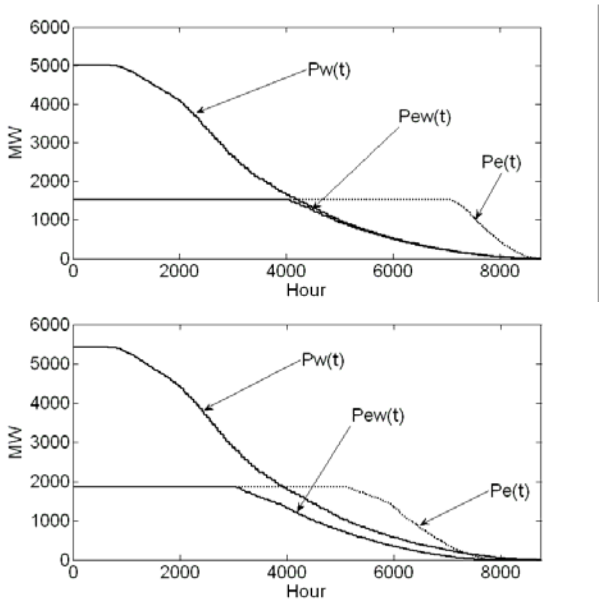


Fig. 6 : Power duration curves for Wind power and ELYC. NO (upper figure) and DE (lower figure). Areas between $P_e(t)$ and $P_{ew}(t)$ represent power import.

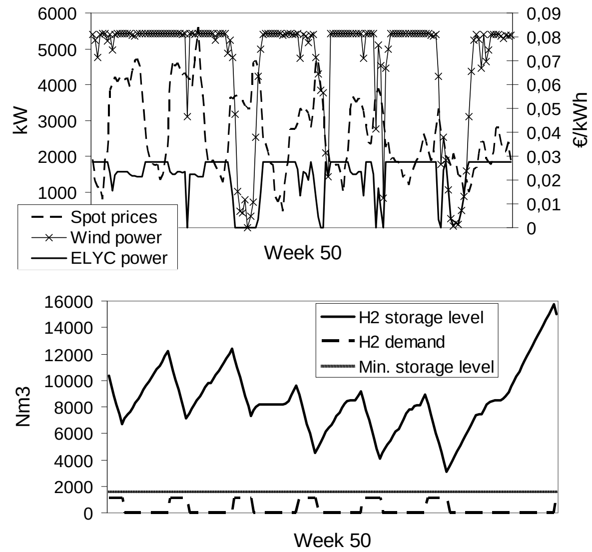


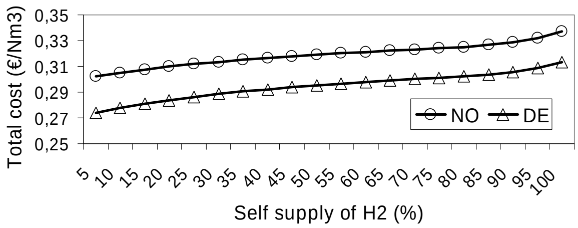
Fig. 7 : Wind power, ELYC power and spot prices (upper figure) and H_2 storage level and demand (lower figure). Both for DE in the week with highest wind power.

Fig. 7 displays hourly results for DE in the week with the highest wind power generation. During week 50 no power is imported. The ELYC power consumption is lowered when spot prices are high, even though the wind power generation is above the maximum ELYC capacity. The minimum storage level decreases from Monday to Friday. During the weekend the storage level steadily increases due to zero filling. The same general trend in storage level is observed in a study regarding H_2 bus filling in London [11]. The characteristic zigzag shape is also observed for the week with the lowest wind power, and the same is true for NO spot prices.

Increasing the minimum operational limit of the ELYC (nP_e^{min}) to 20% shows small or negligible change in component size and H_2 production cost for both NO and DE. The increase in production cost is a result of keeping the ELYC online at high spot market prices.

4.4 H_2 production cost as function of self supply

In this analysis the required level for self supply of H_2 is varied for successive runs of the model. Results are displayed in Fig. 8. For decreasing levels of self supply the optimal system consists of smaller components, less H_2 production in hours with high spot market prices, or a combination of the two. The results indicate that if H_2 import is possible it could be beneficial to rely on e.g. 10-20% import. The decrease in cost for NO is due to lower power import. The decrease for DE is due to a combination of lower power import and decreased component sizes.



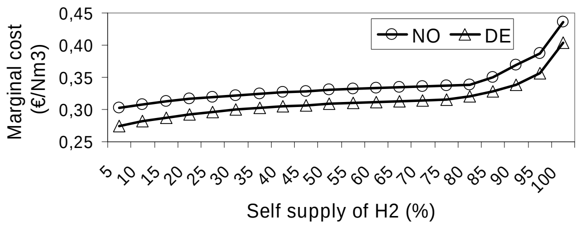


Fig. 8 : Total production cost (upper figure) and marginal production cost (lower figure) of H_2 for increased level of self supply.

High spot prices is the main factor resulting in hours with zero H_2 production. The reason for this is that it would be more economical to sell the electricity on the spot market rather than use it for H_2 production. It will however be very important to have good prediction tools for future wind power generation and spot market prices in order to be able to plan ahead for H_2 import.

4.5 H_2 production cost as function of annual demand

The annual H_2 demand was varied between 12.5% and 400% of the base case in successive runs of the model. Fig. 9 displays the results. The H_2 production cost increases with H_2 load due to higher reliance on power import (relative fraction of available wind power is lower) and eventually oversized components, high grid losses and power dumping.

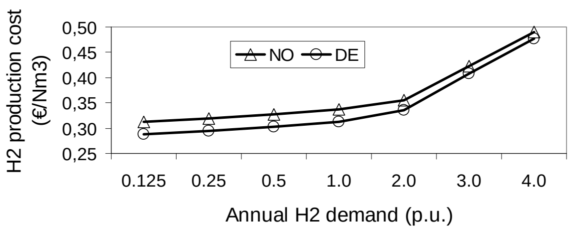


Fig. 9 : H_2 production cost for increased annual H_2 demand with 100% self supply of H_2. 1 p.u. = $2.5 \cdot 10^6$ Nm^3/yr.

4.6 H_2 production cost without wind power

This analysis is conducted with the wind power plant omitted. Because all the electricity is now imported, the power import tariff will form a major part of the H_2 production cost. Total H_2 production cost with 100% self supply is 27% and 33% higher for NO and DE respectively. A reduction in the electricity tariff would actually reduce the benefit of combining wind and H_2.

4.7 H_2 as electric energy storage for wind power

The FC was never chosen in the solutions with the base case inputs. In order to determine the required conditions to make the model choose a FC and thus to use the H_2 cycle for electric energy storage, the model was run with various cost and efficiency assumptions;

- H_2 component cost reduction (CR_H): 50%, 75 %
- FC efficiencies: 45%, 67.5% (LHV)
- ELYC efficiency: 63 and 75% (LHV)
- Wind power AC (C_w): 152 and 97 €/kW·yr

Table 4 displays combinations where the model chose to install a FC.

η_F (%)	η_E (%)	f_{FC} (%)	ΔNI (%)
H_2 as electric energy storage			
67.5	63	3.0	1.0
67.5	75	7.0	3.0
H_2 load combined with electric energy storage			
45	63	0.2	0.1
67.5	63	1.0	0.6
45	75	0.4	0.5
67.5	75	2.1	3.3

Table 4 : Conditions necessary to make the FC cost-effective. C_w always equal to 97 €/kW and CR_H always equal to 75% (75 % cost reduction). f_{FC}: Fraction of annual FC power to total power export. ΔNI: Increase in net income.

A solution with a FC was only given for H_2 component cost reduction of 75% combined with a wind power cost of 97 €/kW·yr. FC sizes range between 300-700 kW. A component cost reduction of 75 % from an originally optimistic value is considered unrealistic and no such future cost estimates have been found in the literature. The results thus strongly indicate that H_2 is not cost-effective as electric energy storage for wind power plants operating in a power market.

More optimistic results were obtained by fixing the FC efficiency at 90%, which could represent a high efficiency CHP unit. However, challenges might arise in rapid on-off operation of a CHP unit, and other options of serving heat demand from surplus (low priced) wind power should be assessed, e.g. electric boilers.

5 CONCLUSION

A two-step method for dimensioning and time-sequential operation of Wind-H_2 plants in power markets has been presented. The method enables a detailed evaluation of the grid through load flow simulations combined with a model for optimization of the Wind-H_2 system. The model is linear in all but the objective function and component relations are simplified. However the model enables an effective assessment of the relations between wind power, energy demand, component costs and grid constraints which combined determine the optimal component sizes and time-sequential operation.

Through a case study it has been found that including a H_2 system to a wind power plant could significantly increase the cost-effective penetration of wind power in weak electric grids. The operational flexibility of the H_2 plant opens for a more optimal power exchange with the grid. When spot market prices are high the plant could export all the wind power to the grid. When spot market prices are low, the electrolyser could be run at full capacity, resulting in less wind power being sold to unfavourable market prices. It is concluded that H_2 produced from wind power could be competitive with fossil fuels. H_2 is however not cost-effective as *electric energy storage* for wind power plants operating in a power market.

Further work is dedicated to enhancing the model to incorporate systems where the wind power plant and the H_2 plant are connected to different grid buses. This results in more complex relations between the units. Such a model could determine the optimal connection point of the H_2 plant, taking the location of H_2 demand and distribution costs into account. There is also a need to incorporate the stochastic nature of wind and wind forecasting errors, in order to assess the potential of H_2 systems to reduce the inbalance costs of wind power.

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APPENDIX

COMPONENT	I (€/UNIT)	OM (% OF I)	LIFE (YR)
Wind turbine(kW)	1250	2	20
Electrolyser (kW)	500[c]	5	21[a]
Compressor[b](kW)	1600[c]	8	10
H_2 storage (Nm^3)	20[c]	0.5	20
Fuel cell (kW)	550[c]	2	10

[a]Cell stack refurbishment every 7 yr at 30% of I. [b]2-out-of-3 configuration. [c] Added 20% installation cost in the calculation of specific annual cost in the paper.

Table 5 : Cost figures based on various literature sources.

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