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Optimizing investments in coupled offshore wind -electrolytic hydrogen storage systems in Denmark

Peng Hou [a], Peter Enevoldsen [b], Joshua Eichman [c], Weihao Hu [a], Mark Z. Jacobson [d], Zhe Chen [a, *]

[a] Department of Energy Technology, Aalborg University, Denmark
[b] Center for Energy Technologies, BTECH Aarhus University, Denmark
[c] National Renewable Energy Laboratory, USA
[d] Department of Civil and Environmental Engineering, Stanford University, USA

HIGHLIGHTS

- An optimized strategy for improving wind farm investments by hydrogen is proposed.
- The coupling opportunities between wind and hydrogen were examined.
- The research presents a critical analysis of wind energy application.

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ABSTRACT

In response to electricity markets with growing levels of wind energy production and varying electricity prices, this research examines incentives for investments in integrated renewable energy power systems. A strategy for using optimization methods for a power system consisting of wind turbines, electrolyzers, and hydrogen fuel cells is explored. This research reveals the investment potential of coupling offshore wind farms with different hydrogen systems. The benefits in terms of a return on investment are demonstrated with data from the Danish electricity markets. This research also investigates the tradeoffs between selling the hydrogen directly to customers or using it as a storage medium to re-generate electricity at a time when it is more valuable. This research finds that the most beneficial configuration is to produce hydrogen at a time that complements the wind farm and sell the hydrogen directly to end users.

1. Introduction

Wind power is one of the fastest growing energy technologies identified by a cumulative capacity of 432,419 MW at the end of 2015, compared with 59,091 MW in 2005 [1]. Denmark is one of the leading manufacturers of wind turbines, as several major wind energy companies and innovations originated from this country [2]. As an example the first offshore wind farm was installed in Denmark in 1991. In 2015, Denmark produced 42% of its electricity demands from wind energy. This includes periods where the cumulative installed wind capacity provides more electricity than the total demand [3]. While this enables a large portion of clean energy to be provided by wind, this also presents challenges with respect to system energy balancing, provision of reserves and cycling of conventional generation. In part, this behavior is reflected by the resulting electricity market prices. To understand the potential challenges of this development, one needs to examine the electricity market in Denmark.

Denmark has several electricity markets that are used to accommodate energy imbalances on the electricity system [4], the spot market (Elspot), balancing market (Elbas), and regulating market. These markets have different timescales for bidding and delivery to ensure that supply meets demand. The unpredictability

* Corresponding author. Department of Energy Technology, Aalborg University, Pontoppidanstræde 111, 9220, Aalborg, Denmark.
E-mail addresses: pho@et.aau.dk (P. Hou), zch@et.aau.dk (Z. Chen).

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of the electricity prices, in part due to variability from wind turbines [5], and the fluctuations in the regulation market price, creates challenges for investors in Danish wind farms. There are a number of techniques to address this variability including energy storage, wider regional interconnection, and demand side management. This paper explores the use of water electrolysis to provide hydrogen fuel for transportation or industrial applications while also buffering wind production, particularly during periods of low electricity market prices, when wind farms do not receive so much revenue from selling electricity. This paper also discusses the option of including a fuel cell to create an energy storage system to further buffer wind plant operation.

Similar systems have been explored in a number of scientific contributions [6–10]. Those reports explored different wind-hydrogen configurations in order to secure a stable renewable energy output. They included methods and approaches on the technological potential of combining the technologies, while measuring the efficiency and predicting the potential; however, they did not include an actual evaluation of the investment potential of such systems, including the discussion of exporting hydrogen directly to the grid. This paper provides a deeper understanding of the economic implications and equipment selection tradeoffs for coupling wind farms with hydrogen electrolysis and fuel cell systems.

Denmark has a national energy strategy that includes the use of storing hydrogen from excessive electricity from renewable energy sources [5], and the combination of these technologies has the potential to alleviate the above-mentioned challenge. Combining wind and hydrogen is not a novel innovation, as the first evidence goes back to 1891, where, the Danish scientist, Poul la Cour produced hydrogen using the power from a wind turbine [11]. Since then, several academic contributions have examined the combination of the technologies, in the search for a stable energy supply based on renewables entirely [12–15].

Commonly those studies are conducted in regions with excellent wind conditions, such as Norway, Ireland, and The Faroe Islands [16]. These studies have been used to advice this research, given the fact that the wind patterns of those countries are very similar to Denmark [17]. Another study found that the cost of using a wind-electrolyzer system to create hydrogen from electricity and then re-generate electricity back to the grid, while technically possible, it is costly [18]. Other articles focused on the integration of a combined wind and hydrogen system with the purpose of delivering a stable 100% renewable energy supply [19]. The result of that research also found that it was possible to use hydrogen as a storage mechanism, although costly and inefficient due to the high capital cost of the electrolyzer and fuel cells. Other papers discuss the efficiency and cost of hydrogen for hydrogen fuel cell vehicles powered by wind turbines [20]. Similarly, a 2016 study focused in the United States found that the high capital cost for fuel cells makes current hydrogen power-to-power storage systems economically preclusive; however, only using an electrolyzer to produce and sell hydrogen while also acting as a responsive load to buffer the grid presented a more favorable business case [21]. Other studies have examined the possibilities of integrating hydrogen systems directly into the grid and participating in electricity markets [19], or simply using the hydrogen as storage capacity for excessive wind energy. This research aims at co-locating a hydrogen system at a wind farm to increase the competitiveness of both technologies. The industrial usage of hydrogen spans from fertilizer production [22,23], powering of vehicles [23], refineries [22], to extracting certain types of metals. Hydrogen is produced applying several methods, ranging from anaerobic digestion using biomass, to water electrolysis to usage of fossil fuels through thermocatalytic cracking and gasification [24], which only emphasizes the possibilities of using hydrogen. More importantly, hydrogen, and the before mentioned industrial usages has been addressed as an important factor in the Danish energy roadmap for 2050 [25,26].

Hydrogen in the (power to hydrogen) PtH system can be used for storage of low-value electricity while also providing additional services to the grid. Currently the most inexpensive way to produce hydrogen in large volumes is by converting natural gas using a steam methane reformer [27]. However, this process uses a fossil fuel which emits carbon during the production of hydrogen. A potential solution to such challenges is to use electrolysis of wind power to mitigate the carbon footprint. The case studies discussed in this section have been used to construct the specifications of the PtH. The authors in Ref. [11] suggested that regions dominated by wind power and excessive electricity can make use of the combination of wind and hydrogen at a large scale. However, as stated in Ref. [15] the environmental benefits come with potentially a higher price for energy. This research aims at exploring the opportunity of co-locating hydrogen equipment at a wind farm to take advantage of the integrated system for renewable power and flexibility. Hence, the main objective is to examine whether there is an incentive for wind farms investors to invest in electrolyzers or fuel cell systems in Denmark.

A variety of research has been conducted on optimization techniques of similar renewable energy systems. As an example, the optimal size and location of wind turbines was found through a nonlinear programming method in Ref. [28]. In Ref. [29], the operating cost of a hybrid bus with fuel cell was minimized using dynamic programming. Sequential quadratic programming (SQP) was adopted to optimize the hybrid fuel cell vehicle controller design in an inner loop while DIRECT and NOMADm algorithms were used for component selection in an outer loop [30]. On account of complexity and nonlinearity associated with component sizing and selection, heuristic optimization algorithms were used in Ref. [31]. In Ref. [32], a biomass based network was optimized with the use of genetic algorithm (GA). An independent renewable energy system with hydrogen storage was optimized by applying the GA in Ref. [33]. GA was also used to optimize an off-grid hybrid PV–Wind–Diesel system with different battery technologies in Ref. [34]. As an alternative, particle swarm optimization (PSO) method was applied to optimize the analogue renewable energy system [35,36]. As mentioned in Ref. [29], the classic optimization method, SQP, has good performance solving non-linear programming problems while the comparison study between PSO and GA in Ref. [37] demonstrated that PSO is a slightly better choice. In addition, an improved PSO, such as adaptive PSO (APSO), is demonstrated to outperform other types of PSO in finding a better result for the objective function [45]. On account of the above reasons, in the present research, SQP was applied for equipment operations optimization while APSO was used to determine the optimal type and capacity of the electrolyzer, fuel cell and storage tank that is most beneficial to wind farm investors.

1.1. Formalizing the optimization approach

The power generated from a wind farm is typically exported to the electricity market. Since the electricity price fluctuates, there is a chance for the wind farm owner to get more benefits by optimizing their selling strategy. If the energy can be stored during a period with lower electricity prices and sold when the price increases, known as price arbitrage, greater profits can be obtained for the wind farm. This is particularly interesting because it can be the wind farm itself that depresses the prices in that area. The electrical equipment sizing and selection of PtH as well as the volume of hydrogen tank has a significant impact on the competitiveness of such combination of technologies. The equipment sizing and selection are interdependent, in other words, the operational strategy should be optimized according to different compositions of PtH. This co-optimization problem is specified later in this section.

1.1.1. Introducing the optimization approach

The research objective is to examine and determine the potential of optimizing investment opportunities of offshore wind farms using a variety of hydrogen system configurations. The return on investment (ROI) which is defined in the following is used to evaluate the economic profitability of the PtH installation project and three scenarios are specified in this section as follows. The price look-ahead used in the optimization is a single day.

Configuration 1. *Wind farm with PtH for electricity market arbitrage*

The hydrogen system consists of a fuel cell and an electrolyzer connected to the wind farm. The system is only used to store electricity in the form of hydrogen and later used to generate electricity that can be sold in electricity market. The mathematical expressions of this problem are shown in the following equations.

Outer layer optimization: The equipment selection and sizing for the PtH system is made in this layer while each selection corresponds to an optimized operational strategy. The objective function of the outer layer is defined as the ROI in this work which is the NPV of cost divided by the yearly revenue. Using this evaluation method, the benefit of different investments can easily be determined.

Inner layer optimization: Based on the selection of equipment, which is completed in the outer layer, the optimized operation strategy is decided in the inner layer. Eq. (1) describes the amount of electricity that is required to generate x_t hydrogen from electrolysis, or the electricity that can be generated by the amount of x_t hydrogen in a fuel cell. Since the PtH can only be used to store hydrogen for a certain amount of time, the operational constraint for the first iteration should be defined separately as (3). The maximum hourly generation of hydrogen by the electrolyzer cannot exceed the size of the PtH plant as well as the available power generation from wind farm. This relation is expressed with the second equation of (4). On the other hand, the maximum allowance of hydrogen transformed into electricity is constrained by the fuel cell capacity which is constrained by the first term in first equation of (4). The accumulated hydrogen in the tank should be within the limit of the tank size which is expressed as (5) and (6). The denominator of (7) represents the yearly earned profits while the numerator shows the net present value of overall cost. y_1 to y_4 represent the capacity of the electrolyzer plant, electrolyzer type, lower and upper limit of tank size as well as the range of capacity of fuel cell, respectively [38].

$$E_t^H(x_t) = \begin{cases} \eta_{EL} x_t & x_t > 0 \\ P_{FC} x_t \eta_{FC} & x_t \le 0 \end{cases} \quad t = [1, 2, \ldots T] \tag{1}$$

Objective function for inner layer:

$$\max\left[I_r^n(x,y)\right] = \max\left\{ \sum_{t=1}^{T} EP_t \left[E_t^W - E_t^H(x_t)\right] \right\} \tag{2}$$

$$\text{S.t.}: \quad 0 \le x_1 \le \frac{P_H}{\eta_{EL}} \tag{3}$$

$$\begin{cases} -\dfrac{P_{FC}}{\eta_{EL}} \dfrac{1}{\eta_{FC}} \le x_t \le 0 \\ 0 < x_t \le \min\left(\dfrac{P_H}{\eta_{EL}}, \dfrac{P_{wind,t}}{\eta_{EL}}\right) \end{cases} \quad t = [2, 3 \ldots, T] \tag{4}$$

$$0 \le \sum_{t=1}^{N_t} x_t \le K_v \quad N_t = [2, 3, 4, \ldots, T] \tag{5}$$

$$\sum_{t=1}^{T} x_t = 0 \quad t = [1, 2, \ldots T] \tag{6}$$

Objective function for outer layer:

$$min(ROI) = min\left\{ \frac{C_{FC}(y) + \frac{C_{FC}(y)}{(1+r)^{T_{FC}}} + C_{EL} + C_{Tk} + \sum_{n=1}^{T_{EL}} \frac{C_{OM}}{(1+r)^n}}{\max\left(I_r^n(x,y)\right)} \right\} \tag{7}$$

$$\text{S.t.} \quad 0.1 \le y_1 \le W_C \tag{8}$$

$$1 \le y_2 \le 3 \tag{9}$$

$$T_L \le y_3 \le T_U \tag{10}$$

$$0.1 \le y_4 \le W_{FC} \tag{11}$$

Configuration 2. *Wind farm with PtH for generating hydrogen*

In this configuration, the PtH does not sell electricity back to the grid, rather, it is used only to generate hydrogen which is sold for transportation fuel or as an industrial product and the flexible operation of the electrolyzer is used to support the wind farm. In this way the capital cost is reduced by removing the fuel cell [38]. The problem can be expressed in the following.

There are two layers in this problem. The operational optimization, defined as the inner layer, and the system sizing and the volume optimization, defined as the outer layer. In this configuration, while the electrolyzer can operate at different points, a constant amount of hydrogen is sold which relies on the storage system as a buffer. It is assumed that customers will require relatively constant supply of hydrogen. In the case of a fueling station, this could come from truck deliveries each day or for a refinery it would be a more constant pipeline delivery requirement. Eq. (12) indicates that the wind power can only be sold to the electricity market or generate hydrogen (i.e., no fuel cell). Eq. (13) shows that the profits of this system can be obtained by both selling hydrogen and electricity. The hydrogen production capability is limited by (14) which is the same as the second equation of (4). Eq. (15) means that the accumulated hydrogen in the tank should be within the limit of the tank size and (16) ensures that all the energy should be sold in the form of hydrogen at the end of each day. In this system, the objective is also in the outer layer which minimizes (17) while satisfying the constraints as the same of (8)–(11).

$$E_t^H(x_t) = \eta_{EL} x_t \quad x_t > 0, t = [1,2,...T] \tag{12}$$

Objective function for inner layer:

$$\max\left[I_r^n(x,y)\right] = \max\left\{\sum_{t=1}^{T} EP_t\left[E_t^W - E_t^H(x_t)\right] + D_H O_e \frac{P_H}{\eta_{EL}}(T-1)S_H\right\} \tag{13}$$

$$\text{S.t.}: \qquad 0 < x_t \le \min\left(\frac{P_H}{\eta_{EL}}, \frac{P_{wind,t}}{\eta_{EL}}\right), t = [1,2...,T] \tag{14}$$

$$0 \le \sum_{t=1}^{N_t} x_t - O_e \frac{P_H}{\eta_{EL}}(t-1) \le K_v, N_t = [2,3,4..,T] \tag{15}$$

$$\sum_{t=1}^{T} x_t - O_e \frac{P_H}{\eta_{EL}}(T-1) = 0 \tag{16}$$

Objective function for outer layer:

$$min(ROI) = min\left\{\frac{C_{EL} + C_{Tk} + \sum_{n=1}^{T_{EL}} \frac{C_{OM}}{(1+r)^n}}{\max\left(I_r^n(x,y)\right)}\right\} \tag{17}$$

The consumers of hydrogen (e.g., refineries, fueling stations) will require a constant supply of hydrogen and cannot afford to turn off or not supply their customers so for the purposes of this analysis, the system operator of the wind farm will sometimes have to acquire electricity from the electricity market when the wind farm is not producing. Hence, whenever the PtH system must purchase electricity from the grid the objective function for the inner layout is modified as follows:

Objective function for inner layer:

$$\max\left[I_r^n(m,y)\right] = \max\left\{D_H O_e \frac{P_H}{\eta_{EL}}(T-1)S_H - \sum_{t=1}^{T} EP_t P_t\right\} \tag{18}$$

$$\text{S.t.}: \qquad 0 < P_t \quad t = [1,2...,T] \tag{19}$$

$$0 \le \sum_{t=1}^{N_t} \frac{P_t}{\eta_{EL}} + \sum_{t=1}^{N_t} \frac{P_{wind,t}}{\eta_{EL}} - O_e N_t \frac{P_H}{\eta_{EL}} \le K_v \quad N_t = [1,2,3,...,T] \tag{20}$$

$$\sum_{t=1}^{T} (P_t + P_{wind,t}) - O_e P_H (T-1) = 0 \tag{21}$$

In (18), the last term represents the money spent on purchased energy at each hour so that the demand from (21) can be set. This mechanism will not be triggered if the wind farm can provide a sufficient amount of energy.

2. Materials and methods

The non-linear optimization problem can be solved using a variety of solution methods including gradient based algorithm and heuristic algorithms. In this paper, the Sequential Quadratic Programming (SQP) method is used to solve the inner layer and the Adaptive Particle Swarm Optimization (APSO) method is adopted as the optimization method for the outer layer. The theory and the optimization procedure are presented in the following subsections.

2.1. Sequential quadratic programming method

The target of the project is to determine the minimum value of the objective function (the system ROI) as expressed in Eqs. (2) and (7) under the constraints and assumptions. In order to solve this problem, a gradient based algorithm, SQP, is proposed in this paper to find the final solution.

As one of the popular nonlinear programming methods, SQP performs well in solving optimization problems under constraints [39]. It arrives at the optimal solution by generating a series of iterations with Lagrange multipliers. So the constrained optimization problem can be transformed into a sub problem that would be used as the basis of an iterative process [40].

2.2. Particle swarm optimization (PSO)

For a non-convex problem, evolutionary algorithms such as GA and PSO are a good choice, with a high probability of finding the optimal solution for the nonlinear optimization problem. Considering the outstanding performance of PSO in computational efficiency [37], it was selected to be implemented in the simulation. In this work, the optimization variables are both continuous and discrete which compose a mixed integer optimization problem as a result. The PSO can be modified to solve an integer problem which can be expressed mathematically as follows [41]:

$$v_i^{k+1} = wv_i^k + l_1 r_1\left(local_i^k - x_i^k\right) + l_2 r_2\left(global^k - x_i^k\right) \tag{22}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{23}$$

The setting of parameters in PSO is critical to the final solution, since a larger inertia weight, w, ensures a stronger global searching ability which increases the chance of finding a better solution in the global region while a smaller w ensures local searching ability. In order to overcome this drawback, work has been conducted on parameter control methods for time varying control strategies [42–44] or adaptive parameter control strategies [45]. Recently, a PSO with multiple adaptive methods (PSO-MAM) was proposed [46] and was demonstrated to be outperformed by the existing common evolutionary algorithms in finding a better solution, however, this method is more suitable for solving continuous optimization problems. Hence, the adaptive PSO algorithm (APSO) [45] is selected to find the solution in this paper.

2.3. Optimization framework

In this paper, the sizing and equipment selection of PtH is optimized together with its operation strategy. The algorithm flow chart is shown in Fig. 1. In the outer layer, the particles of PSO are initialized in the first step and then transferred into the inner layer. In the inner layer, the benefit of using PtH will be calculated first by (2) and (13) for different scenario or (18) if there is not enough energy production. Hereafter, the hydrogen volume for each hour during a year will be updated to recalculate the benefit. The original solution will be replaced if a higher benefit can be obtained, or stopped if no improvement can be made. The best result found from the inner layer will be transferred back to the outer layer and the ROI from (7) or (17) will be calculated and saved as the initial solution which is the basis for comparison later. Then the particles will be updated and transferred into the inner layer. By following

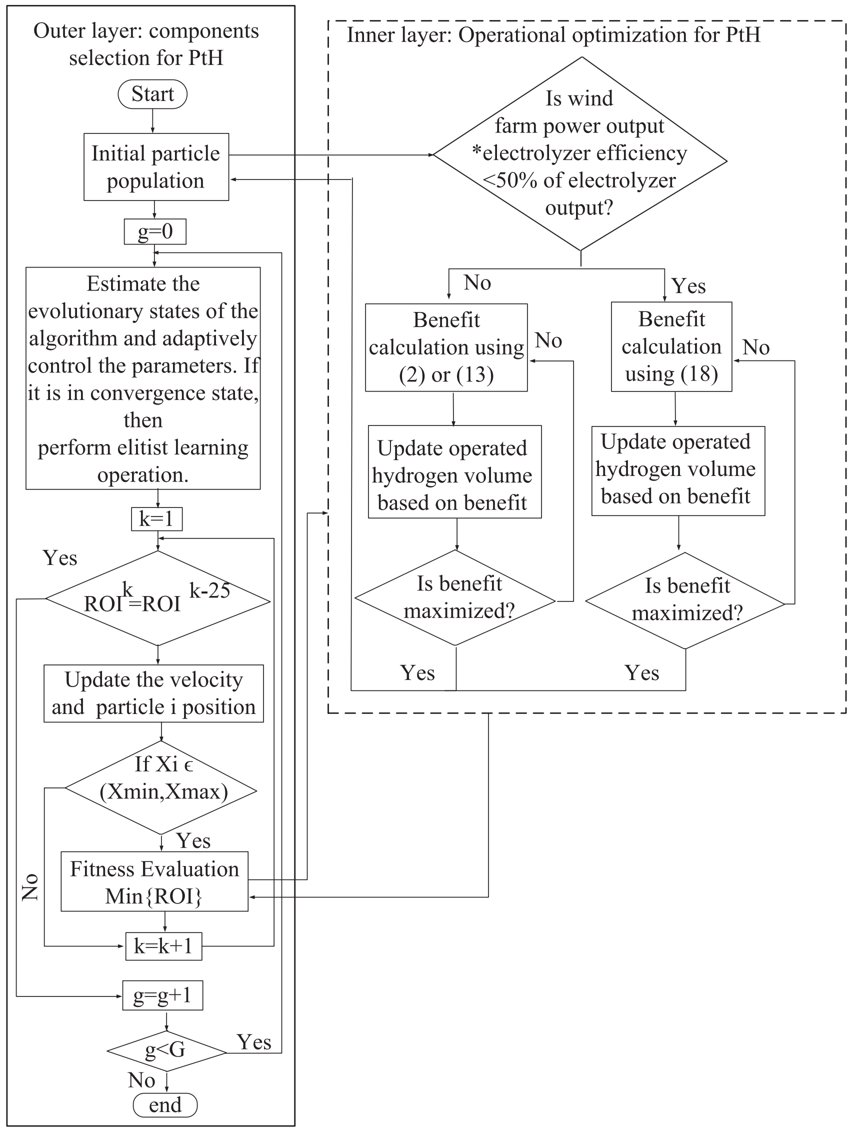

Fig. 1. The optimization framework of proposed method.

the same procedure as the first calculation, the optimized operation strategy under the well-designed PtH structure will be obtained. The program will conclude if the result is stabilized for 25 iterations and output the final result in the end.

2.4. Assumptions

In order to implement the program, the following assumptions were taken into consideration:

- The wind farm is assumed to be constructed with a rectangular shape which is comprised by 20 Siemens 3.6–120 wind turbines (WT) with a 7 rotor diameter spacing between each pair of WTs.
- Based on the relatively small size of the offshore wind farm capacity, 72 MW, the impact of the candidate systems on electricity market price is neglected. Denmark had an installed wind capacity of 5,063 MW by the end of 2015 [47].
- The hydrogen price is set at 2, 5, 9€/kg respectively to represent the range in value of hydrogen for different processes [48].
- Currently, there are three major types of fuel cells on the market: solid oxide fuel cell (SOFC), proton exchange membrane fuel cell (PEMFC) and molten carbonate fuel cell (MCFC). In this paper, the PEMFC of Panasonic is selected to implement the simulation since it can operate more dynamically than the SOFC and MCFC in response to changes in the wind power.
- The hourly wind speed from 2015 in the vicinity of the wind farm location is used as the predicted wind speed. The wind conditions are collected through mesoscale data from EMD ConWx [49], which can be considered reliable for this site, due to the few changes in wind conditions on sea.
- The historical Danish hourly electricity price for 2015 is regarded as the forecasted result. It is acknowledged that the transition towards 100% renewable energy in 2050 [50] could provide different scenarios in a period of 25 years. In the planned transition even more frequent fluctuations can occur, which would only strengthen the recommendations introduced in this paper. It is likely that the current fluctuations in the hourly Danish electricity prices can be expected in the future for countries with a planned but less developed renewable energy plan.
- The hydrogen is stored in above-ground steel tanks. Using above-ground tanks as the main storage method of wind energy

Table 1
Specification of stationary fuel cell [38].[11]

Type	Proton exchange membrane fuel cell
Capacity (kW_e)	0.2–0.7
Technical lifetime (year)	15
Annual average electric efficiency (%, LHV)	35

Table 2
Specification of electrolyzers.

Type	Alkaline		Alkaline		PEM (2015)	
Producer	NEL Atmospheric pressure (S1)		HYDROGENICS (S2)		Proton Onsite (S3)	
Plant size (MW)	10	100	10	100	10	100
Average System Efficiency during lifetime (kWh/Nm^3)	4.9	4.9	5.5	5.5	6.1	6.1
Technical lifetime (year)	25	25	25	25	25	25
Turnkey price (Million Euro)	9.30	84.03	17.20	148.64	9.65	64.08
Total O&M including stack exchange/7th year (Thousand Euro)	510.67	4840	1297.33	12396	174.67	1162.67

would require certain demands for storage facilities, due to security, land area and cost. There are a variety of technologies that can be used including chemical looping, liquefaction, underground, metal hydrides and liquid organic hydrogen carriers. Above-ground steel tank storage is a proven technology that provides a good standard of comparison for the reader.

- The theoretical life time of the fuel cell is assumed to be 15 years in this work.
- The hydrogen tank price is assumed to be directly proportional to its volume.
- The amount of hydrogen sold is assumed to be constant every day at 50% of the electrolyzer's maximum production capability. The assumption is made to allow the wind farm to benefit from the ability of the electrolyzer to provide balancing by reducing consumption during part of the day. Also, the capacity factor of the wind farm is around 56%. Thus to increase the amount of renewable hydrogen produced and reduce the number of hours where the electrolyzer must purchase grid electricity a 50% capacity factor is applied for the electrolyzer.

3. Development of case study

Specifications for the wind farm, electrolyzers and fuel cell are described in this section. These specifications are used in the optimization model in Section 2 to develop the results.

3.1. Electrolyzer, fuel cell and storage specifications

The design of the PtH must consider several aspects of electrolyzer, fuel cell and storage systems. Most importantly for this study is the size, efficiency, lifetime and capital cost of the components. Using these values the optimization can determine the appropriate size for each component and can minimize the ROI for the combined wind farm and hydrogen system. The specifications of common types of components for PtH are listed in Tables 1 and 2. Table 1 contains the technical assumptions for the stationary fuel cell.

In Table 2, the information of common types of electrolyzers in the market is specified [51]. Based on this information, the cost of each type of electrolyzer as well as its O&M cost is modeled according to plant size which is similar to the model adopted in Ref. [52]. The cost curves are illustrated in Fig. 2.

This paper focuses on production and does not include optimization of delivery or dispensing pathways. The above-ground storage tanks considered are for low to medium pressure storage of compressed hydrogen gas. The authors recognize that there are a variety of techniques for storing hydrogen including liquefaction or underground storage and have chosen to focus only on above-ground gaseous storage for this paper. The storage system should be able to provide compressed gas to either a pipeline (27–69 bar) or to a truck (250, 350, or 540 bar) for delivery. According to the US Department of Energy's H2A Analysis Model, depending on the delivery method and compressor configuration, the delivery pressure is as low as 25 bar to over 900 bar.[2] The above-ground storage tanks are assumed to be low to medium pressure and will use a compressor to achieve the required gas delivery rate and pressure. The cost for above ground hydrogen storage tanks (C_{Tk}) is linearized based on the storage volume required which is 80.91€/m^3 [53].

With cost and operational values established for each piece of equipment the optimization can determine the optimal size for each component. Table 3 shows the options for equipment sizing that are available for this study. The power for the fuel cell and electrolyzers can range from 0 MW up to the size of the wind farm, 72 MW. Additionally, the solver can select any of the three types of electrolyzers and vary the storage size to suit the customer hydrogen demand requirement.

3.2. Reference wind farm and electricity market

The reference wind farm is composed of 20 WTs with a diamond quadrilateral shape, in order to maximize the energy output by decreasing wake effects while ensuring minimum expenses to cabling and construction. The preferred wind turbine for the proposed wind farm is SWT-3.6-120 from Siemens Wind Power. Table 4 contains information about the selected wind turbine. The wind turbine type has been chosen as it currently is one of the world's most popular offshore wind turbines, being in operation at three of the largest offshore wind farms in the world, London Array (630 MW), Greater Gabbard (504 MW), and Anholt (400 MW) [54], it has proven its operation in climates similar to the proposed location.

Below is the wind rose presenting the mean wind direction frequencies during the period 2000–2010, which clearly indicates the prevailing wind direction as south-west. Despite using a dataset, which is more than six years old, with no obstacles or changes in the wind direction, the data is considered valid for this research.

[2] U.S. Department of Energy's H2A Delivery Scenario Analysis Model: https://www.hydrogen.energy.gov/h2a_analysis.html.

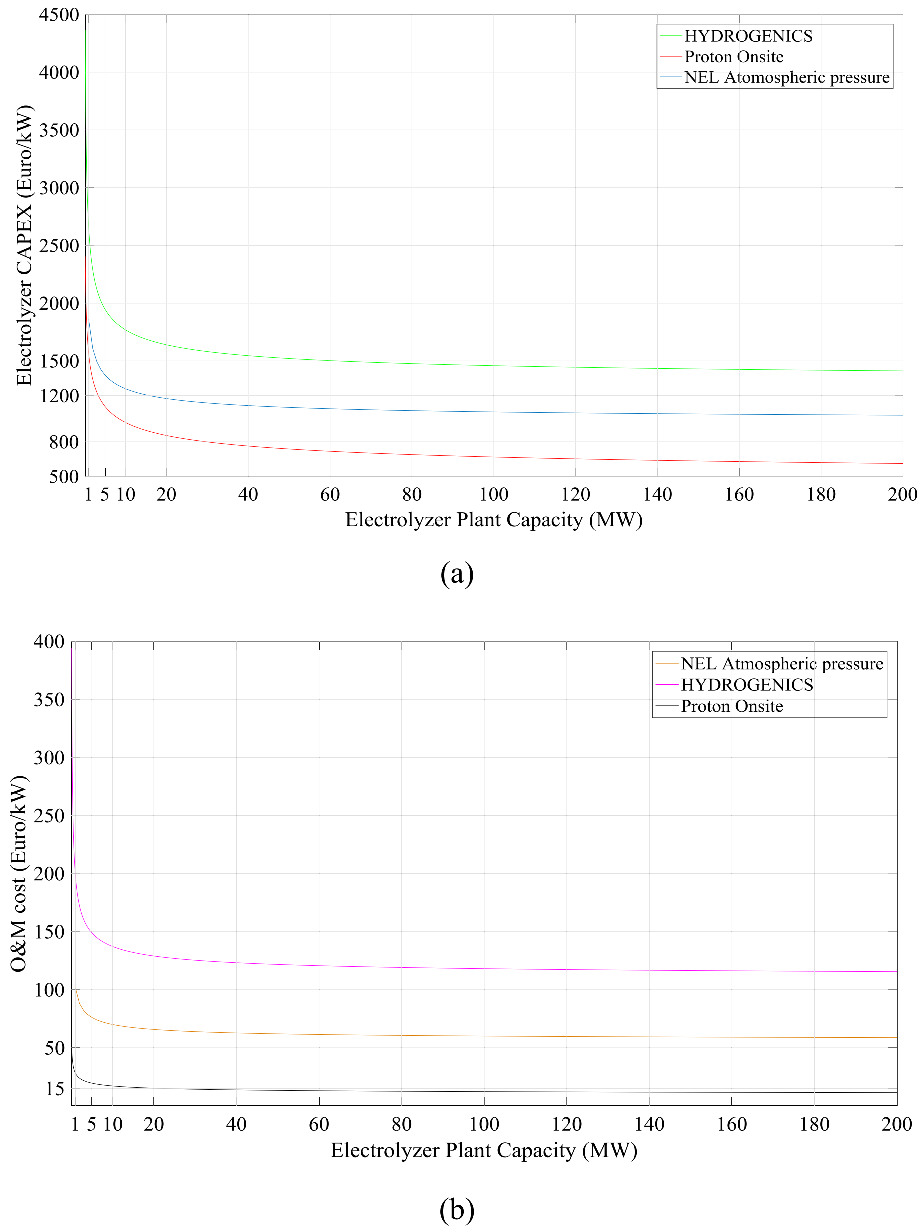

Fig. 2. Cost model illustration. (a) Electrolyzer CAPEX versus plant capacity. (b) Electrolyzer O&M cost versus plant capacity.

Table 3
Optimization variables.

Properties	Available optimization set points
Fuel cell plant capacity (MW)	0 to 72 in increments of 0.0001
Electrolyzer plant size (MW)	0 to 72 in increments of 0.0001
Hydrogen storage tank size (m^3)	0 to 6000 in increments of 0.0001
Electrolyzer type	S1, S2, S3

Table 4
Specification of reference WT.

Parameter	Siemens 3.6–120 WT
Cut-in Wind Speed	3 m/s
Rated Wind Speed	17 m/s
Cut-out Wind Speed	25 m/s
Rotor Diameter	107 m
Rated Power	3.6 MW

The input wind speed is drawn as a wind rose and shown in Fig. 2 (a).

Considering the wake effect, the wind velocity as well as the direction will have an impact on the energy production of wind farm. Based on the wind speed illustrated in Fig. 3. (a) and the WT information in Table 4, the power production of the wind farm for each hour is obtained using the method in Ref. [55] and shown in Fig. 3. (b) The energy production distribution is shown in Fig. 3. (c).

By isolating the spot market as the only revenue stream for wind farms, the cash flows are determined by the electricity price. In this work, the Danish electricity prices for 2015 are selected. This data has hourly resolution and is shown in Fig. 4 [56]. In Fig. 4, the blue

[1] The peak system efficiency for PEM fuel cells can be higher than 35%; however, we assume that the "annual average electric efficiency" includes times when the fuel cell will operate at part-load, which will reduce the overall efficiency, hence the 35% assumption.

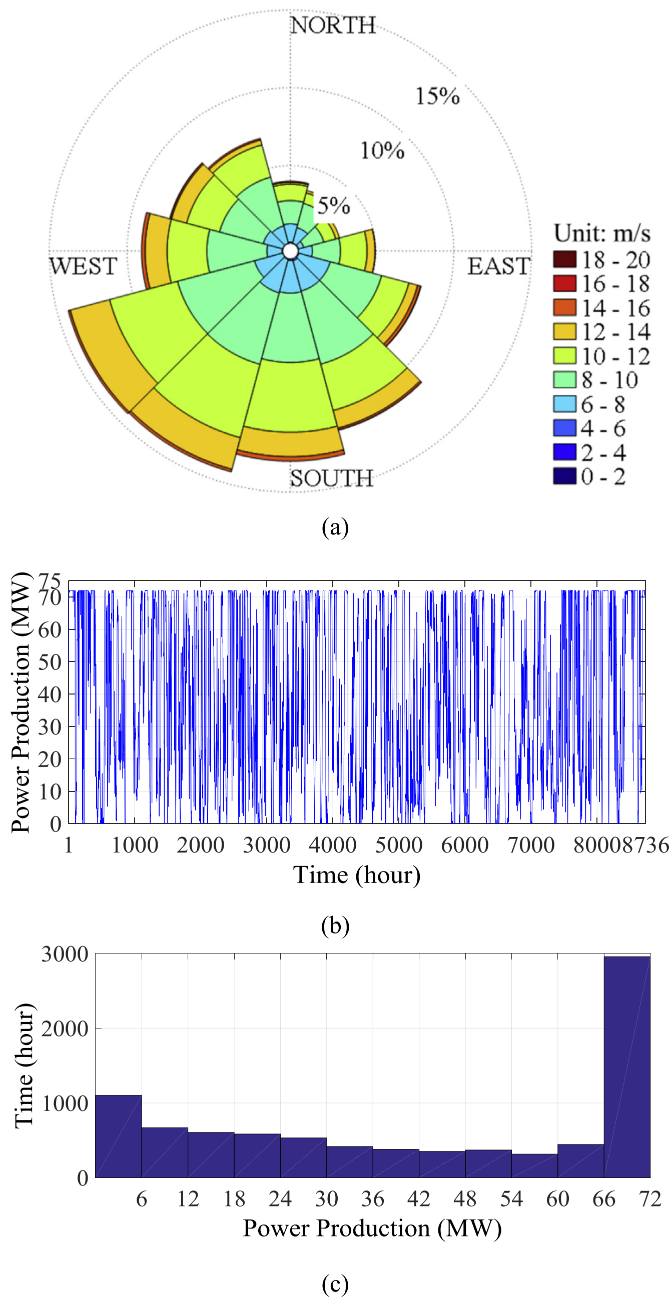

Fig. 3. Wind resource for reference wind farm and corresponding energy production. (a) Wind rose of average wind speed from year 2000–2010. (b) Hourly energy yield of proposed wind farm in one year. (c) Energy yields distribution of proposed wind farm in one year.

lines represent the electricity price for each hour, it can be seen that the higher electricity prices occurred in winter and there are 65 out of 8736 h that have negative prices.

3.3. Results and discussion

The optimization model is used to determine the maximum benefit that can be received from integrating PtH with wind farms. Each of the scenarios is described in subsequent sub-sections.

3.3.1. Case I: power to power mode (scenario I)

In this mode, the electrolyzer uses electricity to produce

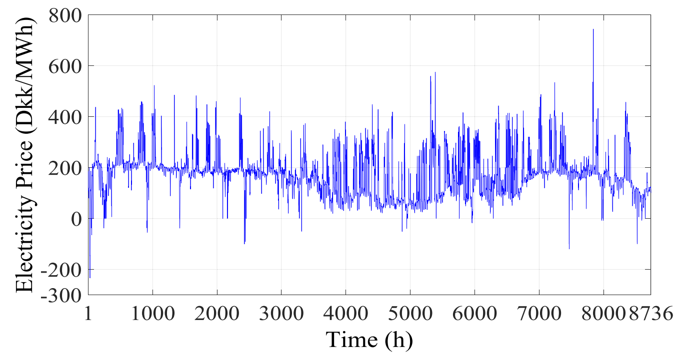

Fig. 4. Danish electricity price of year 2015.

hydrogen, which is then used by a fuel cell to produce electricity during times of high electricity prices in the electricity markets. Without storage, wind energy must be sold the moment it is generated. With the power-to-power system, excess wind energy can be shifted to higher price hours at the expense of the round-trip efficiency loss of the storage system. A business case is established if the price differential is sufficiently high to yield positive returns. Negative prices provide a strong incentive to shift generation however, the occurrence of negative prices in the 2015 data is limited. For positive values the inverse of the round-trip efficiency tells you the necessary price differential to break even from an operation point of view, not including capital investment. For example, given a 20% round trip efficiency the price differential needs to be 5x to offset the efficiency penalty and even higher to offset the capital investment.

Comparing the average price to the actual price in Fig. 4 illustrates that there are very few hours that have a sufficiently high price differential to warrant storage. In this scenario, the objective value is infinite which means that we can never get the investment back. This finding demonstrates the challenge of implementing hydrogen power-to-power systems and is consistent with the previous literature.

The optimal electrolyzer and storage size for scenario I is the minimum (0 MW and 0 m^3 of storage). This means that it is not presently economic to operate in power-to-power mode and only generate revenue from arbitraging energy prices in the Danish system.

3.3.2. Case II: power to gas mode (scenario II-IV)

For scenarios II, III and IV, the wind farm can either sell the electricity to the grid at the wholesale rate or use the electricity in an electrolyzer to produce hydrogen which is then sold as a transportation fuel or to industrial markets. This decision is based on the benefit of choosing one versus the other. Three different hydrogen prices are adopted to implement the simulation (2, 5 and 9€/kg for scenario II, III and IV, respectively). The pricing scenarios have been selected to represent different potential end-users in Denmark (Refineries and Transportation) for the produced hydrogen [15]. It is important to note that with the development of regulation and markets to limit carbon emissions there will likely be a premium for renewable fuels including hydrogen.

To aid in understanding the conditions that are beneficial for PtH in Denmark, the breakeven fuel price is calculated given a fixed efficiency and a range of electricity prices (Fig. 5.). Note that for this illustration, the breakeven price only incudes the electricity cost for an electrolyzer and not capital or O&M. There are three lines for three different efficiency values. The resulting breakeven price is shown if the hydrogen is sold as a heating fuel on the left axis and for direct hydrogen sale on the right axis. The average annual

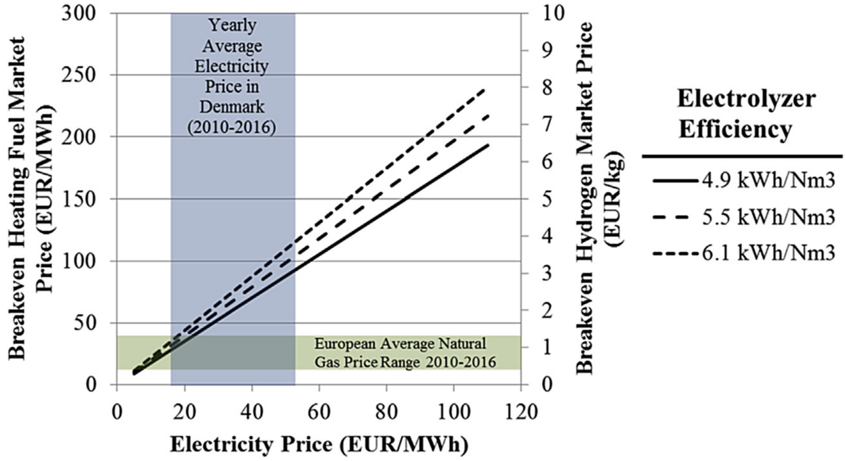

Fig. 5. Breakeven price for selling hydrogen as a heating fuel or directly as hydrogen for a range of electricity prices. Only includes cost of electricity, not capital or O&M for this figure.

electricity price for Denmark and the average European natural gas price are overlaid. This clearly shows that the value for selling hydrogen in heating fuel markets is much lower than sale directly as hydrogen fuel and that the sale price of 5 and 9€/kg is likely to yield a positive business case since those values are significantly higher than the breakeven lines while 2€/kg is likely to not yield a positive business case, based on the average prices seen in Denmark.

The optimization model was run with different hydrogen prices. The daily revenue benefit for scenario II is shown in Fig. 6. (a) For several days (day 23, 293 and 327) the daily benefit for the PtH is negative. This is caused by the requirement that a constant amount of hydrogen is provided each day. Either the opportunity cost of providing hydrogen is lower than the benefit from the sale of wind electricity or there is insufficient wind power and the system has to buy electricity from the grid in order to generate enough hydrogen to meet the demand.

The electricity price for day 23 is illustrated in Fig. 6. (b). The electricity price of some hours in day 23 is over 40€/MWh while the price per kg hydrogen is 2€/kg in scenario II (which equates to 36.4€/MWh for the S1 electrolyzer). If the electricity price is above the equivalent sale price of hydrogen, then there is no benefit for producing hydrogen during those hours.

The optimal size for an electrolyzer in scenario II is 5.5 MW. As will be shown for the subsequent scenarios, an increase in the sale price of hydrogen is sufficient to encourage a much greater PtH

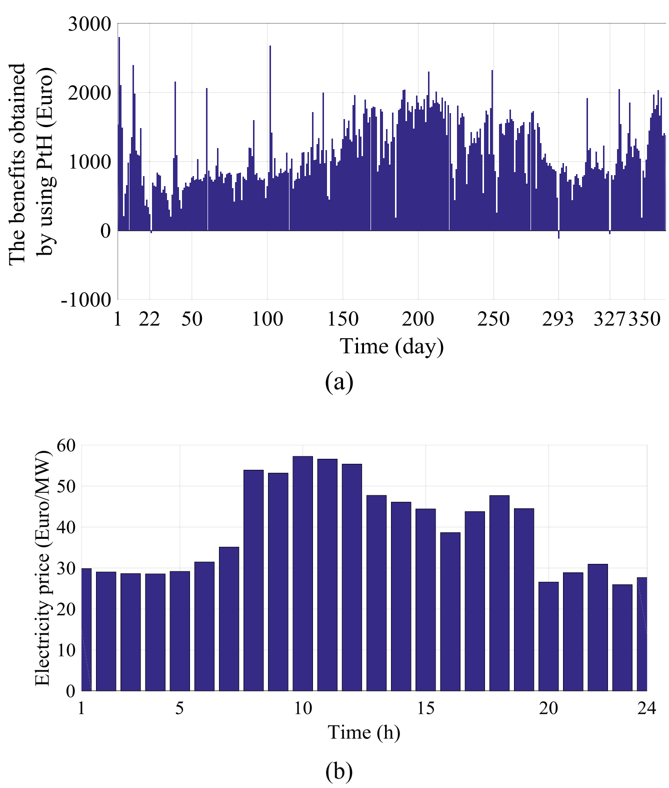

Fig. 6. Simulation results for scenario II. (a) The daily benefits of using PtH for an entire year in scenario II. (b) Example Electricity price for day 23 in 2015.

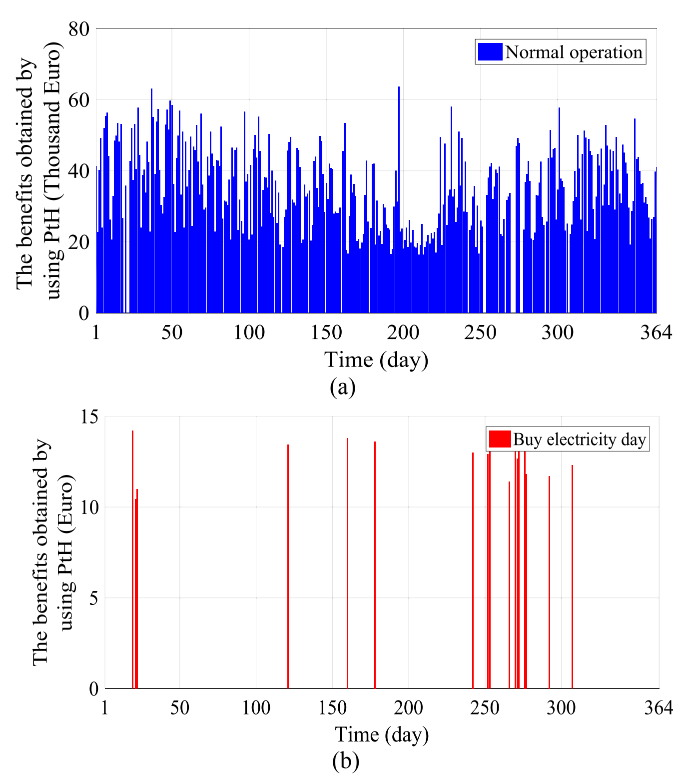

Fig. 7. The daily benefits of using PtH for an entire year in scenario III. (a) Normal operation. (b) buying energy from electricity market.

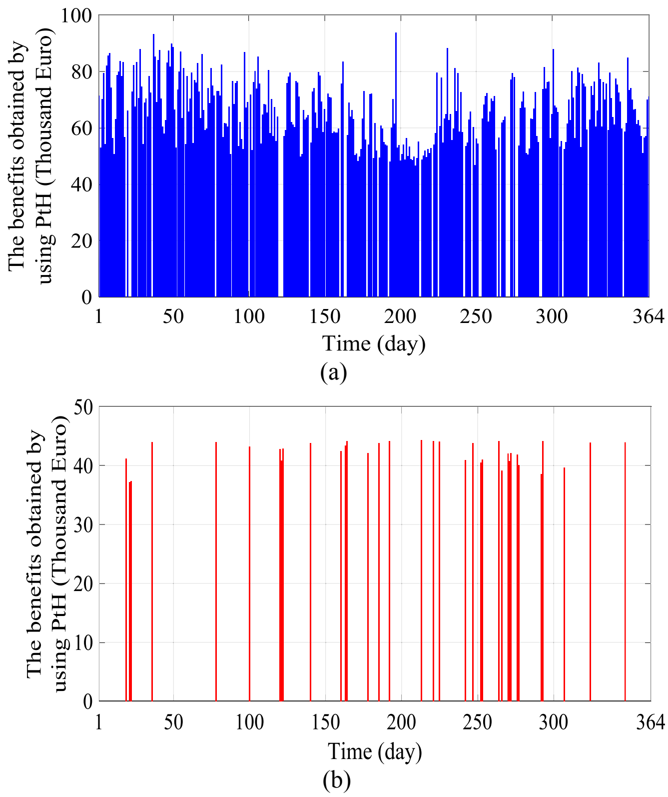

Fig. 8. The daily benefits of using PtH for an entire year in scenario IV. (a) Normal operation. (b) Taking part in electricity market.

installation.

For the last two scenarios the sale price for hydrogen is increased from 2€/kg to 5€/kg in Scenario III and 9€/kg in Scenario IV. This results in greater benefits than Scenario II as shown in Fig. 7 and Fig. 8. The blue bars show the normal operation day and the red bars show the days when the PtH and wind farm needs to buy electricity from the electricity market to meet the required output of hydrogen.

The increase in hydrogen sale price equates to 90.7€/MWh for Scenario III and over 160€/MWh for Scenario IV. As a result the optimization finds that the PtH should build larger electrolyzers (13.5 and 23.4 MW respectively) and hydrogen storage tank (344.5 and 577.3m3 respectively). In the previous scenarios there was not a compelling case for installing hydrogen equipment but the ROI gradually improves as the hydrogen sale price goes up resulting in larger installations as the price increases.

The hydrogen can be used for a variety of applications. The two main applications considered are for transportation fuel, which would require that the hydrogen is delivered to the point of use at fueling stations. The second application is for petroleum refineries. Refineries typically have large steam methane reforming units that use natural gas as a fuel. There is an opportunity to use renewable hydrogen at refineries to reduce the carbon content of all fuels made at that refinery. A 23.4 MW electrolyzer (result for scenario IV) with the 50% production assumption can produce almost 5000 kg per day. This is enough production to supply a fleet of vehicles and is on the scale of steam methane reforming.

For Scenario IV (Fig. 8.), the days that the wind farm must purchase electricity are illustrated in Fig. 8 (b). It can be seen that in Scenario IV, the system needs to buy electricity from the electricity market more frequently than Scenario II and III but the magnitude of the benefit is greater for Scenario IV on account of the higher sale price for hydrogen.

3.3.3. *Summary of results*

A detailed comparison of the value for each scenario and the resulting equipment selection is shown in Tables 5 and 6. For Table 5, the first column shows the ROI, which is also the objective value of the optimization. The next column describes the total benefits in NPV. The hydrogen price is listed in column 3 and the last 7 columns contain component specific NPVs. M€ and T€ represent million euro and thousand euro respectively.

The benchmark only includes the wind farm and is the reference for each scenario. It can be seen that the strategy proposed in scenario I result in an infinite objective value which means the investment for a power-to-power system is not a good proposal and as a result no equipment is installed. The business case for scenario II, III and IV present a favorable investment plan. Even though Scenario II has a low price of hydrogen a small benefit is still achieved but the most compelling cases are Scenarios II and III, which have hydrogen sale price that is high enough to encourage hydrogen production using the wind farm instead of selling the electricity to the grid.

The profitability of PtH is highly related to the hydrogen price.

Table 5
Comparison of different operation strategies.

	Return on Invest-ment (year)	Total benefits in NPV (M€/yr)	Hydro-gen price (€/kg)	NPV of total profits from hydrogen market (M€/yr)	NPV of total profits from electricity market (M€/yr)	NPV of total cost of energy from electricity market (T€/yr)	NPV of electro-lyzer cost (M€)	NPV of storage cost (T€)	NPV of fuel cell cost (M€)	NPV of O&M cost (T€/yr)
Benchmark	/	4.15	/	0	4.15	0	/	/	/	/
Scenario I	Inf	4.15	0	0	4.15	0	0	0	0	0
Scenario II	24.4	4.61	2	0.47	4.14	2.71	5.72	14.38	/	178.4
Scenario III	5.5	7.02	5	2.91	4.11	7.65	12.63	27.87	/	397.3
Scenario IV	2.6	13.13	9	9.10	4.02	42.33	20.82	46.71	/	658.5

Table 6
The equipment selection of different operation strategies.

	Electrolyzer type	Electrolyzer plant size (MW)	Storage volume (m^3)	Fuel cell capacity (MW)
Scenario I	S1	0	0	0
Scenario II	S1	5.5	177.8	–
Scenario III	S1	13.5	344.5	–
Scenario IV	S1	23.4	577.3	–

Notice that the electricity market profits from the sale of wind is reduced (fifth column) but based on the sale price of hydrogen then there is more profit to be made from selling hydrogen than electricity. When the hydrogen price is increased from 2 to 5€/kg, the opportunity cost of using wind electricity to produce hydrogen versus just selling the electricity becomes highly favorable. If the hydrogen price is further increased from 5 to 9€/kg (scenario IV), then the average ROI is reduced even further.

From Table 5, it can be seen that the ROI for scenario III and IV is 5.5 and 2.6 years, respectively. This result is optimistic for a variety of reasons including assumptions around equipment and installation costs at scale, constant demand for hydrogen, price forecasting and limited variability in hydrogen and electricity prices, which would all reduce the calculated benefit. However, this result highlights the potential value for hydrogen to complement wind if the appropriate cost reductions, hydrogen sink and price profiles are realized.

4. Conclusions

Wind energy is one of the dominant renewable resources that continue to grow in Denmark and around the world. Due to the uncertainty in predicting the characteristics of wind, the generated wind must be sold to the electricity market, sometimes resulting in a negative price. The utilization of PtH has proved to be a useful tool for helping the wind farm owner complement profits. As presented in this research, it is beneficial to use the electricity from the wind farm to generate hydrogen that will be sold directly to hydrogen consumers. Hydrogen, and in particular renewable hydrogen, is typically more valuable than electricity and sale directly to consumers is favored compared to transforming it back into electricity and selling that electricity into electricity markets. From this study, integrating hydrogen production systems with a wind farm makes a compelling business case for investors assuming 1) the price for hydrogen is sufficiently high and 2) there is demand for the hydrogen being produced. PtH systems have zero emission when operating. The only emission is during the manufacturing of the components for the involved technologies. Furthermore, such technologies can support renewable electricity production while providing a valuable renewable industrial feedstock or transportation fuel.

The recommendation from Scenario I while not beneficial currently, can change for a variety of reasons including greater prices fluctuate in the future which would cause larger differentials, or the round-trip efficiency of the storage system increases. As an example, the possibility of using PtH for ancillary services in combination with the wind farm can be conducted, and it is expected that the revealed possibilities of wind turbines will further increase the profit expectations for these hybrid systems. This contribution is expected to add focus to the possibilities of applying hydrogen storage technologies, which could drive industry and policy stakeholders to support the continuation of technological development ensuring more efficient systems.

5. Future work

This research did not analyze how political support and changes in hydrogen demand markets will impact the opportunities of the PtH, which should be considered in future work. Additionally, there is a need to understand how the delivery pathways of electrolyzed hydrogen would impact the business case. Lastly, there are other markets that were not explored in this work including ancillary grid services, which can further supplement the competitiveness of PtH systems and should be explored in the future.

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Appendices

Nomenclature

- x_t [Nm^3] Volume of hydrogen that stored in the tank or used from the tank in normal cubic meters
- P_t [MW] Power purchased from electricity market that is used for generating hydrogen to meet the requirement from hydrogen customer at time t
- y Optimization variable of outer layer
- η_{EL} [MWh/Nm^3] Average electrolyzer system transformation efficiency during lifetime
- P_{FC} [MW] Fuel cell capacity
- η_{FC} Fuel cell efficiency
- T Total operation time
- T_{EL} Life time of electrolyzer which is 25 years in this work
- T_{FC} Life time of fuel cell which is 15 years in this work
- $E_t^H(x_t)$[MW] Energy used for generating x_t hydrogen or the energy that generated by hydrogen x_t at time interval t
- E_t^W[MW] The energy production of wind farm at time interval t
- EP_t [euro/MWh] Electricity price at t
- I_r^n[euro] Income obtained from electricity market in year n
- $P_{wind,t}$ [MW] The power production of wind farm at each hour
- P_H [MW] Power plant capacity of electrolysis system
- N_t Operation sequence index
- K_V [m^3] The volume of tank
- S_H [euro/kg] The price of hydrogen
- D_H [kg/m^3] Mass density of hydrogen under standard air pressure
- z_t [m^3] The volume of hydrogen sold at time interval t
- C_{FC}, C_{EL} The cost of fuel cell, and electrolyzer
- C_{Tk} The cost of above ground compressed hydrogen storage tank
- C_{OM} The operation and maintenance cost of electrolysis system (including stack exchange cost)
- O_e The hydrogen production indicator for each hour which is 50% in this paper
- r Interest rate which is 0.05 in this paper

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