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Stochastic Scheduling of Renewable-Based Energy Systems Considering Power-to-Hydrogen and Hydrogen-to-Power Units

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Abstract: This paper proposes a stochastic optimization problem for local integrated hydrogen-power energy systems. In the proposed model, the integrated system tries to reduce the day-ahead operation costs using dispatchable resources, renewable energy resources, battery energy storage systems, demand response programs, and energy trading with the upstream network. Also, the integrated system is able to transact electricity with the upstream network to get more benefits. When the generation of renewable resources is high, the integrated system can convert the surplus electricity to hydrogen by power-to-gas units. The generated hydrogen can be sold to different industries or stored in the hydrogen tank storage. During peak hours, the stored hydrogen can be imported into the gas-to-power unit to generate the required electricity. The sector coupling between electricity and hydrogen provides more flexibility for integrated systems and is an effective solution to control the uncertainty of renewable energy resources in order to increase the power and energy flexibilities. The simulation results show that the proposed sector coupling provides the opportunity for electricity and hydrogen trading for integrated system. The benefit of the integrated system by electricity and hydrogen trading with the upstream network and different industries are 88.39 $, and 6846 $, respectively.

Keywords: Micro-energy systems, Hydrogen-to-power, Power-to-hydrogen, Sector coupling, Demand response programs

1 Introduction

1.1 Motivations

IN recent years, various studies have been conducted on the smart distribution networks [1, 2]. The growth of renewable energy resources (RES) smart distribution networks is one of the main solutions to mitigate carbon emissions in the world. The operation of RES in the decentralized mode as the local energy system can improve the environmental problems, power quality, voltage drop, and power losses in the energy systems [3], [4]. Micro energy systems are known as the best technical solution to integrate RES in power systems that can be operated in both grid-connected and isolated modes [5], [6].

1.2 Literature review

In recent years, different research works have been conducted on the operation scheduling of micro-energy systems. A robust framework has been suggested in [7] that considered the uncertainty of the price market for optimal management of microgrid systems. The authors in [8] presented a low carbon emission framework for the operation of microgrid systems where the distributed energy resources were considered to supply the industrial loads. Chen et al. [9] proposed a decentralized approach that integrated renewable energy resources, battery storage, and controllable resources to supply the electrical loads of microgrids. However, the demand response programs were not studied. Kumar et al. [10] presented a control approach for renewable-based microgrid systems in the islanded mode. However, the uncertainty of RES and load demands were not considered. A multi-layer framework has been introduced in [11] that integrated the storage devices in the microgrid systems to control the generation of wind

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and solar energy systems. The authors applied the stochastic approach to model the uncertainty of renewable generation. However, the demand response programs and carbon emissions of fuel-based resources were not studied. The authors in [12] investigated the role of the metaheuristic approach in the operation scheduling of micro-energy systems. A four-objective optimization scheduling has been developed in [13] that simultaneously optimized operation costs, carbon emission, water extraction from the underground resources, and trading energy with the upstream network. However, the power-to-hydrogen and hydrogen-to-power units were not considered to increase the flexibility of the micro-energy system. The authors in [14] integrated the electrical, thermal, cooling, and hydrogen systems in the micro-energy systems to increase the flexibility of the system. However, the ability of hydrogen trading with large customers was not considered. Lu et al. [15] suggested a two-layer model for real-time scheduling of micro-energy systems that are considered the worst condition for uncertain parameters. However, the hydrogen-to-power and power-to- hydrogen, and hydrogen trading were ignored.

The application of demand response programs (DR) in the operation management of micro-energy systems was presented in [16-20]. The authors in [16] applied electric vehicles and price-based DR programs in the energy management system to increase the consumers' benefits. To enhance the reliability of the proposed model, the authors considered the uncertainty in load estimation of electric vehicles in both charging and discharging modes. The efficiency of electrical and thermal DR programs on multi-energy systems has been investigated in [17]. The proposed model studies the cooperation among neighbor energy systems to increase the efficiency of the system. The authors show that 10% participation in electrical and thermal DR programs reduces the operating cost by $ 28.48 and $ 10.48, respectively. However, hydrogen trading with large costumers was not considered in the proposed model. A hybrid intelligence optimization approach is developed in [18] to study the performance of micro-energy system management in both fixed price tariffs and time-of-use tariffs. In addition, the proposed model provides a trade-off between economic and sustainable scheduling. The simulation results show that the time-of-use tariff as price-based DR programs is able to reduce the peak load by 3.5 %. A stochastic framework has been proposed in [19] that integrated DR programs and energy storage in the energy system to simultaneously minimize the day-ahead cost and carbon emission. Reference [20] proposed a hybrid bi-level model for energy management of multi-microgrid systems that are equipment with RES, electric vehicles, and energy storage systems. To cover the uncertainty of RES, the authors applied DR programs in the energy management system. However, the hydrogen storage system and hydrogen trading with large industries were not modeled.

1.3 Research gaps

An overview of the recent publication on micro-energy systems shows that the most of research works integrated the battery energy storage systems, dispatchable resources, and demand-side management to control the uncertainty of renewable resources. However, little attention was paid to investigating the efficiency of hydrogen-to-power systems and power-to-hydrogen systems.

The power-to-hydrogen systems can significantly increase the flexibility of renewable-based micro-energy systems. When the generation of renewable resources is more than loads, the power-to-hydrogen systems can convert the surplus electricity into hydrogen by electrolyzer units. The electrolyzer consumes the electricity to split water into hydrogen and oxygen. Also, the generated hydrogen can be used by hydrogen-to-power units during peak hours when the generation of renewable resources is less than the required power. Also, the hydrogen trading with the local industries was the main gap of the recently published works that are studied in this work.

1.4 Contributions

According to the literature, the main contributions can be listed as follows. Table 1 provides a comprehensive comparison between the proposed model and recent related published works.

- Unlike [8], [9], [10], and [15], we proposed a stochastic framework that integrated the hydrogen-to-power and power-to-hydrogen systems in the energy systems to increase the power and energy flexibility of the system.
- Unlike [8], [9], [10], [11], [13], [14], and [15], we model the ability of hydrogen trading between micro-energy systems and industrial customers to provide the opportunity for cost-reduction for micro-energy systems.
- The hydrogen storage tank is integrated into the proposed model to store the generated hydrogen of electrolyzer units. The hydrogen storage tank significantly increases the flexibility of micro energy system to control the uncertainty of RES.
- Unlike [8-15], the performance of the proposed model is investigated by different solvers to ensure the efficiency of hydrogen-to-power units in the micro-energy systems.

Table 1 Comparison of the proposed model with recent related published works.

Ref.	Year	Uncertainty	DR program	Power-to-hydrogen	Hydrogen-to-power	Hydrogen trading
[8]	2023	×	×	×	×	×
[9]	2023	✓	×	×	×	×
[10]	2024	×	×	×	×	×
[11]	2024	✓	×	✓	✓	×
[13]	2023	✓	✓	×	×	×
[14]	2023	✓	✓	✓	✓	×
[15]	2024	✓	✓	×	×	×
This work		✓	✓	✓	✓	✓

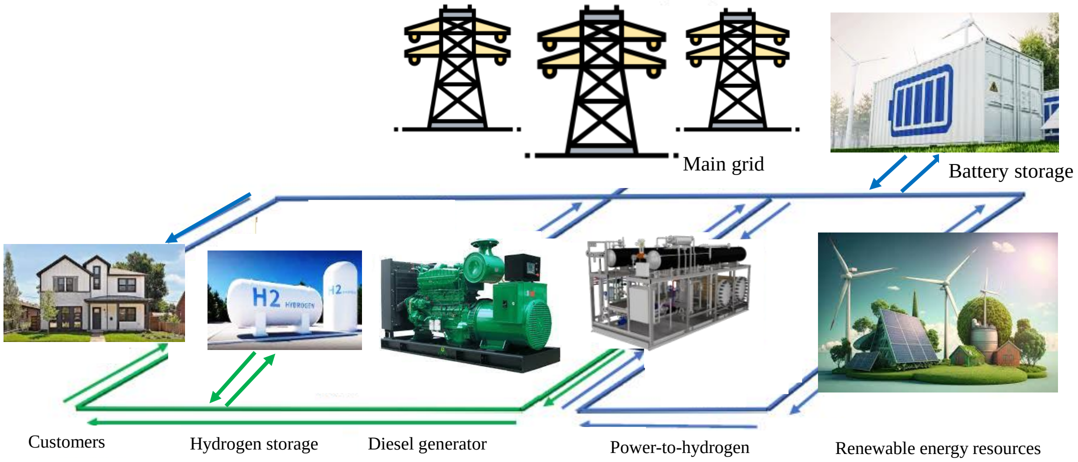

Fig. 1 Structure of the proposed model

1.5 Paper organization

The organization of the paper is as follows. Section 2 presents the technical constraints of generation resources, storage devices, and hydrogen system. Section 3 provides the simulation results and discussion. Finally, the conclusion is presented in section 4.

2 Mathematical formulation and objective function

In this paper, we present an optimization problem for energy scheduling of local integrated hydrogen-power energy systems (LIHPES). The LIHPES is responsible for supplying its electrical loads with minimum cost and the highest reliability. To this end, the LIHPES considers different renewable resources such as photovoltaic and wind energy for generating clean energy. The generation of renewable resources is dependent on the weather conditions that are associated with uncertainty. To control the intermittent behavior of RES resources, the LIHPES operates some dispatchable resources such as diesel generators to cover the shortage in RES generation. The production of dispatchable resources depends on the input fuels, which can be adjusted by the LIHPES. Therefore, the utilization of dispatchable resources alongside RES can increase the flexibility of the LIHPES to manage the shortage in the generation of RES.

The LIHPES utilizes the hydrogen-to-power and power-to-hydrogen units to increase its flexibility. During off-peak hours, the LIHPES consumes the electricity by power-to-hydrogen units to electrolyze water into hydrogen and oxygen. The generated hydrogen can be stored in hydrogen storage tank. The LIHPES utilizes the stored hydrogen during peak hours by hydrogen-to-power units to help the system for power balance. Therefore, this energy conversion increases the ability of LIHPES to manage the uncertainty of renewable generation and increases the system's flexibility.

Therefore, LIHPES operates different renewable resources, dispatchable units, power-to-gas units, gas-to-power units, battery storage devices, hydrogen storage, and demand response programs to this end. Also, LIHPES is able to transact electricity with the upstream network. Besides, it can produce hydrogen by power-to-hydrogen units and sell the generated hydrogen to industries to get more benefits. Figure 1 shows the structure of the proposed model. The objective function of LIHPES is presented in Eq. (1).

$$\min \sum_t \delta_t^E P_t^{Grid} - \sum_t \delta_t^E P_t^{sell} + \sum_i \sum_t (\alpha_i + \beta_i \zeta_i) P_{i,t} + \gamma_i u_{i,t} - \sum_h \sum_t \delta_t^h H_{h,t}^{sell} \tag{1}$$

Where δ_t^E refers to the transactive prices with the upstream network. Also, P_t^{Grid} and P_t^{sell} show the imported energy and selling energy to the upstream network. $P_{i,t}$ is the power generation of dispatchable resources. Parameters α_i, β_i, and ζ are the cost coefficients of dispatchable resources. γ_i shows the start-up cost of dispatchable resources. $H_{h,t}^{sell}$ and δ_t^h indicate the volume and prices of selling hydrogen to industries, respectively. The generating constraints of energy trading with the upstream network are provided in Eqs. (2) and (3) [14].

$$P^{g,\min} \le P_t^{Grid} \le P^{g,\max} \tag{2}$$

$$P^{sell,\min} \le P_t^{sell} \le P^{sell,\max} \tag{3}$$

$P^{g,\min}$ and $P^{g,\max}$ show the minimum and maximum imported energy from the upstream network, respectively. Also, $P^{sell,\min}$ and $P^{sell,\max}$ refer to the minimum and maximum selling energy to the upstream network. The operation cost and generating constraints of dispatchable resources are presented in Eqs. (4) to (7) [21].

$$\cos t^{DG} = \sum_i \sum_t (\alpha_i + \beta_i \zeta_i) P_{i,t} + \gamma_i u_{i,t} \tag{4}$$

$$u_{i,t} P_i^{\min} \le P_{i,t} \le u_{i,t} P_i^{\max} \tag{5}$$

$$P_{i,t} - P_{i,t-1} \le R_i^{\max,up} \tag{6}$$

$$P_{i,t-1} - P_{i,t} \le R_i^{\max,down} \tag{7}$$

Where $R_i^{\max,up}$ and $R_i^{\max,down}$ show the ramp-up and ramp-down power if dispatchable resources. Also, $P_i^{\min}$ and $P_i^{\max}$ refer to the minimum and maximum generation of dispatchable resources. $u_{i,t}$ is a binary variable that shows the on/off status of dispatchable resources. The Eq. (4) shows the generation cost of dispatchable resources. The minimum and maximum power generation of dispatchable resources at time *t* is shown in Eq. (5). The ramp-up and ramp-down generation limits are presented in Eqs. (6) and (7), respectively.

The generation of renewable resources such as photovoltaic energy and wind energy at time t and scenario s are presented in Eqs. (8) and (9), respectively [22]. Also, the stochastic approach is considered to generate the related scenarios for solar radiations, wind speeds, and market prices using Beta, Weibull, and normal probability distribution functions, respectively. The stochastic approach is described in detail in [22].

$$P_{i,t,s}^{PV} = \eta^{PV} N_i^{PV} S_i^{PV} I_{t,s} (1 - 0.005 (T_t^{Out} - 25)) \tag{8}$$

$$P_{i,t,s}^{WT} = \begin{cases} 0 & 0 \le v_{t,s} \le v_{ci} \ or \ v_{co} \le v_{t,s} \\ P_{i,r}^{WT} \dfrac{v_{t,s}^2 - v_{ci}^2}{v_{i,r}^2 - v_{ci}^2} & v_{ci} \le v_{t,s} \le v_{i,r} \\ P_{i,r}^{WT} & v_{i,r} \le v_{t,s} \le v_{co} \end{cases} \tag{9}$$

Where $P_{i,t,s}^{PV}$, η^{PV}, N_i^{PV}, and S_i^{PV} refer to the generating power of PVs, efficiency, number of panels, and area of each solar panel, respectively. Also, $I_{t,s}$ and T_t^{Out} indicate the solar radiation and temperature at time *t*, respectively. $P_{i,t,s}^{WT}$ and $P_{i,r}^{WT}$ are the generating power and rated power of wind turbines. v_{ci}, v_{co}, and $v_{i,r}$ present the cut-in, cut-out, rated speed of wind turbines. Also, $v_{t,s}$ refers to the wind speed at time *t* and scenario *s*. Equations (10) and (11) represent the charging and discharging limits. The charging level of storage devices is shown in Eq. (12). The acceptable level of stored energy in battery devices is shown by Eq. (13). Equation (14) determines the charging and discharging status of battery storage devices. Finally, Eq. (15) states that the final stored energy in the battery devices should be the same as the initial energy [23, 24].

$$0 \le P_{b,t}^{ch} \le X_{b,t}^{ch} P_b^{ch} \tag{10}$$

$$0 \le P_{b,t}^{disch} \le X_{b,t}^{disch} P_b^{disch} \tag{11}$$

$$SoC_{b,t+1} = SoC_{b,t} + \Delta T (\eta_b^{ch} P_{b,t}^{ch} - \frac{P_{b,t}^{disch}}{\eta_b^{disch}}) \tag{12}$$

$$SoC_b^{\min} \le SoC_{b,t} \le SoC_b^{\max} \tag{13}$$

$$X_{b,t}^{ch} + X_{b,t}^{disch} \le 1 \tag{14}$$

$$SoC_{b,t1} = SoC_{b,t4} \tag{15}$$

Where $P_{b,t}^{ch}$ and $P_{b,t}^{disch}$ show the charging and discharging power of battery storage devices. P_b^{ch} and P_b^{disch} are the maximum charging and discharging powers. $SoC_{b,t}$ refers to the state-of-charge of battery storage devices. $SoC_b^{\min}$ and $SoC_b^{\max}$ are the minimum and maximum state-of-charge of battery storage devices. η_b^{ch} and η_b^{disch} are the charging and discharging efficiency of battery storage devices. Also, $X_{b,t}^{ch}$ and

$X_{b,t}^{disch}$ are the binary variables that determine the charging and discharging status of battery storage devices. The mathematical formulations of demand response programs are presented in Eqs. (16)-(18) [25].

$$P_{l,t}^{flex} = P_{l,t}^{base}(1 - DR_{l,t}) + ldr_{l,t} \tag{16}$$

$$DR^{\min} \le DR_{l,t} \le DR^{\max} \tag{17}$$

$$\sum_{t=1}^{T} ldr_{l,t} = \sum_{t=1}^{T} P_{l,t}^{B} DR_{l,t} \tag{18}$$

Where $P_{l,t}^{flex}$ and $P_{l,t}^{base}$ are the load profile of micro-energy system after and before DR programs. $DR_{l,t}$ is the level of DR participation and $ldr_{l,t}$ refers to the shifted loads. Also, $DR^{\min}$ and $DR^{\max}$ present the minimum and maximum DR participation. The load profile of LIHPES after DR participation is shown in Eq. (16). The maximum load shifting is limited by Eq. (17). Finally, Eq. (18) ensures that the LIHPES cannot cut their load demands. The related operation of power-to-hydrogen and hydrogen-to-power systems is presented in Eqs. (19)-(26) [26].

$$P_{h,t}^{E \to H_2} \chi_{h,t} = H_{h,t}^{in} \tag{19}$$

$$HL_{h,t} = \begin{cases} HL_{h,t}^{0} & t = 1 \\ HL_{h,t-1} + \left(\phi_{h,t} H_{h,t}^{in} - \dfrac{H_{h,t}^{out}}{\varphi_{h,t}} \right) & t \ge 2 \end{cases} \tag{20}$$

$$H_{h,t}^{out} = H_{h,t}^{E} + H_{h,t}^{sell} \tag{21}$$

$$H_{h,t}^{E} \psi_{h} = P_{h,t}^{H_2 \to E} \tag{22}$$

$$HL_{h}^{\min} \le HL_{h,t} \le HL_{h}^{\max} \tag{23}$$

$$HL_{h,t}^{E} \le \chi_{h,t} HL_{h}^{E,\max} \tag{24}$$

$$HL_{h,t}^{sell} \le \sigma_{h,t} HL_{h}^{sell,\max} \tag{25}$$

$$\sigma_{h,t} + \chi_{h,t} \le 1 \tag{26}$$

Where $P_{h,t}^{E \to H_2}$ refers to consumed electricity by power-to-hydrogen unit. $H_{h,t}^{in}$ and $H_{h,t}^{out}$ are input and output hydrogen, respectively. $\chi_{h,t}$ is a binary variable that shows the on/off status of power-to-hydrogen units. $HL_{h,t}$ is the level of stored hydrogen in hydrogen tank while $HL_{h,t}^{0}$ refers to the initial stored hydrogen. Also, $\phi_{h,t}$ and $\varphi_{h,t}$ present the efficiency of power-to-hydrogen and hydrogen-to-power units, respectively. $H_{h,t}^{E}$ and $H_{h,t}^{sell}$ are the consumed hydrogen for power generation and selling hydrogen to the industries, respectively. $HL_{h}^{\min}$ and $HL_{h}^{\max}$ show the minimum and maximum level of stored hydrogen in hydrogen tank. $HL_{h}^{E,\max}$ and $HL_{h}^{sell,\max}$ refer to the maximum used hydrogen and selling hydrogen, respectively. Also, $P_{h,t}^{H_2 \to E}$ presents the generated electricity by hydrogen-to-power units. $\sigma_{h,t}$ and $\chi_{h,t}$ are binary variables that show the application of hydrogen by micro-energy system. Equation (19) indicates that the LIHPES converts the excess power of renewable generation to produce hydrogen by electrolyzer unit. The generated hydrogen can be stored in the hydrogen storage tank according to Eq. (20). The stored hydrogen can be used by fuel cell units to generate electricity when it is needed or can be sold to different industries. These two ways are shown by Eq. (21). The generated electricity by hydrogen-to-power units is determined by Eq. (22). The minimum and maximum capacity of stored hydrogen in the storage tank, maximum generated electricity by hydrogen-to-power units, and maximum selling hydrogen are limited by Eqs. (23) to (25), respectively. Finally, Eq. (26) indicates the status of selling hydrogen or generated electricity by hydrogen-to-power systems.

Finally, Eqs. (27) and (28) present the active and reactive power balances, respectively. Where Q_{t}^{Grid}, $Q_{i,t}^{DG}$, $Q_{i,t}^{PV}$, $Q_{i,t}^{WT}$, $Q_{b,t}$, $Q_{c,t}$ and $Q_{l,t}$ show the reactive power of upstream network, dispatchable resources, photovoltaic, wind turbines, battery storage devices, capacitor banks, and loads, respectively.

$$\begin{aligned} P_{t}^{Grid} &+ \sum_{i} P_{i,t}^{DG} + \sum_{i}\sum_{s} \rho_{s} (P_{i,t,s}^{PV} + P_{i,t,s}^{WT}) \\ &+ \sum_{b} (P_{b,t}^{disch} - P_{b,t}^{ch}) + \sum_{h} P_{h,t}^{H_2 \to E} \\ &= P_{t}^{sell} + \sum_{h} P_{h,t}^{E \to H_2} + \sum_{l} P_{l,t}^{flex} \end{aligned} \tag{27}$$

$$\begin{aligned} Q_{t}^{Grid} &+ \sum_{i} (Q_{i,t}^{DG} + Q_{i,t}^{PV} + Q_{i,t}^{WT}) \\ &+ \sum_{b} Q_{b,t} + \sum_{c} Q_{c,t} = \sum_{l} Q_{l,t} \end{aligned} \tag{28}$$

3 Simulation results

The proposed optimization model is solved by employing solver LINDO, SCIP, LINDOGLOBAL under General algebraic modelling system (GAMS) software on a Core i7, 3 GHz processor with 2 GB of RAM, and the time duration for solving this model is 0.33 s.

Table 2 Characteristics of dispatchable resources

Resources	Min generation (kW)	Maximum generation (kW)	Ramp rate power (kW)	Coefficient costs		
				α	β	ζ
Dispatchable unit 1	10	100	50	0.04	5	0.0003
Dispatchable unit 2	100	500	125	0.25	65	0.000417
Dispatchable unit 3	100	500	125	0.25	65	0.000417

Table 3 Characteristics of renewable energy resources

Resources	Model	Cut-in speed (m/s)	Cut-out speed (m/s)	Rated speed (m/s)	Rate power (kW)
Wind turbine 1	ACSA A27/225	3.5	25	13.5	225
Wind turbine 2	ACSA A20/100	4.5	25	13	100
Wind turbine 3	CSA A17/90	3.3	28	16.8	90
Resources	Model	Length (*m*)	Width (*m*)	Efficiency (%)	number
Photovoltaic 1	CS6W-545MS	2.26	1.134	21.26	100
Photovoltaic 2	CS6W-545MS	2.26	1.134	21.26	200
Photovoltaic 3	CS6W-545MS	2.26	1.134	21.26	150

The proposed model is tested on a standard case study consisting of three dispatchable resources, three battery energy storages, three wind turbines, three photovoltaic systems, five capacitors, and two hydrogen systems. The characteristics of dispatchable resources are shown in Table 2. Also, the characteristic of renewable energy resources are presented in Table 3.

The optimization results of the local energy system are shown in Table 4. According to Table 4, the total daily cost of the local energy system is $ 3182.88. The generation cost of dispatchable resources is $ 6066.08 and purchasing energy from the upstream network is $ 4051.2. Also, the benefit of the local energy system from electricity and hydrogen trading with the upstream network is $ 88.39 and $ 6846, respectively.

Figures 2 and 3 show the generation of dispatchable resources and energy trading with the upstream network, respectively. As we can see, the dispatchable unit 1 is operated at the maximum capacity during hours 2-24 because it has the minimum coefficient costs among the dispatchable resources.

Since the coefficient costs of dispatchable units 2 and 3 are more than unit 1, the energy system utilizes them when needed. During hours 1-7, the generation of dispatchable units 2 and 3 is less than maximum capacity because the energy system consumes less energy at these times. Figure 3 shows that the energy system mostly imported energy from the upstream grid.

Table 4 Revenue and total cost of energy system

Revenue from energy trading		Cost of dispatchable resources ($)	Cost of imported energy ($)	Total cost ($)
Electricity($)	Hydrogen($)			
88.39	6846	6066.08	4051.2	3182.88

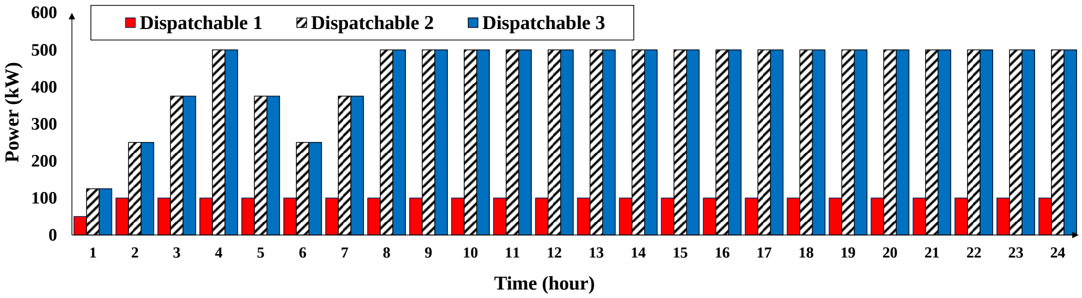

Fig. 2 Generation power of dispatchable resources

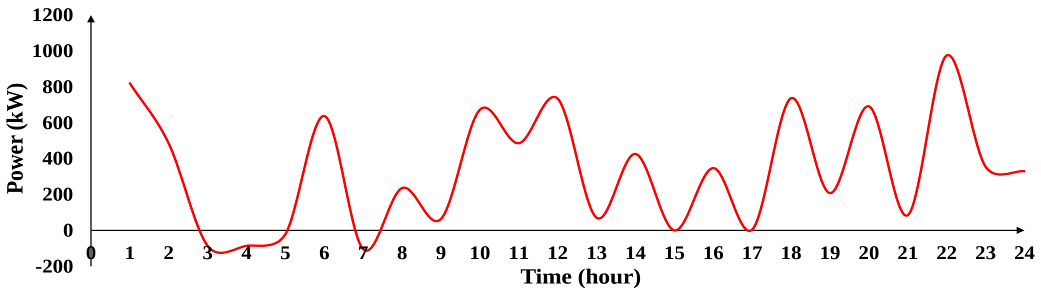

Fig. 3 Energy trading with upstream grid

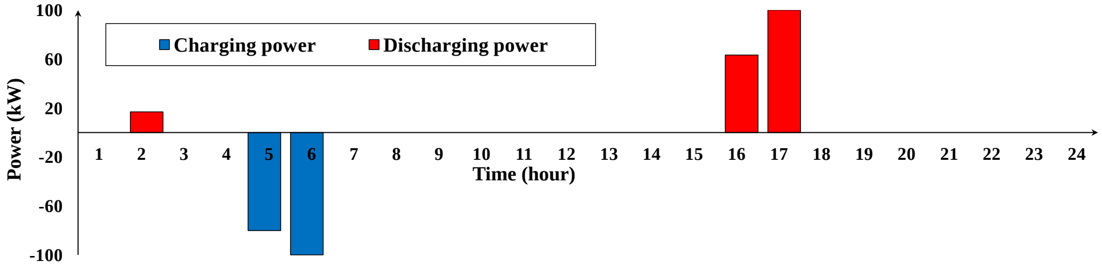

Fig. 4 Energy storage charging and discharging

Table 5 Results of micro-energy system by different solvers

Solver	Revenue from energy trading Electricity ($)	 Hydrogen ($)	Cost of dispatchable resources ($)	Cost of imported energy ($)	Total cost ($)
SCIP	88.39	6846	6066.08	4051.2	3182.88
LINDO	88.39	6846	6066.08	4051.2	3182.88
LINDOGLOBAL	88.39	6651.6	6066.08	3969.79	3295.87

Only during hours 3-5 and 7, when the generation of wind turbines is more, the energy system sells the electricity to the upstream grid to get benefit. The profit of the energy system from energy trading with the upstream grid during hours 3-5 and 7 is $ 88.39 and its payment for imported energy at other hours is $ 4051.2. Also, Fig. 3 shows that the energy system decreases the imported energy from the upstream grid during hours 13-21 because the energy prices are higher than other hours. Figure 4 presents the charging and discharging schedule of each battery energy storage system.

According to Fig. 4, the storage devices are charged at hours 5 and 6 when the generation of wing turbines is more than at other times. Also, charging energy is injected into the system during hours 16-17 to reduce the buying energy from the upstream network.

Figure 5 presents amount of selling hydrogen and electricity of energy system to the industries and upstream network. According to Fig. 5, the energy system sells 299.5 kWh electricity to the upstream network. Also, it utilizes the electrolyzer units to generate hydrogen when the electricity prices are low. It sells the generated hydrogen to industries to get revenue. The simulation results show that the amount of generated hydrogen by energy system is 4125 kW. More than 27.6% of this generated hydrogen (1141 kW) is sold to various industries and the rest of it is stored in the hydrogen storage units. Also, the simulation results show that the fuel cell units did not use hydrogen for electricity generation because the energy system can sell the hydrogen to industries at higher prices.

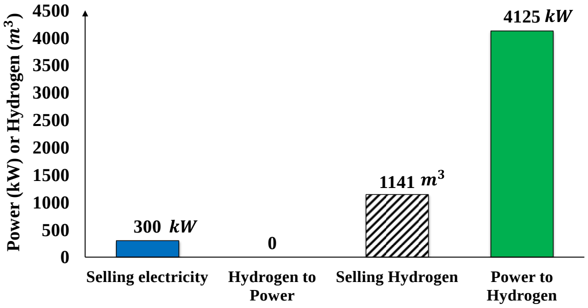

Fig. 5 Selling hydrogen, selling power, hydrogen to power, and power to hydrogen in energy system.

Table 5 presents the operation cost of LIHPES by different solvers to ensure the efficiency of hydrogen-to-power systems. The results of Table 5 shows that the LIHPES receives at least $ 6651.6 by hydrogen trading with industries. Figures 6 and 7 show the efficiency of DR programs and maximum allowable energy trading with the upstream network on the operation cost of LIHPES.

As can be seen, when DR programs are not considered, the operation cost of the LIHPES is more than $ 4000. By increasing the participation of LIHPES in DR programs, the operation cost is significantly reduced because LIHPES is able to shift its consumption from peak hours to off-peak hours. According to simulation results, by 30 % participation in DR programs reduces the operation cost from $ 4085 to $ 2731. Also, Fig. 7 shows that as the ability to exchange energy between the LIHPES and the upstream network increases, the operation cost decreases because LIHPES can sell more energy during peak hours to get more benefits. For example, when maximum energy trading is 500 kW, the operation cost of LIHPES will be $ 3505.1 while in 1000 kW its operation cost decreases by $ 182.24 and reaches to $ 3182.80.

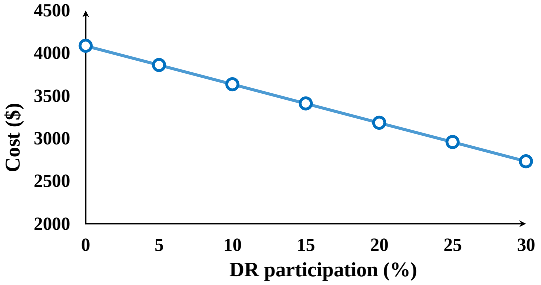

Fig. 6 DR efficiency on the operation cost.

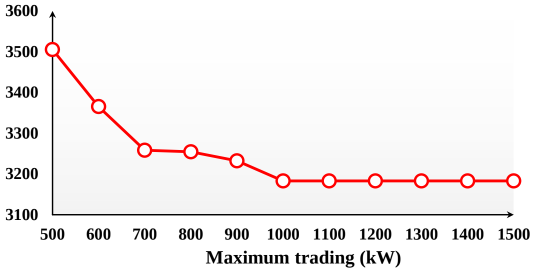

Fig. 7 Efficiency of power trading with the upstream network

4 Conclusion

This work presented a stochastic framework for the operation scheduling of hydrogen-electricity-based energy systems where the uncertainty of renewable generation and transactive prices are considered. The energy system integrated different renewable resources, dispatchable units, battery energy storage devices, power-to-hydrogen, and hydrogen-to-power systems to supply the required electricity needs. To manage the uncertainty of renewable generation resources, the energy system participates in demand response programs to enjoy load flexibility. Also, it can convert the surplus generation of renewable resources into hydrogen by power-to-gas units. The generated hydrogen can be used by gas-to-power units during peak hours to reduce the imported energy from the upstream grid. Also, the energy system is able to sell the generated hydrogen to industries to achieve more revenue. The simulation results show that the energy system is able to reduce its costs by hydrogen trading to different large customers. The simulation results show that the integrated system can achieved $ 6848 and $ 88.39 $ from hydrogen trading with industries and selling electricity to the upstream network, respectively. Also, 20% participation of LIHPES in demand response programs reduce the operation cost by $ 902.94. In future work, the role of machine learning in the operation scheduling of hydrogen-based energy systems will be investigated.

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