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Day-ahead economic optimization scheduling model for electricity–hydrogen collaboration market

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Abstract

This paper presents a day-ahead economic optimization scheduling model for Regional Electricity–Hydrogen Integrated Energy System (REHIES) with high penetration of renewable energies. The electricity–hydrogen coupling devices are modelled with energy storage units and Insensitive Electrical Load (ISEL). The proposed objective function is able to capture the maximum benefits for REHIES in terms of economic benefits and can be summarized as a Quadratic Programming (QP) problem. The simulation verification is performed by MATLAB/CPLEX solver. The simulation results show that the proposed optimization model adapts the market requirement by contributing flexible collaboration between electricity and hydrogen. Also, the translational properties of ISEL can implement higher economic profits and more effective utilization of renewable energy.

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Keywords: Economic optimization; Regional electro-hydrogen integrated energy system (REHIES); Electro-hydrogen collaboration; Industrial energy market; Insensitive electrical load (ISEL)

1. Introduction

Hydrogen is becoming an emerging energy vector in modern energy system with reduced carbon emission [1]. Nowadays, hydrogen is increasingly applied in various industrial fields such as chemical industry [2], fuel mixed natural gas [3] and Fuel Cell-driven Electric Vehicle (FCEV) [4], etc. Therefore, the marketization of hydrogen can contribute to the development of low carbon energy system. The Regional Electricity–hydrogen Integrated Energy System (REHIES) is an effective solution to integrate hydrogen energy in energy system by means of microgrid technologies with advanced power management, optimal grid connection operation, and Power to Hydrogen (P2H) technologies, etc. [5–8]. Fully supported by hydrogen technology in producing, storing and transportation, industrial parks based on REHIES can exploit hydrogen energy to expect zero carbon pollution.

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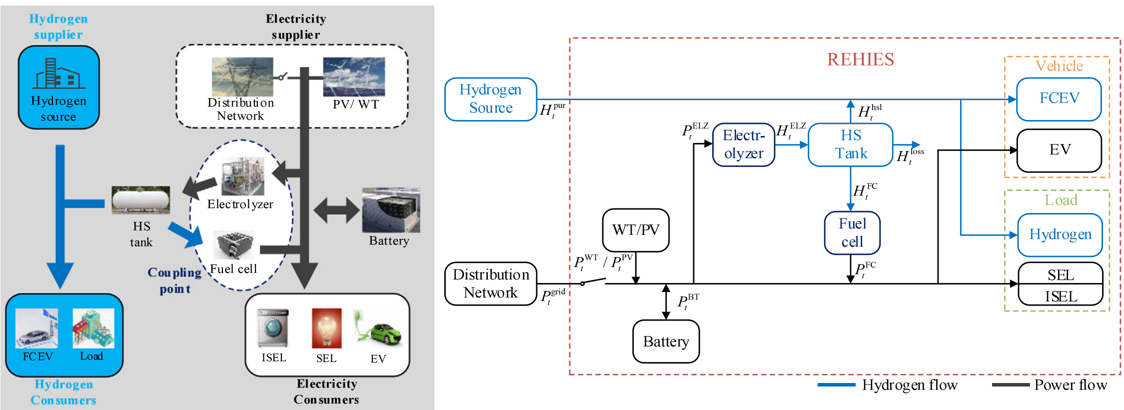
Previous efforts have been performed to efficiently utilize hydrogen energy. In [9], a dynamic model of hydrogen storage (HS) system is presented and validated to reduce the power absorption of the hydrogen-based microgrid. Concerning the control strategy in [10], the fuel cell input/output stability constraints improve the robustness of hydrogen hybrid energy system under small disturbances. However, the aforementioned work mainly focuses on the technical issues in hydrogen system, and the coupling relationship among multi energy vectors is merely concerned. In [11], an optimal REHIES dispatch strategy is proposed, where the transportation of hydrogen and electricity is also considered. The concept of energy sharing is presented in [12], where hydrogen and electricity are coupled by P2H devices, electric vehicle (EV) and FCEV to minimize the energy storage cost. In [13], a control strategy is developed according to the characteristics of renewable energy for a hybrid system integrated with the electricity subsystem, hydrogen subsystem and DC traction power system. However, the aforementioned management and control strategies slightly consider the load characteristics of hydrogen and electricity consumers, especially adjustable insensitive electrical loads (ISEL) on the demand side of energy system. In addition, the economic optimization method considering the market behaviour of operators and customers under dynamic electricity prices should be further addressed.

Therefore, it is urgent to develop the optimal scheduling model of REHIES with penetration of hydrogen energy, and implement the optimal collaboration between electricity and hydrogen. To maximize the economic benefits of REHIES, a day-ahead optimization model with adjustable ISEL is established in this paper for the optimal cooperation operation of electricity and hydrogen in REHIES. The rest of this paper is organized as follows. In Section 2, the REHIES optimization problem is modelled considering the coupling between hydrogen and electricity. In Section 3, a case study is given to validate the effectiveness of the proposed model. The conclusions are drawn in Section 4.

2. System modelling of REHIES

2.1. electricity–hydrogen integrated system description

Fig. 1(a)–(b) show the diagram of REHIES. Fig. 1(a) presents the diagram of electricity–hydrogen integrated system in distribution level, where the electricity and hydrogen energies are jointly supplied to meet various demand side response through the interconnected framework. The REHIES can be operated in grid-connected mode or islanded mode. Fig. 1(b) gives the energy flow relationship of REHIES. It can be seen that electricity vector and hydrogen vector are coupled with various electricity and hydrogen loads.



(a) The diagram of REHIES (b) The energy flow relationship of REHIES

Fig. 1. The diagram of regional electricity–hydrogen integrated energy system. (a) The diagram of REHIES. (b) The energy flow relationship of REHIES.

In this REHIES, the electricity can be purchased from distribution grid or generated by renewable energy sources including Wind Turbine (WT) and photovoltaic (PV) panel, and hydrogen can be purchased from hydrogen source and obtained from renewable energy electrolysis. The energy is bought to supply electrical loads including sensitive electrical loads (SEL) and ISEL, hydrogen load and EV/FCEV to obtain economic benefits, and the electricity is sold to the distribution grid with sufficient price incentive. Also, the FCEV contributes to carbon neutral benefits to REHIES. The electrolyzers and fuel cell stacks can realize the conversion between electricity and hydrogen to supply sufficient energies for customers. The hydrogen tank stores the hydrogen produced by electrolyzer, and supplies it to the hydrogen load and FCEV. The day-ahead distribution process is regulated by REHIES operator to bid for electricity and hydrogen, and control the electrolyzer, fuel cell stacks, battery, HS tank, EV/FCEV and ISEL. These devices act as the energy providers or consumers to perform the market behaviours. In this day-ahead economic scheduling operation, the REHIES operator pursues the maximum commercial benefits.

2.2. Models and constraints of adjustable units in REHIES

To reveal the power coupling relationship of electricity vector and hydrogen vector, the model of REHIES is first developed. As shown in (1), the hourly electrical load P_t^{Load} consists of SEL P_t^{SEL} and ISEL P_t^{ISEL}. SEL refers to the uninterrupted power loads. Different from SEL, ISEL can be flexibly supplied to some extent considering economic benefits such as washing machines and air conditioner, etc. as shown in (2) and (3).

$$P_t^{\mathrm{Load}} = P_t^{\mathrm{SEL}} + P_t^{\mathrm{ISEL}} \tag{1}$$

$$\sum_{t=1}^{24} P_t^{\mathrm{ISEL}} = \sum_{t=1}^{24} P_{\mathrm{pre},t}^{\mathrm{ISEL}} \tag{2}$$

$$\begin{cases} 0 \le P_t^{\mathrm{ISEL}} \le \sigma_t P_{\mathrm{pre},t}^{\mathrm{ISEL}} \\ \sigma_t \ge 1 \end{cases} \tag{3}$$

where $P_{\mathrm{pre},t}^{\mathrm{ISEL}}$ is hourly day-ahead predicted value of ISEL, and σ_t is the hourly regulation coefficient, which is a positive value higher than 1.

The energy conversion efficiency of electrolyzer and fuel cell is linear over a certain voltage range as shown in (4), which can be measured by curve fitting [14], The output of electrolyzer and fuel cell unit can be controlled by managing its energy injection, as shown in (5).

$$\begin{cases} \eta^{\mathrm{ELZ}} P_t^{\mathrm{ELZ}} = H^{\mathrm{ELZ}} \\ \eta^{\mathrm{FC}} H_t^{\mathrm{FC}} = P_t^{\mathrm{FC}} \end{cases} \tag{4}$$

where during the time period t, $P_t^{\mathrm{ELZ}}/H_t^{\mathrm{FC}}$ refers to the hourly electricity/hydrogen input of ELZ/FC unit. $H_t^{\mathrm{ELZ}}/P_t^{\mathrm{FC}}$ indicates the hourly hydrogen/electricity output of electrolyzer/fuel cell unit. $\eta^{\mathrm{ELZ}}/\eta^{\mathrm{FC}}$ means the electricity–hydrogen/hydrogen–electricity energy conversion coefficient.

The output of battery during each period is the difference between the current period of battery storage and the previous period, and daily electricity storage is constant, as shown in (5). For the HS tank, hydrogen loss is considered as shown in (6) [15]. In this work, $P_t^{\mathrm{BT}}/H_t^{\mathrm{HS}}$ is defined as a negative value when the battery/HS tank is operated under charging state, while $P_t^{\mathrm{BT}}/H_t^{\mathrm{HS}}$ is defined as a positive value when the energy storage unit is operated under discharging state. The hydrogen change in the HS tank is the ejection minus the injection of hydrogen, as shown in (7).

$$\begin{cases} P_t^{\mathrm{BT}} = CAP^{\mathrm{BT}} \cdot SOC_t^{\mathrm{BT}} - CAP^{\mathrm{BT}} \cdot SOC_{t-1}^{\mathrm{BT}} \\ \sum_{t=1}^{24} P_t^{\mathrm{BT}} = 0 \end{cases} \tag{5}$$

$$\begin{cases} H_t^{\mathrm{HS}} = CAP^{\mathrm{HS}} \cdot SOC_t^{\mathrm{HS}} - CAP^{\mathrm{HS}} \cdot SOC_{t-1}^{\mathrm{HS}} - H_t^{\mathrm{loss}} \\ \sum_{t=1}^{24} H_t^{\mathrm{HS}} = 0 \\ H_t^{\mathrm{loss}} = \theta \cdot CAP^{\mathrm{HS}} \cdot SOC_{t-1}^{\mathrm{HS}} \end{cases} \tag{6}$$

$$H_t^{\mathrm{hsl}} + H_t^{\mathrm{FCEV}} + H_t^{\mathrm{loss}} - H_t^{\mathrm{elz}} = H_t^{\mathrm{HS}} \tag{7}$$

where $P_t^{\mathrm{BT}}/H_t^{\mathrm{HS}}$ dedicates the hourly output of battery/HS tank, $CAP^{\mathrm{BT}}/CAP^{\mathrm{HS}}$ refers to the capacity of battery/HS tank, $SOC_t^{\mathrm{BT}}/SOC_t^{\mathrm{HS}}$ is the state of charge (SOC) of battery/HS tank, θ is the loss coefficient of HS tank. H_t^{hsl} is the hydrogen supply from the HS tank to hydrogen load and FCEV.

In this electricity–hydrogen energy market, each energy vector is required to meet the constraints as shown in (8)–(9).

$$\begin{cases} P_{\min}^{x} \le P_t^{x} \le P_{\max}^{x} \,\big|_{x=\mathrm{WT,PV,FC,EV}} \\ H_{\min}^{y} \le H_t^{y} \le H_{\max}^{y} \,\big|_{y=\mathrm{ELZ,FCEV}} \end{cases} \tag{8}$$

where in (8), the energy output of distributed units WT/PV/electrolyzer/fuel cell and the consumption of EV/FCEV (P_t^x, H_t^y) should be within the range with upper bound $P_{\max}^x/H_{\max}^y$ and lower bound $P_{\min}^x/H_{\min}^y$.

$$\begin{cases} P_{\min}^{\mathrm{BT}} \le P_t^{\mathrm{BT}} \le P_{\max}^{\mathrm{BT}} \\ H_{\min}^{\mathrm{HS}} \le H_t^{\mathrm{HS}} \le H_{\max}^{\mathrm{HS}} \\ SOC_{\min}^{x} \le SOC_t^{x} \le SOC_{\max}^{x} \,\big|_{x=\mathrm{BT,HS}} \end{cases} \tag{9}$$

The first two terms of constraint (9) mean that the energy exchange between the battery/hydrogen storage tank and REHIES must be lower than its limits, where $P_{\max}^{\mathrm{BT}}/H_{\max}^{\mathrm{HS}}$ is the maximum discharge value, and $P_{\min}^{\mathrm{BT}}/H_{\min}^{\mathrm{HS}}$ is the maximum charge value. The third term refers to the SOC range of energy storage unit x, where $SOC_{\min}^{x}/SOC_{\max}^{x}$ is the lower/upper bound.

In addition, the volume of electricity transactions with the distribution network and the hydrogen purchased from hydrogen should not exceed its upper limit, as shown in (10).

$$\begin{cases} P_{\min}^{\mathrm{grid}} \le P_t^{\mathrm{grid}} \le P_{\max}^{\mathrm{grid}} \\ 0 \le H_t^{\mathrm{pur}} \le H_{\max}^{\mathrm{pur}} \end{cases} \tag{10}$$

where in (10), $P_{\mathrm{t}}^{\mathrm{grid}}$ is the hourly active power exchange between REHIES and distribution network, $P_{\max}^{\mathrm{grid}}$ is the maximum electric power acquired from the distribution network, $P_{\min}^{\mathrm{grid}}$ is the maximum amount of electricity available for sale, $H_{\mathrm{t}}^{\mathrm{Pur}}$ is hourly energy acquisition from hydrogen source, $H_{\max}^{\mathrm{pur}}$ is the maximum hydrogen acquisition from the hydrogen source.

In addition, the power balance of electricity and hydrogen between supply and demand side should be met as shown in (11).

$$\begin{cases} P_t^{\mathrm{grid}} + P_t^{\mathrm{WT}} + P_t^{\mathrm{PV}} + P_t^{\mathrm{BT}} + P_t^{\mathrm{FC}} - P_t^{\mathrm{elz}} - P_t^{\mathrm{EV}} - P_t^{\mathrm{Load}} = 0 \\ H_t^{\mathrm{pur}} - H_t^{\mathrm{hsl}} - H_t^{\mathrm{FCEV}} - H_t^{\mathrm{Load}} = 0 \end{cases} \tag{11}$$

3. Optimization problem formulation

In the electricity–hydrogen market, the REHIES operator earns benefits through the price difference between the purchase and sale of energy, the objective function can be modelled as (12), which consists of three terms. The details about the economic benefits C_{Pro} of REHIES is given in (13), including energy marketing profits and carbon neutrality benefits $U_t^{\mathrm{HV}}/U_t^{\mathrm{FC}}$ of fuel cell/FCEV unit. The cost of purchased energy C_{Pur} for the system is given in (14). And the power acquisition cost of REHIES from renewable energy units C_{RE} can be described as distributed generator cost function, as shown in (15).

$$\max C_{\mathrm{REHIES}} = C_{\mathrm{Pro}} - C_{\mathrm{Pur}} - C_{\mathrm{RE}} \tag{12}$$

$$C_{\mathrm{Pro}} = \sum_{t=1}^{24} \varphi_{\mathrm{t}}^{\mathrm{H}}(H_{\mathrm{t}}^{\mathrm{Load}} + H_{\mathrm{t}}^{\mathrm{FCEV}}) + \varphi_{\mathrm{t}}^{\mathrm{ele}}(P_{\mathrm{t}}^{\mathrm{Load}} + P_{\mathrm{t}}^{\mathrm{EV}}) + U_t^{\mathrm{FCEV}} + U_t^{\mathrm{FC}} \tag{13}$$

$$C_{\mathrm{Pur}} = \sum_{t=1}^{24} \lambda_{\mathrm{t}}^{\mathrm{H}} H_{\mathrm{t}}^{\mathrm{Pur}} + \lambda_{\mathrm{t}}^{\mathrm{ele}} P_{\mathrm{t}}^{\mathrm{grid}} \tag{14}$$

$$C_{\mathrm{RE}} = \sum_{t=1}^{24} \alpha^x P_t^{x2} + \beta^x P_t^x + \gamma^x \big|_{x=\mathrm{WT,PV}}. \tag{15}$$

where $\varphi_t^H/\varphi_t^{ele}$ and $\lambda_t^H/\lambda_t^{ele}$ are the prices where hydrogen/electricity is purchased and sold in one hour, H_t^{Load} is hourly predicted hydrogen/electric load, P_t^x is the active power output of renewable energy unit x, $\alpha^x/\beta^x/\gamma^x$ is the cost coefficient of renewable energy unit x. Noted that a negative P_t^{grid} value means that REHIES sells the redundant power to the distribution grid, while the positive P_t^{grid} means that REHIES purchases the electric power from the distribution grid.

Each fuel cell stack or FCEV can be regarded as an individual retailer for sharing its CO2 emission credits with fossil energy consumers in REHIES without any cost. The carbon utility function of fuel cell stacks and FCEV considering CO_2 emission credits are shown as (16) [16].

$$U_t^x = \mu^{CO_2} P_t^x \big|_{x=FC,FCEV} \tag{16}$$

where μ^{CO_2} is the carbon benefit coefficient.

As shown in (17), this optimization model consisting of summing the primary and quadratic terms of the variables can be transformed into the quadratic programming (QP) problem, which can be solved using the MATLAB/CPLEX solver.

$$\begin{cases} f(x) = \min\limits_{\{P_{Grid},P_{WT},P_{PV},P_{BT},P_{ELZ},P_{EV},P_{ISEL},H_{Pur},H_{HS},H_{FC},H_{hsl},H_{FCEV}\}} \sum_{t=1}^{24} C_{Pur} + C_{RE} - C_{Pro} \\ s.t. \quad (2), (4)\text{–}(11) \end{cases} \tag{17}$$

4. Case study

4.1. Description of simulation case

Fig. 2 gives the diagram of REHIES with electricity subsystem and hydrogen subsystem. In this work, an electrical bus with WT, PV, battery, electrolyzer and EV unit is exemplified, where SEL and ISEL are arranged in electrical load. Also, a hydrogen bus with FCEV is integrated into REHIES. The two buses are connected by the fuel cell stacks and an HS tank is located to receive the electrolytic hydrogen production from the electrolyzer unit. The REHIES are supplied by the distribution network and the hydrogen source. The hydrogen loads are represented in the form of energy loads. Two analysis cases are given to validate the proposed optimal strategy.

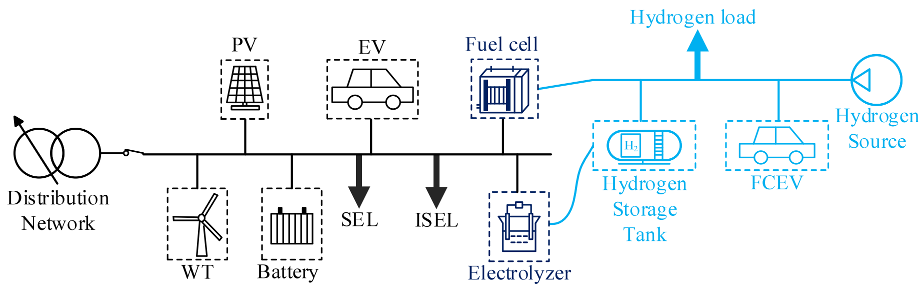


Fig. 2. The diagram of the exemplified REHIES.

Assuming that for each hour of the scheduling day, σ_t is 1.2 and θ is 0.04, and the network losses are ignored. The electricity price is shown in Fig. 3. The data related to predicted SEL/ISEL and hydrogen demand, forecasting wind and solar power levels [17] are shown in Fig. 4. More details and parameters about devices and the electricity–hydrogen network are listed in Table 1.

The QP problem has been developed using the MATLAB/CPLEX solver. Case I focuses on economic optimization of an energy system containing ISEL. In Case II, all ISEL are considered as SEL.

4.2. Simulation analysis

Case I: Economic optimization of REHIES with ISEL

This Case I is given to validate the effectiveness of the established optimization model. Fig. 5 shows the simulation results about the day-ahead optimal scheduling model of the REHIES in Case I. In this case, the

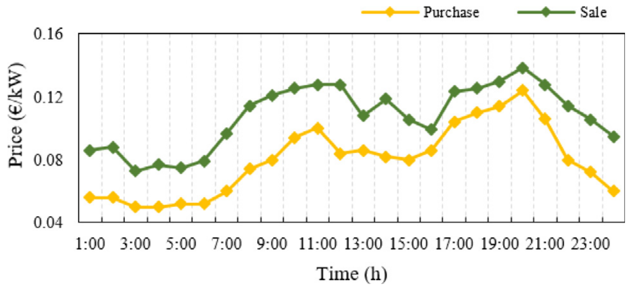


Fig. 3. Hourly price forecast for the trade of electricity in the day-ahead market.

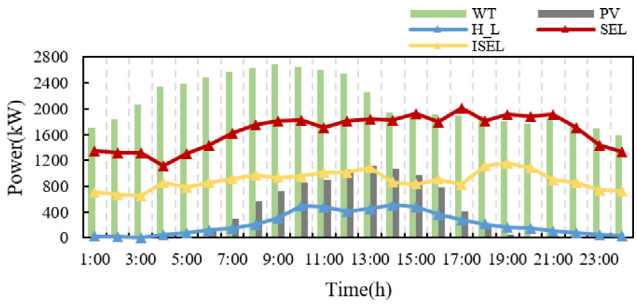


Fig. 4. Predicted REHIES load and renewable energy output.

Table 1. Parameters of devices and system in REHIES.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$H_{\min}^{\mathrm{FC}}$	0 (kW)	$H_{\max}^{\mathrm{FC}}$	300 (kW)	$P_{\min}^{\mathrm{BT}}$	−150 (kW)	$P_{\max}^{\mathrm{BT}}$	150 (kW)
$H_{\min}^{\mathrm{FCEV}}$	50 (kW)	$H_{\max}^{\mathrm{FCEV}}$	200 (kW)	$P_{\min}^{\mathrm{ELZ}}$	0 (kW)	$P_{\max}^{\mathrm{ELZ}}$	300 (kW)
α^{WT}	1.7×10^{-5} (€/kW^2)	β^{WT}	0.022 (€/kW)	$P_{\min}^{\mathrm{EV}}$	30 (kW)	$P_{\max}^{\mathrm{EV}}$	250 (kW)
α^{PV}	1.5×10^{-5} (€/kW^2)	β^{PV}	0.031 (€/kW)	$SOC_{\min}^{\mathrm{BT}}$	0.45	$SOC_{\max}^{\mathrm{BT}}$	0.9
γ^{WT}	32.7 (€)	λ_t^{H}	0.12 (€/kW)	$SOC_{\min}^{\mathrm{HS}}$	0.5 [18]	$SOC_{\max}^{\mathrm{HS}}$	0.95
γ^{PV}	38.1 (€)	φ_t^{H}	0.15 (€/kW)	SOC_0^{BT}	0.65	SOC_0^{HS}	0.75
$P_{\min}^{\mathrm{grid}}$	−1200 (kW)	$P_{\max}^{\mathrm{grid}}$	1200 (kW)	CAP^{BT}	400 (kW)	CAP^{HS}	1000 (kW)
H_t^{pur}	400 (kW)	$\mu^{\mathrm{CO_2}}$	0.085 (€/kW)	η^{FC}	0.49 [14]	η^{ELZ}	0.74 [14]

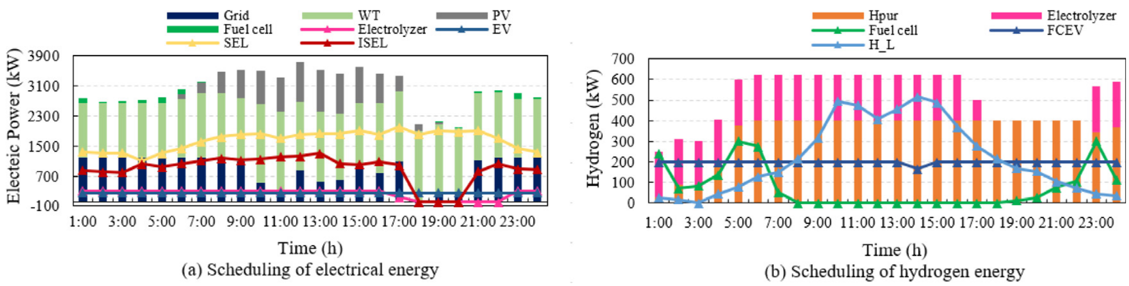
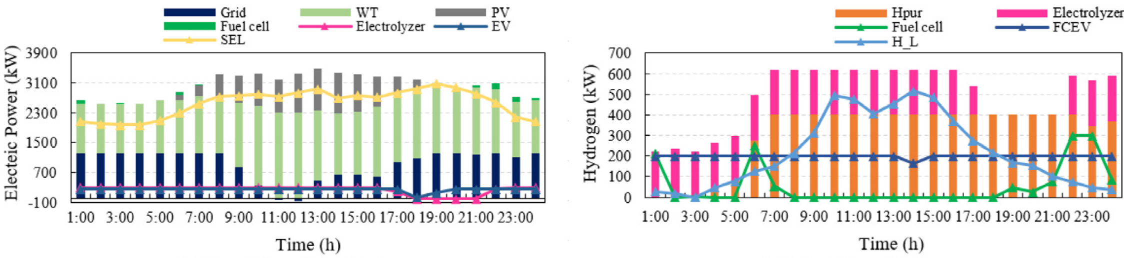


Fig. 5. Simulation result of Case I. (a) Scheduling of electrical energy; (b) Scheduling of hydrogen energy.

electrolyzer acts as a main hydrogen supplier if the hydrogen source fails to supply fully the system loads. Driven by profits, the demand for EV unit reaches maximum energy load during low electricity price hours. Also, additional



(a) Scheduling of electrical energy (b) Scheduling of hydrogen energy

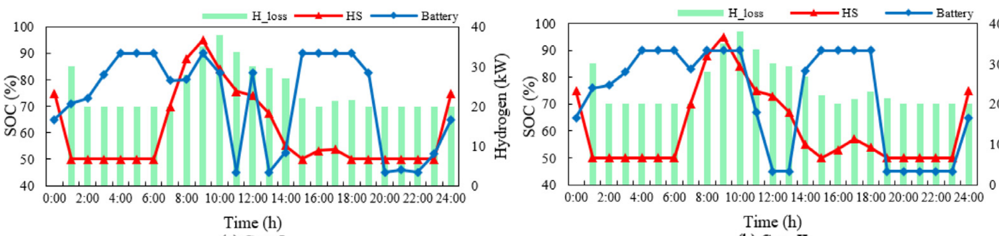
Fig. 6. Simulation result of Case II. (a) Scheduling of electricity energy; (b) Scheduling of hydrogen energy.

carbon gains incentivize FCEV hydrogen consumption during the whole day. The economic benefits in Case I is 3566.7€.

Case II: Economic optimization of REHIES with only SEL

This Case II is simulated as a comparison. Fig. 6 shows the simulation results of Case II. It can be seen from Case I that there is low power supply for ISEL from 19:00–21:00. It means that the IESL will be flexibly activated at other time periods based on the fluctuation of electricity prices, which thus reduces the electrical demands in REHIES and further optimizes the electricity costs. For 1:00–8:00, the electricity used in advance consumes wind power extra 884.2 kW in total compared with case 2. Meanwhile, the output power of fuel cell is increased since more hydrogen is then produced by wind power. The economic benefits in Case II is 2611.4€ and 955.3€ lower than Case I.

Fig. 7 shows the SOC of energy storage units with the hydrogen losses in HS tank in two cases. At 10:00, 12:00, and 19:00 in case I, and 11:00 12:00, and 20:00 in case II, the battery is operated under discharging mode when the electricity price is relatively high within one day. Also, the battery is operated under charging mode when the electricity price is relatively low from 0:00 – 4:00. While the SOC of HS tank is almost the same in both cases.



(a) Case I (b) Case II

Fig. 7. SOC of energy storage units with the hydrogen loss. (a) Case with ISEL. (b) Case without ISEL.

5. Conclusion

This paper presents a day-ahead economic optimization model for regional electricity–hydrogen integrated energy system (REHIES), which is able to reveal the power coupling relationship of electricity vector and hydrogen vector. Then, the optimal cost function is established according to the economic optimization model. The optimization model is a QP problem and computed by MATLAB/CPLEX solver. Simulation verification is performed in power system with utilization of hydrogen source, hydrogen storage and hydrogen loads. Simulation results show that the established optimization model with insensitive electrical load (ISEL) can achieve electricity–hydrogen coupling flexibly according to the market requirement. Additionally, the redistribution during the periods with low electricity prices of adjustable ISEL brings 955.3€ better economic benefits to REHIES and facilitates carbon neutrality.

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.

Data availability

No data was used for the research described in the article.

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