Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Optimal operation of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets

Pengfei Xiao [a], *Weihao Hu* [a,*], *Xiao Xu* [a], *Wen Liu* [b], *Qi Huang* [a], *Zhe Chen* [c]

[a] *School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, China*

[b] *Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, Utrecht, 3584 CB, the Netherlands*

[c] *Department of Energy Technology, Aalborg University, Pontoppidanstraede 111, Aalborg, Denmark*

HIGHLIGHTS

- A wind-electrolytic hydrogen storage system in different markets is proposed.
- The uncertainties of wind power outputs and electricity prices are considered.
- Conditional value-at-risk is used to measure its potential financial risks.
- The operational problem is formulated as a MILP problem.

ARTICLE INFO

Article history:
Received 20 May 2020
Received in revised form
29 June 2020
Accepted 30 June 2020
Available online 29 July 2020

Keywords:
Electricity market
Hydrogen market
Wind power
Conditional value-at-risk
Mixed-integer linear programming

ABSTRACT

Wind power, the most promising renewable energy source in the world, plays an important role in the electricity markets. Wind power curtailment cannot be avoided in some countries due to its output has a special feature of randomness and volatility. Since the excess wind power being converted into hydrogen and sold to the hydrogen market will be the future trend. This study proposes a wind-electrolytic hydrogen storage system to participate in the electricity/hydrogen markets for selling electricity and hydrogen, which can help to improve the benefits of wind power in the electricity markets and addree the wind power curtailment effectively. With considering the uncertainties of wind power outputs and electricity prices, the optimal operation strategy is proposed with the objective of maximizing profits. The scenario-based stochastic method is adopted to describe the uncertainties, and the financial risk is evaluated using conditional value-at-risk. The operational problem of the proposed system is formulated into a mixed-integer linear programming model. Finally, the feasibility of the proposed operational strategy is validated by a case study. The results show that the expected revenue increases with the increase of the hydrogen selling price, indicating that investors can obtain profits by converting electricity into hydrogen. The optimal expected revenue increases by 33.42% when hydrogen price increases from 1.2 DKK/kWh to 1.8 DKK/kWh and the risk factor is equal to 0. Based on the analysis of the results, the importance of hydrogen can be proven.

* *Corresponding author.*
E-mail address: whu@uestc.edu.cn (W. Hu).
https://doi.org/10.1016/j.ijhydene.2020.06.302

Nomenclature

A. Abbreviation

CVaR	Conditional Value at Risk
EM	Electricity Market
HM	Hydrogen Market
HST	Hydrogen Storage Tank
MILP	Mixed-Integer Linear Programming
PEM	Proton Exchange Membrane
SOE	Solid Oxide Electrolyzers
VaR	Value at Risk
WF	Wind Farm

B. Index

s	Index for scenarios
t	Index for time periods
Ω_s	Set of scenarios

C. Parameters

$EP_{t,s}$	Electricity price at time t and scenario s ($/kWh)
F_c	Faraday constant (C mol^{-1})
HP	Hydrogen price ($/m^3)
$N_{t,s}^{EL}$	Produced hydrogen molar by electrolyzer at time t and scenario s (mol h^{-1})
P_e	Rated power of wind turbine (kW)
$P_{t,s}^{WT}$	wind power output at time *t* and scenario *s* (kW)
P_{max}^{EL}	Maximum power of the electrolyzer (kW)
P^{HST}	The pressure of hydrogen storage tank (Mpa)
$\Re$	Gas constant (Mpa (mol K)$^{-1}$)
R_{EH}	The total expected revenue from selling electricity to the electricity market and selling hydrogen to the hydrogen market ($)
T^{HST}	The temperature of the hydrogen storage tanks (K)
ΔT	Time constant
U^{EL_work}	The working voltage of the electrolyzer (V)
$V_{t,s}^{wind}$	The real wind speed at time t and scenario s (m/s)
$V_{t,s}^{HST}, V_{t-1,s}^{HST}$	The amount of hydrogen stored in the hydrogen storage tank at time *t* and scenario *s* and at time *t-1* and scenario *s* (m^3)
$V_{min}^{HST}, V_{max}^{HST}$	Lower and upper limits of hydrogen storage tank capacity (m^3)
V_e	Rated wind speed (m/s)
V_{ci}	Cut in wind speed (m/s)
V_{co}	Cut out wind speed (m/s)
α	The confidential level of CVaR (%)
β	Risk factor (%)
η^C	Compressor efficiency (%)
δ_s	Probability of scenario s
ξ_{CVaR}	The value of CVaR under the confidential level α

D. Variables

$P_{t,s}^{WT\_EL}$	Power supplied to the electrolyzer from a wind farm (kW)
$P_{t,s}^{WT\_EM}$	Power sold to the electricity market from a wind farm (kW)
$V_{t,s}^{HST\_HM}$	The amount of hydrogen sold from hydrogen storage tank to hydrogen market at time t and scenario s (m^3)
ζ_α, χ_s	Auxiliary variables for calculating CVaR

Introduction

With the reducing costs and the increasing social needs of renewable energy, installed wind power capacity is expected to grow rapidly in the future [1]. Denmark is rich in wind power resources including onshore and offshore wind power [2]. As the penetration rate of wind power increasing, traditional fossil energy is gradually being replaced. Some traditional power plants are in standby state all year round, which provides necessary system auxiliary services only for grid stability [3]. The concept of using solar and wind energy to power plug-in hybrid vehicles is proposed in [4]. A novel battery/photovoltaic (PV)/wind energy hybrid power source is used to replace the small PV module on the top of the car and the internal combustion engine located at the front of the car. In [5], the integration of wind turbine and battery storage system is investigated to maximize the profit. The wind power output can be directly injected into the grid or used to charge the battery storage system. However, with the rapid development of wind power, it is also facing serious wind power consumption problems. The main reason for the problem of wind power curtailment is that wind power is characterized by fluctuation and uncertainty, and it has relatively weak flexibility compared with conventional power sources. In 2020, wind power as green energy will play an important role in the Danish heating and transportation industry, especially in the production of hydrogen and ammonia through wind power [6].

With the rapid development of renewable energy technologies, countries around the world should be following the needs of social and economic development to promote the renewable energy [7]. Under the premise of ensuring the safe and stable operation of power grids and sustainable development, most of the countries in the world are accelerating the construction of electricity markets [8]. Danish electricity markets include the spot market, regulating, and balancing market. These markets are used to regulate energy imbalances in power systems. Renewable energy is seen as the cornerstone of sustainable development in the future [9]. With the rapid development of renewable energy, the problem of solar, wind, and hydro-power curtailment is becoming more and more serious [10]. The development of electricity markets relates to the promotion of renewable energy [11]. Renewable energy plays an important role in the electricity market, which can bring more economic benefits to investors. Denmark is abundant in wind power [12], and the generated wind power can be sold directly to the electricity markets. For power systems, wind power is always an uncontrollable power source, the uncertainty of the wind power generation brings huge challenges to the investors. To solve this problem, energy storage systems are adopted to implement wind power dispatch.

Nowadays, global awareness of renewable energy is gradually increasing, and investment is also increasing. Incorporating large-scale renewable energy into the grid can affect the stable and safe power supply [13]. The problem with abandoning electricity is becoming more and more serious. Many ways can be used to store the excess electricity produced by renewable energy. Such as energy storage system (lithium-ion battery [14,15]), and energy conversion (power to gas [16], the power to hydrogen [17]). Electricity energy can be transformed into other types of energy, such as producing hydrogen by electrolysis and selling the produced hydrogen to the hydrogen market (HM) to gain more profits. Energy storage systems can be used to implement wind power scheduling, such as battery storage systems are not feasible. Because the battery storage system has the disadvantages of small capacity, high cost, and environmental pollution. Therefore, energy conversion (power to hydrogen) is used in this paper. Hydrogen energy is recognized as clean energy and is used by more and more countries as a zero-carbon energy source. Hydrogen energy has the advantages of no pollution, multiple utilization forms, low loss, high utilization rate, and convenient transportation. Hydrogen energy can be used for hydrogen-fuel cell vehicles, and it can also be used for production needs, such as petroleum, chemical, electronics, metallurgy, aerospace, light industry, and other fields. In [18], the operational strategy of the off-grid hybrid hydrogen/electricity refueling station is proposed which aims to provide hydrogen/electricity to the hydrogen fuel cell vehicles/battery electric vehicles. The feasibility of the proposed system is verified by a case study.

Several methods can be used to produce hydrogen [19], such as the conversion of natural gas steam, methanol steam, and electrolysis of water. It is proven that the hydrogen produced by electrolysing water is a mature technology in practice [20], and the efficiency of hydrogen production exceeds 70%. Renewable energy resources are used to decompose water molecules into hydrogen and oxygen in an electrolyzer. Then, the hydrogen is transported to various corners of the world through pipes and ships [21]. Also it can be sold to the HM. Hydrogen will become the world's third-largest energy source after oil and natural gas in the future [22]. Plenty of literature [23,24] investigates the operational process of the hydrogen production system from renewable energy resources. The hydrogen production system powered by nuclear energy and solar energy is investigated in [24], the system includes hydrogen storage system and the conversion of hydrogen into electricity through a regenerative fuel cell, and results show that the feasibility of the system is verified. A hydrogen production system powered by a hybrid renewable energy power generation system such as wind power, photovoltaic is analyzed in [25]. The results prove that wind power shows the best performance in producing hydrogen.

With the increase in wind power installed capacity and the development of the electricity market, the problem of abandoning electricity is becoming more and more serious. Therefore, to reduce the renewable energy generation curtailment and make investors get more profits, this study proposes a wind-electrolytic hydrogen storage system consisting of a wind farm (WF), an electrolyzer, a compressor, and a hydrogen storage tank (HST). It can provide electricity to the electricity market and hydrogen to the hydrogen market. The HST provides hydrogen to the hydrogen market, and wind power provides electricity directly to the electricity market. It is worth noting that the entire energy of the system comes from the WF. Based on the proposed models, this paper studies the operational strategy of the wind-electrolytic hydrogen storage system by considering the uncertain wind power and electricity prices. In [26], the authors planned the coupled offshore wind-electrolytic hydrogen storage system. The uncertainties of wind power outputs and electricity prices will have a great impact on the system, but the author did not consider the uncertainty. The uncertainty of the pool market price is analyzed using robust optimization in [27]. Robust optimization technique is studied in the large electricity consumer model with and without considering demand response program. In [28], a risk-averse stochastic optimization of hydrogen storage system and wind generation is studied. Also, downside risk constraints are proposed to manage the risk caused by uncertainties. In order to solve the uncertainties of wind power outputs and electricity prices, a scenario-based stochastic optimization method [29] is used for research. This method has been widely used for addressing operational problems [30,31]. Furthermore, the Conditional Value-at-Risk (CVaR) is taken into account to measure its financial risk [32].

The main contributions of the study are summarized as follows:

1. It proposes a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets, which can participate in the electricity market and hydrogen market.
2. It considers the uncertainties of wind power outputs and electricity prices, a scenario-based stochastic optimization approach is employed to study the operational strategy of a wind-electrolytic hydrogen storage system. The objective is to obtain the maximum profits, and the CVaR is used to measure its potential financial risks.
3. The operational problem is converted into a mixed-integer linear programming (MILP) problem. Then, the Gurobi optimization solver is used to obtain the global optimal solution.

The structure of the paper is divided into the following sections. Section Models and problem formulation presents the model of the WF and the hydrogen production system and formulates a MILP problem. Section Case study presents a case study to demonstrate the feasibility of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets. Finally, the whole paper is summarized in Section Conclusion.

Models and problem formulation

Models

The schematic of the proposed wind-electrolytic hydrogen storage system is given in Fig. 1, which consists of a WF, electrolyzer, HST, hydrogen market and electricity market. The red arrow in Fig. 1 indicates the power flow. One part of the generated wind power can be sold directly to the electricity market when the electricity price is relatively high. Due to the uncertainty of the electricity price in the electricity market, the operational strategy of the system should be optimized to get more profits. When electricity price is relatively low and there is excess wind power, the electricity can be stored in the hydrogen storage system. Therefore, the other part can produce hydrogen through the electrolyzer. The green arrow in Fig. 1 indicates the hydrogen flow. The hydrogen produced by electrolyzer can be compressed and stored in an HST. All the generated hydrogen during the day will be stored in the HST firstly. Then it will be transported to hydrogen market for selling at the end of the day, in order to get more profits. It is assumed that the process of transporting the hydrogen does not cause any loss. All the energy of a wind-electrolytic hydrogen storage system is powered by a WF. The system can achieve zero pollution and is suitable for the green development concept advocated by today's society. In this section, the concrete models for each part of the wind-electrolytic hydrogen storage system are described in detail.

Wind-farm model

At present, with the rapid development of renewable energy, such as solar and wind power. Modern power systems face huge challenges. Renewable energy generation has the characteristics of randomness, intermittency and fluctuation. To some degree, the uncertainty of wind power output brings risks to investment in wind power projects. Therefore, to reduce the passive influence caused by the uncertainties of wind power outputs, it is necessary to predict and estimate wind speed. The power generated from a WF [33] can be calculated using Eq. (1).

$$P_{t,s}^{WT} = \begin{cases} 0 & V_{t,s}^{wind} < V_{ci} \\ p_e \times \left(\dfrac{V_{t,s}^{wind} - V_{ci}}{V_e - V_{ci}} \right)^3 & V_{ci} < V_{t,s}^{wind} < V_e \\ p_e & V_e < V_{t,s}^{wind} < V_{co} \\ 0 & V_{t,s}^{wind} > V_{co} \end{cases} \tag{1}$$

where $P_{t,s}^{WT}$ represents the wind power output at time t and scenario s, p_e is the rated power of wind turbine, $V_{t,s}^{wind}$ is the real wind speed at time t and scenario s, V_e, V_{ci} and V_{co} are the rated wind speed, cut in and cut out wind speeds respectively.

Hydrogen production system modeling

Numerous models of hydrogen production systems are mentioned in the literature [34–36]. The hydrogen production system used in this paper is convenient for design and operation problems, and it has characteristics such as high efficiency and safety. The hydrogen production system consists of electrolyzer and HST connected to the WF. Among them, the compressor and cooling system are also included in the hydrogen storage system. When wind power resources are available, hydrogen can be produced through the electrolyzer and stored in the HST. The hydrogen in the HST can be sold to the HM. The models of each component are introduced in turn below.

For the electrolyzer model, the proton exchange membrane (PEM) is used as the electrolyzer in this paper. More electrolyzers are used in an energy storage system, such as alkaline, PEM, and solid oxide electrolyzers (SOE) [37]. Among them, alkaline electrolyzer technology is the first to mature and has a high degree of commercialization [38]. However, the electrolytic efficiency of alkaline electrolyzer is relatively low. The PEM electrolyzer overcomes the shortcomings of the low efficiency of the alkaline electrolyzer. It has good chemical stability and low electrolytic loss. Until now, the optimal electrolysis efficiency of PEM electrolyzer has exceeded 85% [39]. Also, the purity of hydrogen reaches 99.999%. In the

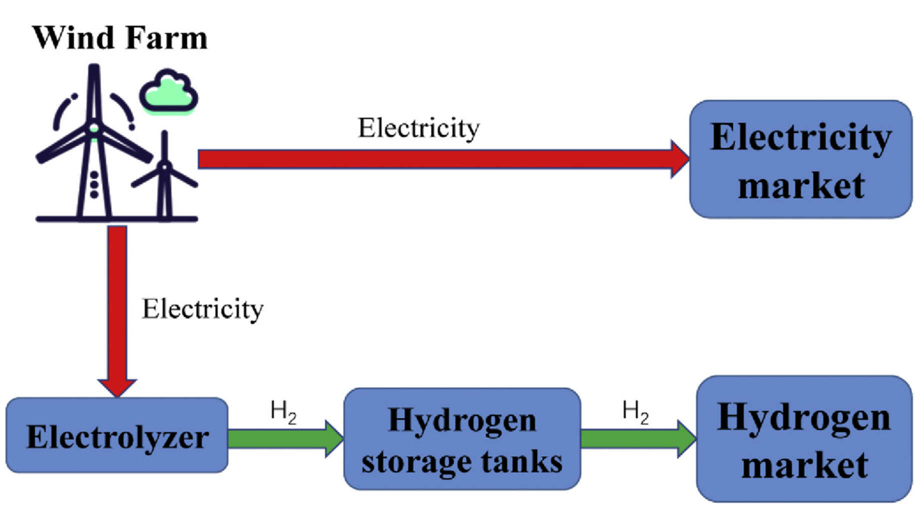

Fig. 1 – The schematic of a wind-electrolytic hydrogen storage system powered by a wind farm.

electrolyzer, water can be electrolyzed by using direct current. Water produces hydrogen and oxygen through redox reactions. The overall reaction can be expressed as:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

Eq. (2) indicates that the produced hydrogen molar by the electrolyzer. The lower and upper limits of the power consumed by the electrolyzer are shown in constraint (3).

$$N_{t,s}^{EL} = \eta^C \frac{P_{t,s}^{WT\_EL}\Delta T}{2U^{EL\_work}F_c} \tag{2}$$

$$0 \le P_{t,s}^{WT\_EL} \le P_{max}^{EL} \tag{3}$$

where $N_{t,s}^{EL}$ is the produced hydrogen molar by the electrolyzer at time t and scenario s, $P_{t,s}^{WT\_EL}$ is the power supplied to the electrolyzer from the WF, P_{max}^{EL} is maximum power of the electrolyzer, η^C is compressor efficiency, ΔT is time constant, U^{EL_work} is the working voltage of the electrolyzer, F_c is Faraday constant.

For the HST model, when there are sufficient wind power outputs, the hydrogen produced by the electrolyzer can be stored in HST. The capacity of the HST can be adjusted according to the actual demand of the HM, and it can be sold to the HM after storing a certain amount of hydrogen [26]. The dynamic model of the pressure of the hydrogen storage system can be considered as Eq. (4). The lower and upper limits of the HST are provided in constraint (5).

$$V_{t,s}^{HST} = V_{t-1,s}^{HST} + \frac{\Re T^{HST}}{P^{HST}} N_{t,s}^{EL} - V_{t-1,s}^{HST\_HM} \tag{4}$$

$$V_{min}^{HST} \le V_{t,s}^{HST} \le V_{max}^{HST} \tag{5}$$

where $V_{t,s}^{HST}$ and $V_{t-1,s}^{HST}$ are the amount of hydrogen stored in the HST at time t and scenario s and at time t-1 and scenario s, $V_{t-1,s}^{HST\_HM}$ is the amount of hydrogen sold from HST to the HM at time t-1 and scenario s, V_{min}^{HST} and V_{max}^{HST} are upper and lower limits of HST capacity, $\Re$ is the gas constant, T^{HST} is the temperature of HST, P^{HST} is the pressure of HST.

Conditional value-at-risk (CVaR)

Compared with VaR, CVaR is coherent and has the characteristics of sub-additivity and convexity, which is a good risk measurement index. CVaR retains the convexity of the optimization model. Therefore, the optimization problem can be solved. Because VaR is incoherent and does not completely use the information in the tail of the loss, in this paper, CVaR is used to evaluate the financial risk of the proposed model when considering the uncertainties of wind power outputs and electricity prices. CVaR can be calculated by Eqs. {(6)–(8)} [40].

$$\xi_{CVaR} = \max\left(\zeta_\alpha - \frac{1}{1-\alpha}\sum_{s=1}^{\Omega_S}\delta_s\chi_s\right) \tag{6}$$

$$\text{s.t. } \chi_s \ge \zeta_\alpha - R_s, \forall s \tag{7}$$

$$\chi_s \ge 0, \forall s \tag{8}$$

where ξ_{CVaR} is the value of CVaR under the confidential level, ζ_α and χ_s are auxiliary variables for calculating CVaR, δ_s is probability of scenario s, α is the confidential level of CVaR. In the above equation, if the difference between ζ_α and R_s is positive, the value of χ_s is equal to the difference between ζ_α and R_s, otherwise, the value of χ_s is equal to 0. Therefore, the optimal expected revenue is ζ_α, given the confidential level α [41].

Problem formulation

This paper proposes a wind-electrolytic hydrogen storage system powered by a WF. Retailers of the system can sell electricity to the electricity market and sell hydrogen to the hydrogen market to get maximize profits. The research objective of this paper is given by Eq. (9), which maximizes the expected revenue while taking into account CVaR financial risks. The first part of Eq. (9) represents the expected revenue of the system. Expected revenue can be calculated by Eq. (10). The second part of Eq. (9) shows the calculation process of CVaR, and at the same time it is multiplied by the weighting factor β, which represents the preference of decision makers for risk. Eq. (10) consists of two parts. The first part represents the expected revenue from selling electricity directly to the electricity market, and the second part represents the expected revenue from hydrogen production system, which selling hydrogen to the hydrogen market. Eq. (11) shows that the total power delivered to the electricity market and electrolyzer is affected by the wind power outputs. At the same time, Eqs. (12) and (13) are formulated according to Eqs. (7) and (8), so as to measure and evaluate the financial risks of the system. The other constraints of the model are organized as shown in Eq. (14), and the detailed Eqs. {(1) − (5)} are shown above.

$$\max R_{EH} + \beta\left[\zeta_\alpha - \frac{1}{1-\alpha}\cdot\sum_{s=1}^{\Omega_S}(\delta_s\chi_s)\right] \tag{9}$$

$$R_{EH} = \sum_{s=1}^{\Omega_S}\delta_s\sum_{t=1}^{T}\left[P_{t,s}^{WT\_EM}\cdot EP_{t,s} + V_{t,s}^{HST\_HM}\cdot HP\right] \tag{10}$$

$$0 \le P_{t,s}^{WT\_EM} + P_{t,s}^{WT\_EL} \le P_{t,s}^{WT} \tag{11}$$

$$\chi_s \ge \zeta_\alpha - \sum_{t=1}^{T}\left[P_{t,s}^{WT\_EM}\cdot EP_{t,s} + V_{t,s}^{HST\_HM}\cdot HP\right], \forall s \tag{12}$$

$$\chi_s \ge 0, \forall s \tag{13}$$

$$\{(1)-(5)\} \tag{14}$$

where R_{EH} is the total expected revenue from selling electricity to the electricity market and selling hydrogen to the hydrogen market, β is the risk factor, $P_{t,s}^{WT\_EM}$ is the power sold to the electricity market from a wind farm, $EP_{t,s}$ is electricity price at time t and scenario s, HP is hydrogen price.

The optimization flowchart of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets is presented in Fig. 2. The operational problem of the proposed system is formulated into a MILP model. At the same time, the

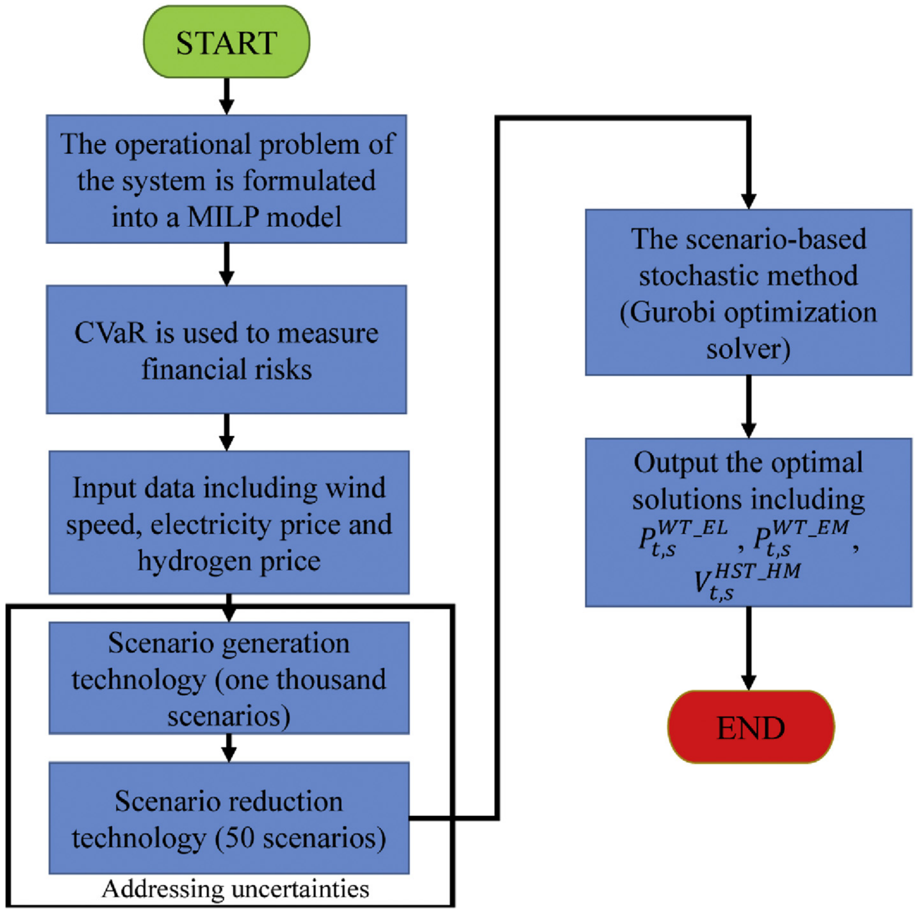

Fig. 2 – Optimization flowchart.

CVaR is used to evaluate the financials risks of the system. The uncertainties of wind power outputs and electricity prices are considered in this paper. Scenario analysis is used to describe uncertainty. Scenario generation technology is used to generate one thousand scenarios. Then, scenario reduction technology is used to reduce to 50 representative scenarios. According to the above modeling and analysis, the optimal solutions are solved by the Gurobi optimization solver, including $P_{t,s}^{WT\_EL}$, $P_{t,s}^{WT\_EM}$, $V_{t,s}^{HST\_HM}$. Finally, the global optimal results can be obtained.

Case study

In this section, a case study is presented to demonstrate the feasibility of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets. This part studies the operational strategy of the system, and elaborates on the operation of this process in detail. The operational problem was transformed into a MILP model and solved using the Gurobi optimization solver in the Python environment.

Data

This paper has studied the proposed wind-electrolytic hydrogen storage system. The parameters of the WF are presented in Table 1 [32]. The detailed parameters of the electrolyzer and HST are presented by Table 2 and Table 3 [42]. To optimize the operational strategy of a wind-electrolytic hydrogen storage system, this work considers deterministic predictions and uses scenario generation techniques to generate scenarios to predict the uncertainties of parameters. The uncertainties of wind power outputs and electricity prices are considered in this paper. Scenario analysis is a common way used to describe uncertainty and randomness [43]. The objective of the scenario generation is to obtain large-scale scenarios for power system analysis. Scenario generation is based on the probability distribution function or statistical characteristics of the research object to obtain uncertainty scenarios through the sampling method. The uncertainties of wind power outputs and electricity prices in this paper are represented by the prediction error, and the prediction error is assumed to follow a normal distribution. For these two uncertainty parameters, scenario generation technology was used to generate one thousand scenarios respectively. Then the scenario reduction technology was used to reduce one thousand scenarios to 50 scenarios. The objective of scenario reduction is to describe a large number of complex scenarios

Table 1 – The parameters of the wind farm.

Parameters	P_e	V_{ci}	V_e	V_{co}
Value	1400 kW	2 m/s	14 m/s	24 m/s

Table 2 – The detailed parameters of the electrolyzer.

Parameters	$P_{min}^{EL}, P_{max}^{EL}$	ΔT	η^C	U^{EL_work}	F_C
Value	0, 1300 kW	3600	94%	2 V	96485 C mol^{-1}

Table 3 – The detailed parameters of the hydrogen storage tank.

Parameters	$V_{min}^{HST}, V_{max}^{HST}$	$\Re$	T^{HST}	p^{HST}
Value	0, 7.42 m^3	0.00821 Mpa (mol K)$^{-1}$	298 K	20 Mpa

features with a small number of representative scenarios. The scenario reduction technology reduces the number of similar scenarios through data analysis, to reduce the computational complexity [44]. Finally, the 50 scenarios are used to represent the uncertainties of wind power outputs and electricity prices. The wind power outputs in one day are shown in Fig. 3(a). All available power in the electricity market and hydrogen market are provided by the WF. The size of the WF is set to 1400 kW. Fig. 3(b) shows the electricity price for one day in 50 scenarios. In this paper, the uncertainty of electricity prices is also considered. The hydrogen price is fixed and it is assumed to be 1.4 DKK/kWh, in which the unit of the hydrogen price is converted into the same unit as the electricity price. In the following, detailed simulation results are given when $\beta = 0$.

Simulation results

The value of CVaR and the expected revenue under different risk factors are presented in Fig. 4 and Fig. 5, respectively, where a confidential level of 95% is considered ($\alpha = 0.95$), It can be seen from Figs. 4 and 5 that when the risk factor gradually increases, the value of CVaR is increasing, and the expected revenue is decreasing. When the risk factor $\beta = 0$, the decision-maker can bear the highest risk. With the increase of the risk factor, the ability of the decision-maker to tolerate risk has gradually diminished. Under different risk factors, the operational strategy of the wind-electrolytic hydrogen storage system is also different. The detailed data on the value of CVaR and expected revenue under different risk factors are presented in Table 4. It can be seen from Table 4 that when the risk factor is equal to 0, the revenue from selling electricity and hydrogen are 3350.28 DKK and 5430.03 DKK, respectively. At this time, the volume of hydrogen electrolyzed in a day is 7.19 m^3. The simulation results are given below and analyzed when the risk factor is equal to zero ($\beta = 0$). The risk factor is equal to 0 indicating that investors can maximize expected revenue without considering any financial risks.

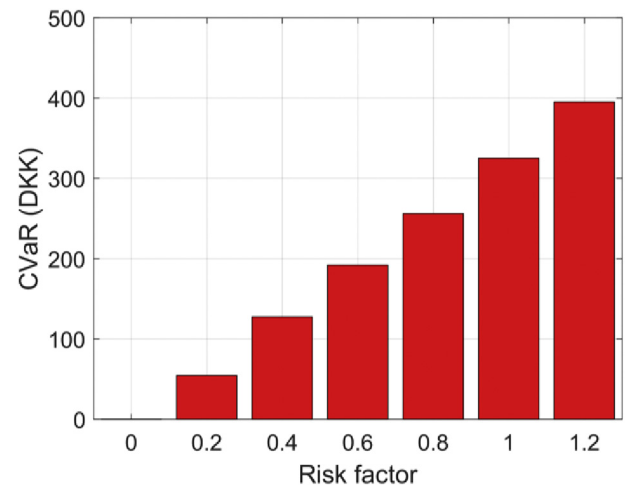

Fig. 4 – The value of CVaR under different risk factors.

The generated wind power can be applied to produce hydrogen through electrolyzer, and the hydrogen can be sold to the HM. The power consumed by the electrolyzer is given in Fig. 6. It can be found in Figs. 3 and 6 that when there is sufficient wind power output and the electricity price is relatively low, especially in the early morning and in the evening, the electrolyzer consumes more power to generate hydrogen. Hydrogen can be sold to the HM to make decision-makers get more profits. The power sold to the electricity market from a WF is presented in Fig. 7. As can be seen in Fig. 7 that from 6:00 to 10:00 in the morning, from 13:00 to 15:00 and from 17:00 to 19:00, when the electricity price is relatively high, the wind power outputs sold directly to the electricity market. As the electricity price is relatively low, in the early morning and the night, the economic income of the decision-maker is considered, electricity will not be sold to the electricity market.

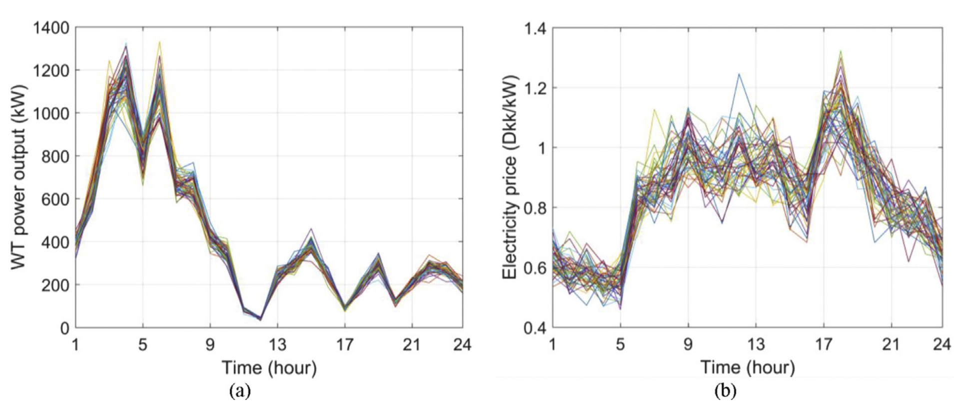

Fig. 3 – Simulation dataset. (a) Wind power output in 50 scenarios. (b) Electricity price in 50 scenarios.

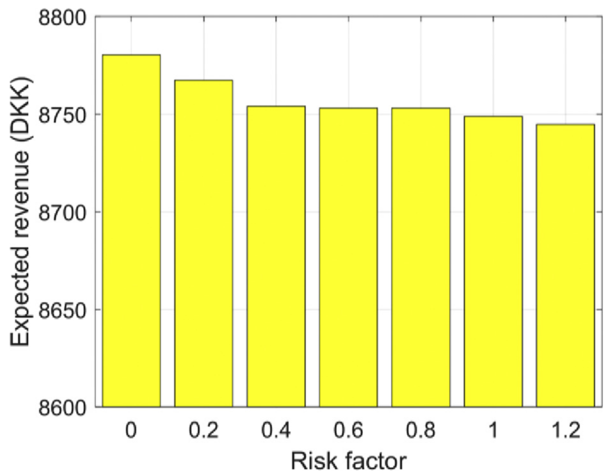

Fig. 5 – The expected revenue under different risk factors.

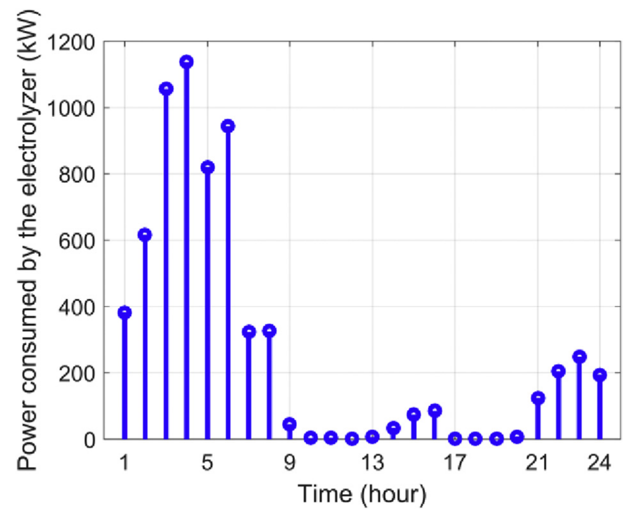

Fig. 6 – Wind power consumed by the electrolyzer.

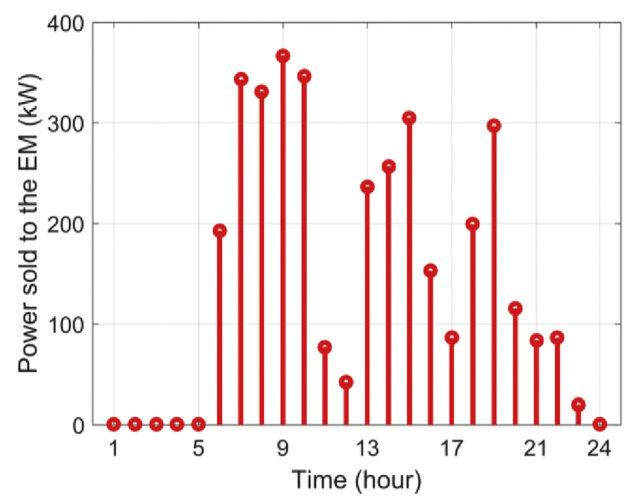

Fig. 7 – The power sold to the electricity market from a wind farm.

Fig. 8 shows the volume of hydrogen electrolyzed in a day. When there is sufficient wind power output, the electrolyzer works to produce hydrogen, which is stored in an HST. All the energy of hydrogen produced during a day will be stored in the HST firstly, and then transported to sell at the end of the day. The capacity of the HST can be adjusted according to the actual demand of the HM. It is assumed that the process of transporting hydrogen does not cause any loss. The HST provides a continuous supply of hydrogen resources to the HM. It can be seen from Fig. 8 that in the early morning, when the electricity price is low, hydrogen is produced by electrolysis and stored in an HST. Especially from 1:00 to 5:00 and from 20:00 to 24:00, more hydrogen energy is produced by electrolysis. It is worth noting that the electrolyzer does not work to generate hydrogen during the electricity price peak of 9:00 am. At this time, the investor directly sells electricity to the electricity market to obtain more profits. The volume of hydrogen electrolyzed in a day is 7.19 m^3, and the revenue from selling hydrogen to the HM is 5430.03 DKK. Based on the above analysis, the importance of the existence of HST can be confirmed.

The objective of this paper is to maximize the expected revenue. The expected revenue is equal to the revenue from selling electricity to the electricity market plus the revenue from selling hydrogen to the hydrogen market. Fig. 9 shows the expected revenue from the electricity market and hydrogen market when the risk factor is equal to zero ($\beta = 0$). It can be seen from Fig. 9 that when the electricity price is relatively high, there is more electricity sold to the electricity market, and when the electricity price is relatively low, there is more hydrogen sold to the HM. It is worth noting that in the early morning, the generated wind power will not be sold to the electricity market due to lower electricity prices. At this time, only the electrolyzer works to generate more hydrogen, and hydrogen sold to the HM to obtain more profits. Expected profits are affected by some factors such as electricity price, hydrogen price, and energy conversion efficiency. At this time, CVaR is considered and the risk factor is set to 0.4 ($\beta = 0.4$). The expected revenue from the electricity market and the hydrogen market is presented in Fig. 10.

In this paper, the price of hydrogen is fixed, and it is assumed to be 1.4 DKK/kWh, in which the unit of the hydrogen price is converted into the same unit as the

Table 4 – The value of CVaR and expected revenue under different risk factors.

Risk factor	0	0.2	0.4	0.6	0.8	1.0	1.2
Expected revenue (DKK)	8780	8767	8754	8753	8753	8748	8744
Revenue from selling electricity (DKK)	3350.28	3406.27	3453.16	3494.65	3494.65	3519.10	3541.57
Revenue from selling hydrogen (DKK)	5430.03	5361.02	5300.86	5258.51	5258.51	5229.66	5203.17
CVaR (DKK)	0	54.99	127.73	192.46	256.62	325.35	395.06

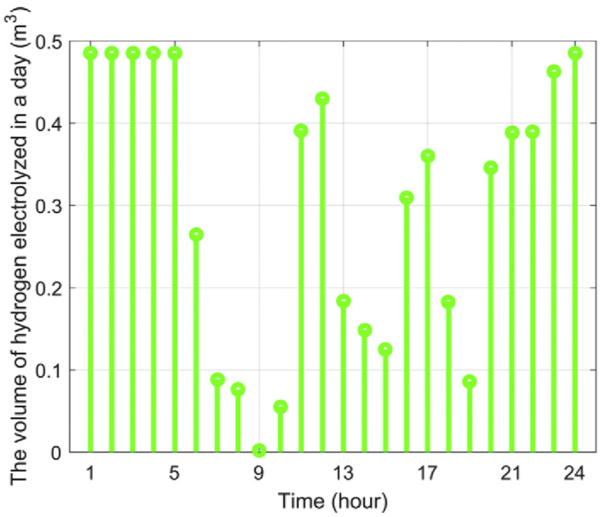

Fig. 8 – The volume of hydrogen electrolyzed in a day.

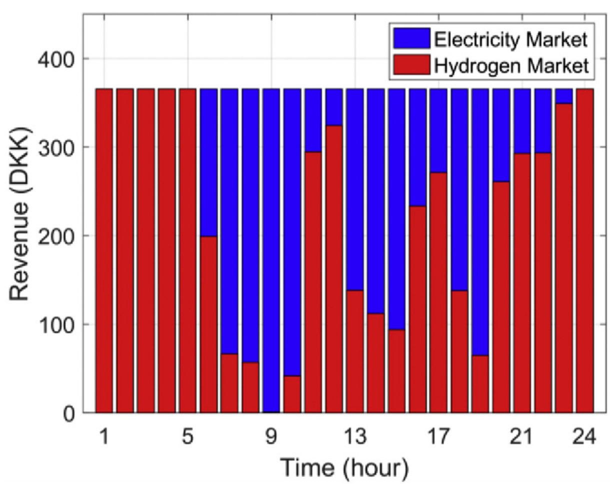

Fig. 9 – The expected revenue from the electricity market and hydrogen market ($\beta = 0$).

electricity price. The expected revenue under different hydrogen prices is presented in Fig. 11. When the hydrogen price increases from 1.2 DKK/kWh to 1.8 DKK/kWh, the curve of hydrogen price also shows an increasing trend. Table 5 gives detailed data on the expected revenue under different hydrogen prices. Therefore, it can be concluded that the price of hydrogen is one of the important parameters in the operational problem, and the hydrogen price will affect the expected revenue. High hydrogen prices could encourage the decision-maker to use wind power to produce more hydrogen to get more profits. The expected revenue under different electrolyzer capacities is given in Fig. 12. It can be seen from Fig. 12 that with the capacity of the electrolyzer increases, the expected revenue will also increase. The maximum capacity of the electrolyzer used in this paper is 1300 kW.

To prove the advantages of this study, three cases, which are without considering HM, without considering EM and with considering both EM and HM, are investigated and compared. Fig. 13 presents the expected revenue under different cases. It can be observed that the expected revenue in case III is higher than that in case I and case II. Besides, with the increase of the hydrogen price, the expected revenue increases in case II and case III. Table 6 gives detailed results of the expected revenue under different cases when the hydrogen price is 1.4 DKK/kWh. The optimal expected revenue can reach 8780.31 DKK when both EM and HM are considered (case III). Compared to case III, the expected revenue for case I and case II decreases by 88.71% and 5.17%, respectively. Therefore, it can be concluded that the expected revenue can be significantly improved with considering both EM and HM.

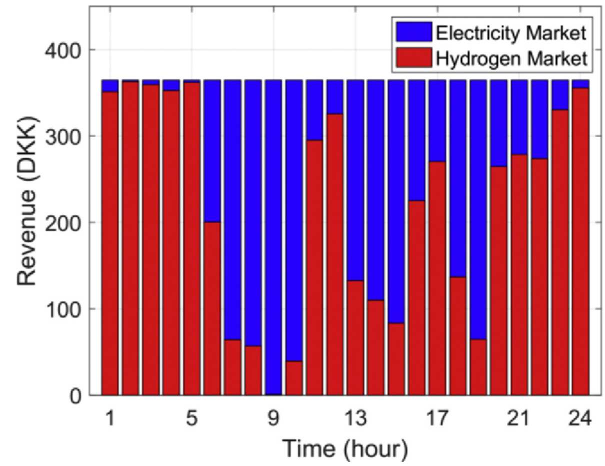

Fig. 10 – The expected revenue from the electricity market and hydrogen market ($\beta = 0.4$).

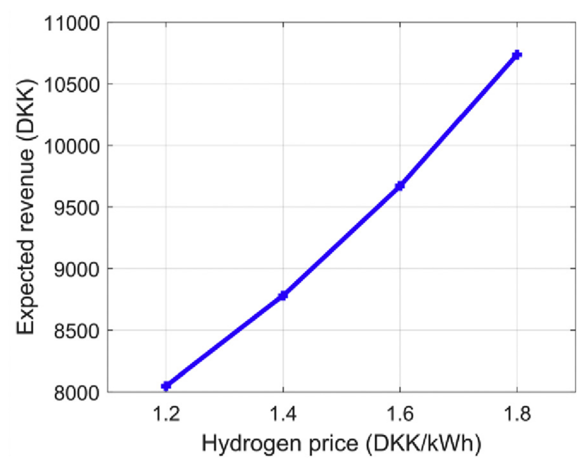

Fig. 11 – The expected revenue under different hydrogen price.

Table 5 – The expected revenue under different hydrogen price.

Hydrogen price (DKK/kWh)	1.2	1.4	1.6	1.8
Expected revenue (DKK)	8048.02	8780.31	9668.14	10737.48

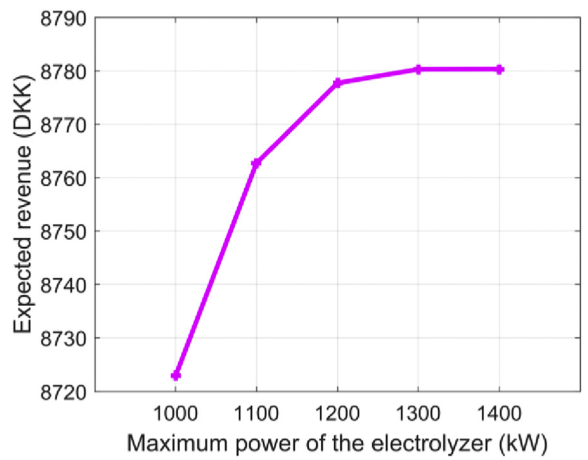

Fig. 12 – The expected revenue under different electrolyzer capacities.

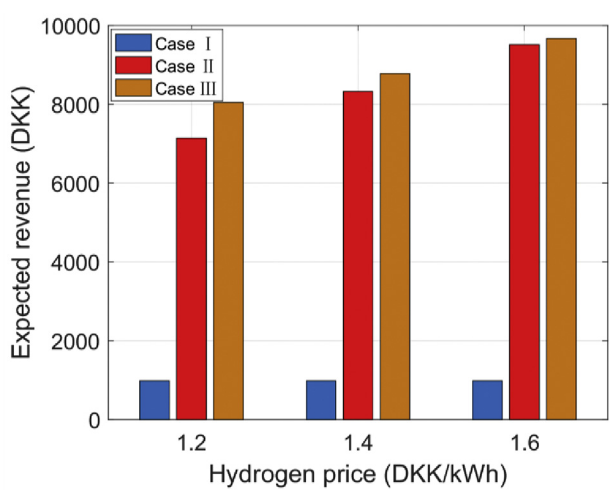

Fig. 13 – The expected revenue under different cases.

Table 6 – The expected revenue under different cases when the hydrogen price is 1.4 DKK/kWh.

Different cases	Case I Without considering HM	Case II Without considering EM	Case III With considering both EM and HM
Revenue from selling electricity (DKK)	991.04	0	3350.28
Revenue from selling hydrogen (DKK)	0	8326.32	5430.03
Expected revenue (DKK)	991.04	8326.32	8780.31
Reduced percentage of expected revenue (%)	88.71	5.17	–

Conclusion

This study proposes a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets. Wind power output is the source of all energy for the electricity market and hydrogen market. Wind power operators can either directly sell electricity to the electricity market or convert excess electricity into hydrogen via electrolyzers and sell it to the hydrogen market. This will be the main trend of renewable energy development in the future. To pursue optimal profits, the proposed HST is used to store hydrogen so that it is sold to the HM at the right time. The objective of the paper is to maximize the expected revenue for investors. The uncertainty of wind power outputs, electricity prices, and risks are considered. Based on the above analysis, the operational problem of the wind-electrolytic hydrogen storage system is investigated. The analysis results verify the feasibility of the proposed system. The expected revenue increases by 33.42% when the hydrogen price varies from 1.2 DKK/kWh to 1.8 DKK/kWh. It indicates that the hydrogen price is a key factor affecting the expected revenue. It is worth noting that the size of the WF also affects the expected revenue. The proposed wind-electrolytic hydrogen storage system is worthy of extensive research and promotion in the future. The planning of the hybrid renewable energy system will be studied in future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2018YFE0127600).

REFERENCES

[1] Jacob Ladenburg, Hevia-Koch Pablo, Petrović Stefan, Knapp Lauren. The offshore-onshore conundrum: preferences for wind energy considering spatial data in Denmark. Renew Sustain Energy Rev 2020;121:109711.
[2] Jacobsen Henrik Klinge, Hevia-Koch Pablo, Wolter Christoph. Nearshore and offshore wind development: costs and competitive advantage exemplified by nearshore wind in Denmark. Energy Sustain Dev 2019;50:91–100.
[3] Kruyt Bert, Lehning Michael, Kahl Annelen. Potential contributions of wind power to a stable and highly renewable Swiss power supply. Appl Energy 2017;192:1–11.
[4] Hassan Fathabadi. Utilizing solar and wind energy in plug-in hybrid electric vehicles. Energy Convers Manag 2018;156:317–28.
[5] Jermsittiparsert K. Bidding and offering strategies for integration of battery storage system and wind turbine. In:

Electricity markets: new players and pricing uncertainties; 2020. p. 247–61.
[6] Bühler Fabian, Nguyen Tuong-Van, Elmegaard Brian. Energy and exergy analyses of the Danish industry sector. Appl Energy 2016;184:1447–59.
[7] Ostergaard PA, Duic N, Noorollahi Y, Mikulcic H, Kalogirou S. Sustainable development using renewable energy technology. Renew Energy 2020;146:2430–7.
[8] Guo Shaopeng, Liu Qibin, Sun Jie, Jin Hongguang. A review on the utilization of hybrid renewable energy. Renew Sustain Energy Rev 2018;91:1121–47.
[9] Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature 2012;488:294–303.
[10] Khare Vikas, Nema Savita, Baredar Prashant. Solar–wind hybrid renewable energy system: a review. Renew Sustain Energy Rev 2016;58:23–33.
[11] Pinson P, Mitridati L, Ordoudis C, Ostergaard J. Towards fully renewable energy systems: experience and trends in Denmark. CSEE J Power Energy Syst 2017;3:26–35.
[12] Hvelplund Frede, stergaard Poul Alberg, Meyer Niels I. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Pol 2017;107:573–84.
[13] Rehmani MH, Reisslein M, Rachedi A, Erol-Kantarci M, Radenkovic M. Integrating renewable energy resources into the smart grid: recent developments in information and communication technologies. IEEE Trans Ind Informat 2018;14:2814–25.
[14] He Guannan, Chen Qixin, Kang Chongqing, Pinson Pierre, Xia Qing. Optimal bidding strategy of battery storage in power markets considering performance-based regulation and battery cycle life. IEEE Trans Smart Grid 2016;7:2359–67.
[15] Diouf Boucar, Pode Ramchandra. Potential of lithium-ion batteries in renewable energy. Renew Energy 2015;76:375–80.
[16] Guandalini G, Robinius M, Grube T, Campanari S, Stolten D. Long-term power-to-gas potential from wind and solar power: a country analysis for Italy. Int J Hydrogen Energy 2017;42:13389–406.
[17] Ye Jun, Yuan Rongxiang. Stochastic scheduling of integrated electricity-heat-hydrogen systems considering power-to-hydrogen and wind power. J Renew Sustain Energy 2018;10:221–34.
[18] Xu Xiao, Hu Weihao, Cao Di, Huang Qi, Wen Liu, Jacobson Mark Z, Chen Zhe. Optimal operational strategy for an offgrid hybrid hydrogen/electricity refueling station powered by solar photovoltaics. J Power Sources 2020;451:227810.
[19] Nikolaidis Pavlos, llikkas AndreasPou. A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 2017;67:597–611.
[20] An L, Zhao TS, H Chai Z, Tan P, Zeng L. Mathematical modeling of an anion-exchange membrane water electrolyzer for hydrogen production. Int J Hydrogen Energy 2014;39:19869–76.
[21] Ahmad Gondal Irfan, Masood Syed Athar, Khan Rafiullah. Green hydrogen production potential for developing a hydrogen economy in Pakistan. Int J Hydrogen Energy 2018;43:6011–39.
[22] Won W, Kwon H, Han J-H, Kim J. Design and operation of renewable energy sources based hydrogen supply system: technology integration and optimization. Renew Energy 2017;103:226–38.
[23] Acar Canan, Dincer Ibrahim. Experimental investigation and analysis of a hybrid photoelectrochemical hydrogen production system. Int J Hydrogen Energy 2017;42:2504–11.
[24] Orhan Mehmet F, Babu Binish S. Investigation of an integrated hydrogen production system based on nuclear and renewable energy sources: comparative evaluation of hydrogen production options with a regenerative fuel cell system. Energy 2015;88:801–20.
[25] Al-Sharafi Abdullah, Sahin Ahmet Z, Ayar Tahir, Yilbas Bekir S. Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia. Renew Sustain Energy Rev 2017;69:33–49.
[26] Hou Peng, Enevoldsen Peter, Eichman Joshua, Hu Weihao, Jacobson Mark Z, Chen Zhe. Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark. J Power Sources 2017;359:186–97.
[27] Yu Dongmin, Zhang Tao, He Guixiong, Nojavan Sayyad, Jermsittiparsert Kittisak, Ghadimi Noradin. Energy management of wind-PV-storage-grid based large electricity consumer using robust optimization technique. J Energy Storage 2020;20:101054.
[28] Yu Dongmin, Wang Jiawei, Li Dezhi, Jermsittiparsert Kittisak, Nojavan Sayyad. Risk-averse Stochastic operation of a power system integrated with hydrogen storage system and wind generation in the presence of demand response program. Int J Hydrogen Energy 2019;44:31204–15.
[29] Wang Zongfei, Jochem Patrick, Wolf Fichtner. A scenario-based stochastic optimization model for charging scheduling of electric vehicles under uncertainties of vehicle availability and charging demand. J Clean Prod 2020;254:119886.
[30] Shuai Hang, Fang Jiakun, Ai Xiaomeng, Tang Yufei, Wen Jinyu, He Haibo. Stochastic optimization of economic dispatch for microgrid based on approximate dynamic programming. IEEE Trans Smart Grid 2019;10:2440–52.
[31] He Li, Pan Liu, Guo Shenglian, Ming Bo, Cheng Lei, Yang Zhikai. Long-term complementary operation of a large-scale hydro-photovoltaic hybrid power plant using explicit stochastic optimization. Appl Energy 2019;238:863–75.
[32] Tavakoil Mehdi, Shokridehaki Fatemeh, Akorede Mudathir Funsho, Marzband Mousa, Vechiu Lonel, Pouresmaeil Edris. CVaR-based energy management scheme for optimal resilience and operational cost in commercial building microgrids. Int J Electr Power Energy Syst 2018;100:1–9.
[33] Xu Xiao, Hu Weihao, Cao Di, Huang Qi, Chen Cong, Chen Zhe. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. Renew Energy 2020;147:1418–31.
[34] Colbertaldo Paolo, Agustin Stacey Britni, Campanari Stefano, Brouwer Jack. Impact of hydrogen energy storage on California electric power system: towards 100% renewable electricity. Int J Hydrogen Energy 2019;44:9558–76.
[35] Marchenko OV, Solomin SV. Modeling of hydrogen and electrical energy storages in wind/PV energy system on the Lake Baikal coast. Int J Hydrogen Energy 2017;42:9361–70.
[36] Li CH, Zhu XJ, Cao GY, Sui S, Hu MR. Dynamic modeling and sizing optimization of stand-alone photovoltaic power systems using hybrid energy storage technology. Renew Energy 2019;34:815–26.
[37] Zhang Fan, Zhao Pengcheng, Niu Meng, Maddy Jon. The survey of key technologies in hydrogen energy storage. Int J Hydrogen Energy 2016;41:14535–52.
[38] Kovač Ankica, Marciuš Doria, Budin Luka. Solar hydrogen production via alkaline water electrolysis. Int J Hydrogen Energy 2019;44:9841–8.
[39] Zhang Fan, Zhao Pengcheng, Niu Meng, Maddy Jon. The survey of key technologies in hydrogen energy storage. Int J Hydrogen Energy 2017;33:14535–52.
[40] Li Y, Liu W, Shahidehpour M, Wen F, Wang K, Huang Y. Optimal operation strategy for integrated natural gas generating unit and power-to-gas conversion facilities. IEEE Trans Sustain Energy 2018;9:1870–9.

[41] Wu JK, Wu ZJ, Wu F, Tang HL, Mao XM. CVaR risk-based optimization framework for renewable energy management in distribution systems with DGs and EVs. Energy 2018;143:323–36.
[42] Nojavan Sayyad, Zare Kazem, Mohammadi-Ivatloo Behnam. Application of fuel cell and electrolyzer as hydrogen energy storage system in energy management of electricity energy retailer in the presence of the renewable energy sources and plug-in electric vehicles. Energy Convers Manag 2017;136:404–17.
[43] Rosenfeld Daniel C, Böhm Hans, Lindorfer Johannes, Lehner Markus. Scenario analysis of implementing a power-to-gas and biomass gasification system in an integrated steel plant: a techno-economic and environmental study. Renew Energy 2020;147:1511–24.
[44] Dolatabadi Amirhossein, Mohammadi-ivatloo Behnam, Abapour Mehdi, Tohidi Sajjad. Optimal stochastic design of wind integrated energy hub. IEEE Trans Ind Informat 2017;13:2379–88.