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Day-Ahead Coordination for Flexibility Enhancement in Hydrogen-Based Energy Hubs in presence of EVs, Storage, and Integrated Demand Response

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ABSTRACT Energy hubs (EHs) enable all types of energy customers to participate in demand response programs (DRPs), such as inelastic loads, by combining electricity, heat, natural gas, and other types of energy. Integrated demand response (IDR) is the result of this new vision. From a global warming perspective, environmental emissions are a significant issue to be considered. Furthermore, hydrogen has been recognized as an attractive fuel for decarbonizing sectors contributing to global warming. Thus, this paper provides a solution for global environmental problems by utilizing renewable energy sources (RESs) and green hydrogen. In addition, electric vehicles (EVs) are expected to contribute significantly to this scenario due to their rapid expansion. This paper focuses on the coordination of EV parking with hydrogen storage system (HSS) and IDR with the goal of flexibility enhancement, in which a robust optimization method has been implemented to solve the problem. Numerical results show that in the case of a deterministic solution to the problem and in cases where uncertainty is considered, the proposed scheme reduces the total operating costs by 13.89% and 8.67%, respectively. This indicates that the proposed scheme could avoid overinvestment and meet the given carbon emission target cost-effectively.

INDEX TERMS Electric vehicle, Hydrogen energy storage, Integrated demand response, Energy hub, Flexibility, Optimal operation

I. INTRODUCTION

A. Motivation and background

Climate change has been exacerbated by massive CO2 emissions, posing a serious threat to modern society's sustainability. Carbon neutrality has been pledged by many countries, including the European Union by 2050 and China by 2060. The use of RESs in the power system has increased due to growing concerns about greenhouse gas emissions. RESs have, however, led to a greater need for flexibility due to their probabilistic nature. The implementation of flexible generation scheduling is therefore necessary [1]. In order to achieve its vision for energy transformation, the European Union is not only aiming to decarbonize the electricity sector, but also to integrate energy transition across different sectors [3]. A distributed energy system is more efficient than a traditional method of energy generation because it uses energy conversion equipment, storage, and flexible management of distributed resources. IDR contributes to flexibility improvement in EHs. The demand and supply sides must work together to achieve high energy efficiency. Modern smart grid technologies have advanced to the point where demand-side management (DSM) strategies like valley filling, peak clipping, and flexible load shaping have become essential. It has been suggested that the DR program, which is in the last category, could provide a decisive solution in this regard [4].

In addition to improving the efficiency and reliability of the system, integrating multiple energy sources under the concept of EH will result in a decrease in environmental emissions. By altering their consumption patterns as well as switching their sources of consumption, customers can play an active role in the DR program. The IDR program, which is a modified innovation of the DR program, decongests the power grid while strengthening the supply and demand balance. Modern power systems cannot be managed effectively and efficiently without IDR programs [4].

Another important issue that has received attention in recent years is the use of EVs in order to reduce emissions. EVs can help reduce greenhouse gas emissions from the transportation sector, which is one of the major sources of carbon dioxide and other pollutants [5,6]. EVs have no tailpipe emissions, which means they do not emit any harmful gases or particles when they operate. However, the environmental impact of EVs also depends on how the electricity they use is generated. If the electricity comes from renewable sources, such as solar, wind, or hydro, then EVs can significantly lower the carbon footprint of the transportation sector. But if the electricity comes from fossil fuels, such as coal, oil, or natural gas, then EVs may still contribute to greenhouse gas emissions indirectly [7,8]. Therefore, the optimal management and operation of the hydrogen-based EH, considering the IDR and EVs, seems to be a necessary issue.

B. Literature review

Researchers have conducted extensive research on this topic in recent years. The risk-based optimal operation of a power, heat, and hydrogen-based microgrid with a plug-in EV is shown in [9], which shows that integrating HSS with the plug-in EV reduces daily costs by 9.28%. A HSS has been used by [10] to improve flexibility in the EH. As shown by this study, the HSS can achieve 100% flexibility conditions for the hubs when it is placed next to the thermal storage device. Renewable EHs can benefit from storage devices by about 9.2%. Integrated hydrogen fueling stations with battery-swapping infrastructure are included in a risk-constrained day-ahead planning model for an EH [11]. The authors of [12] have used DR and HSS together to reduce energy costs. As a result of the experiment, the system operation cost can be reduced by 6% by utilizing HSS and multi-energy demand response [12]. A multi-objective risk-averse optimization of EVs and power-to-hydrogen microgrids is presented in [13]. Simulated results indicate that the proposed energy management strategy for multi-energy microgrids can reduce operation costs and emissions by up to 8.2% and 3.9%, respectively. According to [14], hydrogen-based integrated energy systems can be effectively managed with a multi-stage and multi-timescale approach. In order to participate in the electricity and hydrogen markets, this solution consists of three stages: a day-ahead scheduling stage, an intraday rolling dispatch stage based on model predictive control (MPC) and an intraday real-time adjustment stage. In [15], an optimal energy scheduling method is proposed under the uncertainty of electricity prices in the day ahead for EHs with HSSs. A hybrid robust-stochastic approach is incorporated in [16] to solve wind power generation fluctuations, multiple demands, and electricity market prices. According to [17], a stochastic multi-attribute decision-making approach is used to achieve optimal operation of a hydrogen-based EH based on day-ahead scheduling. A detailed Power-to-Hydrogen (P2H) model forms the basis for the EH model [17]. Using envelope-based methods, [18] outlines a method for managing the EHs with a balance between real-time dispatch and day-ahead scheduling.

IDR has shown to be an effective approach for improving system flexibility, reliability, and reducing operation costs [19-26]. According to [19], the EH planning and operation are affected by IDR and DR. Shiftable IDR program resulted in a reduction of 15.1% in operating costs after modifying the demand curves for electrical, heating, and cooling loads. Based on a bi-level Stackelberg game, [20] proposed a strategy for pricing and managing energy in a multi-energy demand response system featuring a data center and EVs. As a result, this approach optimized a trading scheme that benefits both sources and loads [20]. According to [21], hydrogen-based integrated energy service providers have dynamic pricing and energy management. According to [22], P2G within EH systems can be economically and technically feasible under future market conditions. A stochastic dynamic planning method is used to design the P2G integrated EH (P2G-EH). This method involves dividing the time horizon into sub-horizons, and determining the optimal size of each system component in each sub-horizon. Based on the obtained results, implementing demand response programs (DRPs) besides the P2G system increases system performance and reduces resources required to operate and invest in the P2G-EH system by 4 % and 24 % [22]. Using the variable efficiency of converters, degradation of equipment, and annual growth of load and energy prices, [23] develops a multi-objective design model for hubs. IDR is integrated into the proposed hub through the use of P2G technology. By presenting a particle swarm optimization algorithm, [24] provides an optimal approach to planning EHs that participate in the electricity market and heat market and consider IDR. The simulation results highlight its potential to reduce energy procurement costs from the upstream electrical grid by 4.57 %. A hybrid hydrogen-batteries storage system [25] introduces an integrated energy management system (IEMS) that optimizes operation schedules and provides DR via shifting slots that accommodate the elastic loads of a microgrid setup.

Meanwhile, developed and developing countries are implementing long-term plans that will replace internal combustion vehicles with EVs and use renewable energy to generate electricity. An example is presented in [26] on how to optimize EHs with parking lots for hydrogen vehicles and responsive demands. In the presence of demand response, EH operation costs are reduced by 27.58 %, energy storage systems reduce the cost by 12.68 %, and hydrogen vehicles decrease the cost by 2.9%. In light of uncertainties, [27] proposed scheduling EHs with parking lots for EVs a day in advance. EVs and storage systems, as well as demand response factors and demand participation factors, are examined. As a result of the study, thermal demand response decreases EH operation cost by 12%, compared to 9.3% and 4.2% for electric and cooling demand response, respectively [27]. According to the review of recent studies, in the proposed framework of this paper, the hydrogen-based EH is optimally managed in the presence of EVs and electric, gas, and thermal storage devices, taking into account the IDR.

C. Research gap and contribution

Table I compares the advantages of this paper with recent investigations in the field of flexibility enhancement of the hydrogen-based EH. As can be seen, there is no complete framework that can coordinate with robust day-ahead scheduling of EVs in the presence of hydrogen, thermal and electrical storage, considering IDR. This paper considers this issue as a study gap and focuses on it.

TABLE I
DETAILED COMPARISON OF THIS STUDY WITH PREVIOUS RELATED INVESTIGATIONS

Ref	Year	EHs	Power to H_2	IDR	HSS	EVs
[9]	2021	✓	×	×	✓	✓
[16]	2021	✓	×	✓	✓	×
[13]	2022	✓	✓	×	✓	✓
[19]	2022	✓	×	✓	×	×
[20]	2022	✓	×	✓	×	×
[22]	2022	✓	×	✓	✓	×
[23]	2022	✓	×	✓	×	×
[2]	2023	✓	×	×	✓	×
[11]	2023	✓	✓	×	×	×
[12]	2023	✓	✓	×	✓	×
[15]	2023	✓	×	×	✓	×
[17]	2023	✓	✓	×	✓	×
[18]	2023	✓	×	×	×	×
[21]	2023	✓	×	✓	✓	×
[25]	2023	×	×	✓	✓	×
[5]	2024	×	×	×	×	✓
[10]	2024	✓	×	×	✓	×
[14]	2024	✓	×	×	✓	×
[24]	2024	✓	×	✓	×	×
This research		✓	✓	✓	✓	✓

Other study gaps can be summarized as follows:

- Despite its many advantages, P2H technology has not been considered in many studies, even though it can meet electricity demands and participate in hydrogen markets from an economic perspective.
- In most studies, the effect of smart EV parking on EH performance has not been investigated.
- In some studies, demand response is only considered for electric loads, and thermal demand management is not considered.
- Examining the simultaneous impact of EVs and IDR in the presence of hydrogen, thermal and electric storage and their coordination has not been seen.

The novelties of this paper include (1) integrating storage systems and EV's batteries and an intelligent parking lot into EH and investigating the effect of EV fleet with vehicle-to-grid (V2G) capability on EH operation; (2) using the robust optimization method to solve the coordination problem of EVs and IDR to manage uncertainties in electricity prices; and (3) Provide an optimal framework in which EVs and HSS operate in coordination for day-ahead scheduling using shiftable and transferable IDR.

There is a brief description of the structure of the studied EH in Section 2, and the proposed framework is given in Section 3. The problem formulation is discussed in Section 3, along with objectives, operating constraints, IDR, and robust optimization. In Section 4, simulations and numerical results are presented. Finally, Section 5 presents the conclusion of the paper.

II. The proposed framework

This paper proposes a scheme that is illustrated in Figure 1. A variety of energy sources are available at the EH, including CHP units, steam boilers, wind turbines, electrical storage systems (ESS), gas storage systems (GSS), thermal storage systems (TSS) and HSSs. In order to meet different needs, (HSS) is formed. Following is an analysis of the advantages of IDR from the perspective of both user benefits and system performance. In order to facilitate optimal social welfare within a greater efficiency range, IDR integrates various forms of energy, such as electricity, thermal energy, and natural gas. By minimizing barriers between various types of energy, IDR allows users of energy to adapt their consumption of energy and better utilize DR resources.

It should also be noted that hydrogen from wind energy is a way of producing clean and renewable hydrogen fuel by using wind turbines to power water electrolysis. Water electrolysis is a process that splits water molecules into hydrogen and oxygen using an electric current. Hydrogen can then be stored and used as a versatile energy carrier for various applications, such as transportation, industry, and electricity generation. Hydrogen from wind energy has many advantages, such as reducing greenhouse gas emissions, enhancing energy security, and providing flexibility to the power grid. However, there are also some challenges, such as the high cost of electrolyzers, the variability of wind resources, and the need for infrastructure development [28,29].

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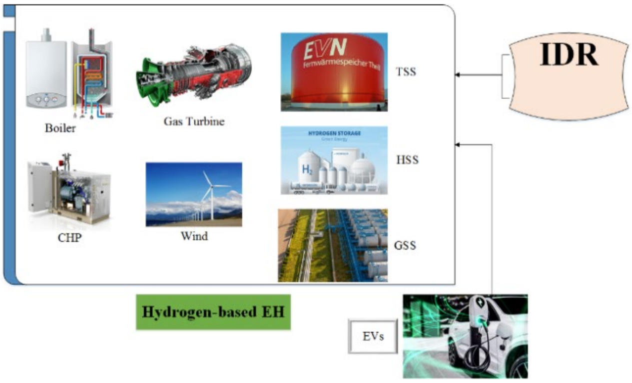

FIGURE 1. Framework of the proposed scheme

III. Problem Formulation

A. Objective Function (OF)

In (1), the OF aims to minimize total system costs over a long period of time. The first and second terms in the OF represent electricity and gas imported from the main grid. Hydrogen gas exports are beneficial to industry, according to the third term. Charge costs for HSS and EVs are represented by terms 4 and 5. There is a cost for curtailing electrical load (term 6) and shifting electrical load (term 7). Costs associated with thermal load curtailment and shifting are the last two terms.

$$Cost = \min \sum_{t=1}^{N_t} [\lambda_t^E P_t^{E,imp} + \lambda_t^G P_t^{G,imp}$$
$$-\lambda_t^{hyd} P_t^{hyd,exp} + C_t^{chr,hyd} P_t^{chr,hyd}$$
$$+C_t^{chr,EV} P_t^{chr,EV} + C^{E,up} dr_t^{E,up}$$
$$+C^{E,dn} dr_t^{E,dn} + C^{T,up} dr_t^{T,up} + C^{T,dn} dr_t^{T,dn} \quad (1)$$

B. The Constraints

The proposed scheme considers all the constraints, including CHP unit, gas turbine, boiler, TSS, HSS, GSS and ESS constraints. More information can be found in [27].

1) EVS CONSTRAINTS

One way to implement integrated demand response is to use smart charging technologies that can communicate with the grid and respond to price signals or grid constraints. For example, EVs can charge when the electricity is cheap or abundant, such as during periods of high renewable generation, and reduce or stop charging when the electricity is expensive or scarce, such as during peak demand hours. EV fleet destruction is shown in equation (2). (3) states that EV batteries' energy levels at any moment equal the sum of their capacity at the previous time, minus storage losses and discharge energy absorbed. Battery performance is constrained by (4) to (8). A predetermined interval should be set for charging and discharging EV batteries according to (4) and (5). In accordance with (6), each EV battery should have an energy level that does not fall below the minimum limit or exceed the upper limit at any time. As a result of constraint (7), batteries cannot be charged and discharged at the same time. Each EV battery is guaranteed to have a final energy level equal to its initial energy level by constraints (8).

$$d_{fleet,s} = \sum_{ev}\left(\frac{RC_{ev}}{TCDC_{ev}} \sum_t \left(P_t^{chr,EV} + P_t^{dischr,EV}\right)\right) \quad (2)$$

$$E_t^{EV} = E_{t-1}^{EV} + \eta^{chr,EV} P_t^{chr,EV} - \frac{P_t^{dischr,EV}}{\eta^{dischr,EV}}$$
$$-SLF_{ev}\left(\frac{E_t^{EV}+E_{t-1}^{EV}}{2}\right) \quad \forall EV, \forall \neq 1 \quad (3)$$

$$\underline{P}^{dischr,EV} \times I_t^{dischr,EV} \leq P_t^{dischr,EV}$$
$$\leq \bar{P}^{dischr,EV} \times I_t^{dischr,EV} \quad (4)$$

$$\underline{P}^{chr,EV} \times I_t^{chr,EV} \leq P_t^{chr,EV} \leq \bar{P}^{chr,EV} \times I_t^{chr,EV} \quad (5)$$

$$\underline{E}^{EV} \leq E_t^{EV} \leq \bar{E}^{EV} \quad (6)$$

$$I_t^{chr,EV} + I_t^{dischr,EV} \leq 1 \quad (7)$$

$$E_{t=0}^{EV} = E_{t=N_T}^{EV} \quad (8)$$

C. Shiftable IDR

Demand-side management will be enabled by the IDR programs for all types of load demand. Equations (9)-(12) provide the constraints of the shifting IDR mechanism simulation. As with the shifting DR program, this program's simulation method is similar, except that cooling and heating loads are included [19].

$$\sum_{t=1}^{T} P_{e,h,c}^{sh,up}(\gamma,\omega,t) =$$
$$\sum_{t=1}^{T} P_{e,h,c}^{sh,do}(\gamma,\omega,t) \quad \forall\gamma,\omega,t \quad (9)$$

$$0 \leq P_{e,h,c}^{sh,up}(\gamma,\omega,t) \leq LPF^{sh,up}$$
$$P_{e,h,c}(\gamma,\omega,t) I_{e,h,c}^{sh,up}(\gamma,\omega,t) \quad \forall\gamma,\omega,t \quad (10)$$

$$0 \leq P_{e,h,c}^{sh,do}(\gamma,\omega,t) \leq LPF^{sh,do}$$
$$P_{e,h,c}(\gamma,\omega,t) I_{e,h,c}^{sh,do}(\gamma,\omega,t) \quad \forall\gamma,\omega,t \quad (11)$$

$$0 \leq I_{e,h,c}^{sh,up}(\gamma,\omega,t) + I_{e,h,c}^{sh,do}(\gamma,\omega,t) \leq 1 \quad \forall\gamma,\omega,t \quad (12)$$

D. Transferable IDR

IDRs of this type involve when a load starts consuming, which can be transferred without affecting consumption duration. It would be difficult to interrupt a load demand of this type, and the total load demand would remain the same throughout the day.

$$P_{e,h,c}^{tr,do}(\gamma,\omega,t) = P_{e,h,c}^{tr,up}(\gamma,\omega,t+N_x) \quad \forall\gamma,\omega,t \quad (13)$$

$$0 \leq P_{e,h,c}^{tr,up}(\gamma,\omega,t)$$
$$\leq LPF^{tr,up} P_{e,h,c}(\gamma,\omega,t) I_{e,h,c}^{tr,up}(\gamma,\omega,t) \quad \forall\gamma,\omega,t \quad (14)$$

$$0 \leq P_{e,h,c}^{tr,do}(\gamma,\omega,t)$$
$$\leq LPF^{tr,do} P_{e,h,c}(\gamma,\omega,t) I_{e,h,c}^{tr,do}(\gamma,\omega,t) \quad \forall\gamma,\omega,t \quad (15)$$

$$0 \leq I_{e,h,c}^{tr,up}(\gamma,\omega,t) + I_{e,h,c}^{tr,do}(\gamma,\omega,t) \leq 1 \quad \forall\gamma,\omega,t \quad (16)$$

E. Demand and supply balance

As long as the utility load is equal to the power purchased from the main grid, the power generated by CHPs, gas turbines and wind turbines, and the power discharged and charged from HSSs, ESSs and EVs, the energy input must be equal to the output. Furthermore, the gas load must be met with imported gas from the gas network, as well as with charging and discharging the GSS. Heat storage systems, CHP units, and boilers were used as a means of meeting thermal demand. Furthermore, exported hydrogen must equal the amount of hydrogen discharged from HSS. In (17)-(20), these statements are discussed.

$$PL_t^{G,imp} + P_t^{CHP} + P_t^{E,imp} + P_t^{wind} - P_t^{P2H} + P_t^{H2P} - P_t^{chr,ES} + P_t^{dischr,ES} + P_t^{dischr,EV} - P_t^{chr,EV} = EL_t^{DR} \tag{17}$$

$$P_t^{G,imp} - P_t^{chr,GS} + P_t^{dischr,GS} - GB_t^b - GC_t^{GT} - GC_t^{CHP} = GL_t \tag{18}$$

$$HB_t^{dischr,TS} - HB_t^{chr,TS} + H_t^{CHP} + H_t^b = GL_t \tag{19}$$

$$P_t^{hyd,exp} = P_t^{ind,hyd} \tag{20}$$

F. Methodology

In order to better manage and control the uncertainties in the price of electricity, the robust optimization method has been used in this article. In the proposed problem, power price uncertainty was modeled using the RO method. By adjusting the uncertainty budget, the RO method enables the operator to be risk-averse. A risk-averse approach becomes more prevalent as the uncertainty budget increases. Day-ahead scheduling is generally described in (21):

$$\min \sum_i f(x_i) + \sum_j d_j . x_j$$
$$h_1(x) < 0, h_2(x) = 0; x \in \{x_i, x_j\} \tag{21}$$

The lower and upper bounds of dj are known, but the parameter itself is unknown. x_i is the decision variable that is continuous, and x_j the binary decision variable. $h_1(x) < 0$ and $h_2(x) = 0$ are inequality and equality constraints respectively. The RO can be formulated as:

$$\min \begin{Bmatrix} \sum_i f(x_i) + \sum_j d_j^{min} . x_j + \\ \max_{\{j||j|\le\Gamma} \{\sum_j (d_j^{max} - d_j^{min})\ x_j\} \end{Bmatrix} \tag{22}$$

All uncertain parameters are included in the max term in the above equation as long as they do not exceed Γ. RO conservatism is controlled by the integer variable Γ, which varies between 0 and N_j. If $\Gamma = 0$, it means uncertainty regarding price was ignored and if $\Gamma = N_j$, it means that uncertainty of price was considered for all time periods. It is difficult to solve the optimization problem of (22); therefore, it can be reformulated as (23) in order to overcome this complex optimization problem:

$$\min \begin{Bmatrix} \sum_i f(x_i) + \sum_j d_j^{min} . x_j \\ + \sum_j \max_{W\le\Gamma, W\le 1, x_j \le m_j} \{\sum_j (d_j^{max} - d_j^{min})\ m_j . w\} \end{Bmatrix} \tag{23}$$

It is difficult to solve the bi-level framework described by equation (23) with available solvers. Therefore, strong duality theory can be used to convert it to a single-level problem:

$$\min\{\sum_i f(x_i) + \sum_j d_j^{min} . x_j + \alpha . \Gamma + \sum_j \beta_j\} \tag{24}$$

With electricity prices uncertain, the OF of the proposed problem is to minimize the total cost. It is given in (25) with related constraints the RO problem of (1) taking the worst-case, i.e., the maximum amount of Γ.

$$Cost = \min \sum_{t=1}^{N_t} [\lambda_t^E P_t^{E,imp} + \lambda_t^G P_t^{G,imp} - \lambda_t^{hyd} P_t^{hyd,exp} + C_t^{chr,hyd} P_t^{chr,hyd} + C^{E,up} dr_t^{E,up} + C_t^{chr,EV} P_t^{chr,EV} + C^{E,dn} dr_t^{E,dn} + C^{T,up} dr_t^{T,up} + C^{T,dn} dr_t^{T,dn} + (\beta_t)] + \alpha . \Gamma + d_{fleet} + d_{TSS} + d_{HSS} + d_{ESS} + d_{GSS} \tag{25}$$

$$\alpha + \beta_t \ge (\lambda_t^{E,max} - \lambda_t^{E,min}) . m_t \tag{26}$$

$$\beta_t \ge 0$$
$$m_t \ge 0$$
$$\alpha \ge 0$$
$$P_t^{E,imp} \le m_t \tag{27}$$

Using the GAMS software environment and the CPLEX solver, it was possible to solve the proposed robust problem.

IV. Simulation and numerical results

EHs are composed of three input sources, namely wind energy, natural gas, and electric energy, which are all inputs to the hubs. Based on the main grid, Figure 2 shows how much natural gas and electric energy cost. A further illustration of Figure 3 shows the power generated through the wind turbine and the loads to be supplied through the EH (such as gas, thermal, and electrical). A number of scenarios are considered in this paper in order to evaluate the impact of HSS, EV, IDR approach and RO on proposed EH:

- Scenario 1: Using IDR to solve OF in a deterministic state
- Scenario 2: Solution of robust OF using IDR in the presence of HSS
- Scenario 3: Solution of robust OF in the presence of HSS, parking of EVs, and application of IDR

In Appendix a detailed description of the technical specifications of all the technologies that were considered in this study is presented.

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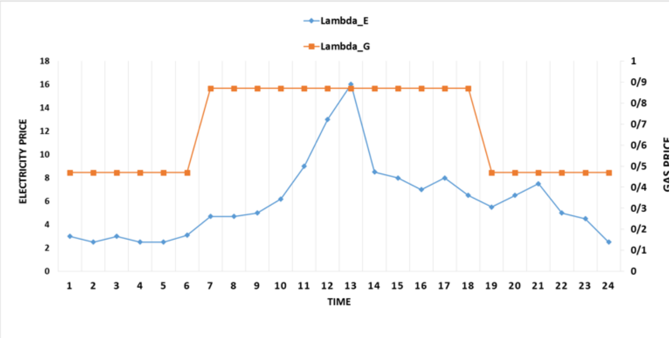

FIGURE 2. Electricity and gas prices in this study

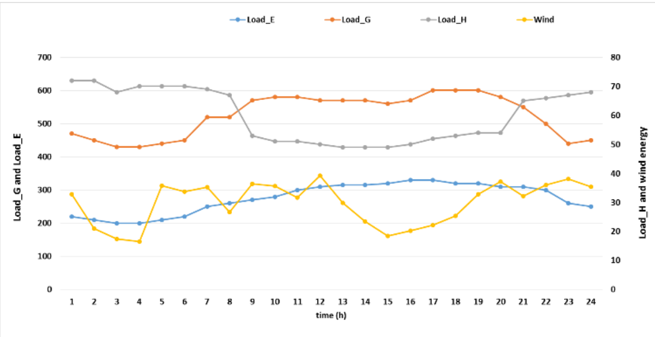

FIGURE 3. Wind energy and loads

A. Scenario 1

This scenario is examined in the case where IDR is applied to the EH. There is also a HSS in this case. The results of this deterministic scenario are compared with the case where there is only HSS (without IDR). As can be seen from Figures 4 and 5, IDR changes electrical (DRE) and thermal demands (DRH). Figures show that electric demand has been reduced during peak hours (for example, t = 11 to t = 19) to non-peak hours (for example, t = 1 to t = 10). Table III shows how the IDR program impacts the total costs, and the cost reductions are sensible. As shown in Table IV, IDR is sensitive to total costs. Table IV shows that the more consumers participate, the less costs are reduced.

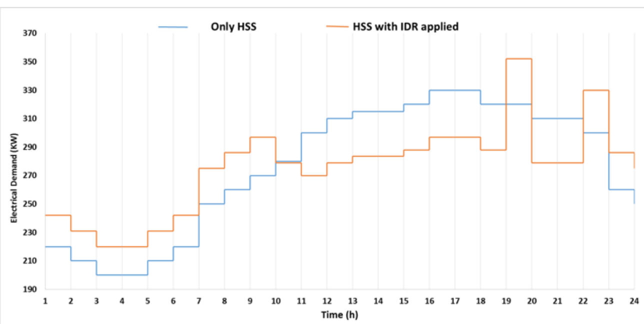

FIGURE 4. Electrical demand in different cases

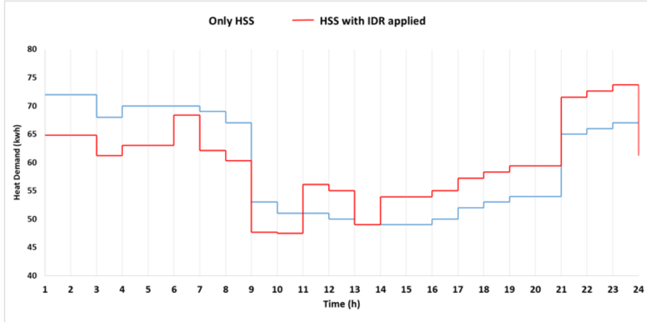

FIGURE 5. Thermal demand in different cases (HSS and HSS+IDR)

TABLE III
ECONOMIC IMPACTS OF IDR

	Cost of total purchased power	Cost of Total Purchased Gas	Total Operation cost
Only HSS	19862.0	22610.7	42161.9
HSS with IDR applied	18411.4	22321.9	40600.8

TABLE IV
SENSITIVITY ANALYSIS OF ELECTRICAL DR AND HEAT DR

	Cost of total purchased power	Cost of Total Purchased Gas	Total Operation cost
DRE=10%	18411.4	22321.9	40600.8
DRE=12%	18088.5	22321.9	40309.6
DRE=14%	17765.6	22321.9	40018.3
DRE=16%	17442.7	22321.9	39727.1
DRE=18%	17144.3	22322.5	39461.1
DRE=20%	16927.0	22277.3	39231.7
DRH=12%	18481.2	22225.2	40577.6
DRH=14%	18542.5	22139.6	40556.9
DRH=16%	18597.3	22063.5	40539.3
DRH=18%	18671.4	21970.6	40524.1
DRH=20%	18622.4	22001.6	40509.8

B. Scenario 2

To account for the uncertainty of the electricity price, the RO method is applied to the system. There is an evaluation of all results for different uncertainty budgets ranging from $\Gamma = 0$ to $\Gamma = 16$. A deterministic case is represented by $\Gamma = 0$, whereas the most conservative case is represented by $\Gamma = 16$. Based on the robust uncertainty budget, Figures 6 and 7 show the variation in the amount of purchased power and gas, respectively. Figure 8 illustrates how variations in the robust uncertainty budget impact the state of charge (SoC) across HSS. Additionally, Figure 9 shows the total operation cost of the proposed EH. The proposed EH's total operation cost increases as the robust uncertainty budget increases. To put it another way, the more risk-averse the state, the higher the cost.

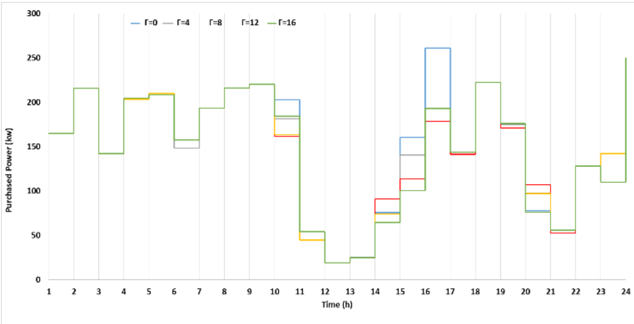

FIGURE 6. Purchased power from grid in Scenario 2

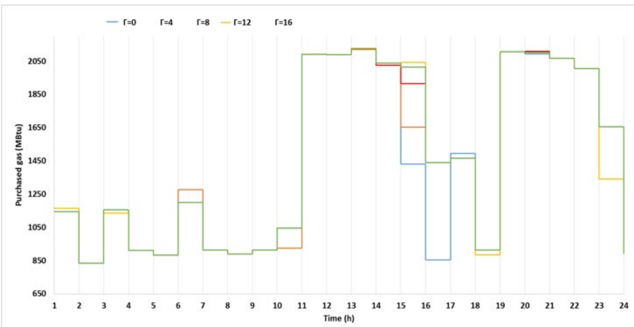

FIGURE 7. Purchased gas from the grid in Scenario 2

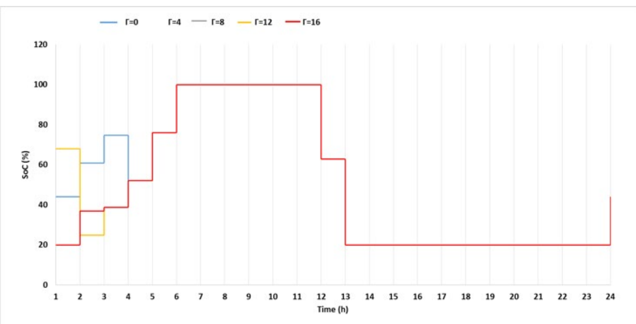

FIGURE 8. SoC of HSS in Scenario 2

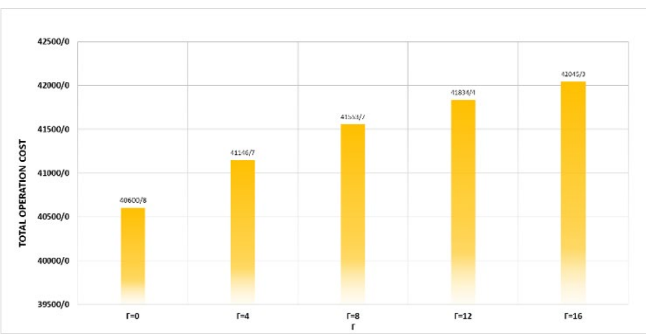

FIGURE 9. Total operation cost of EH in Scenario 2

C. Scenario 3

In this scenario, the proposed scheme has been fully applied and implemented on the EH. For this purpose, the impact of smart EVs parking which includes 12 EVs along with HSS and IDR is investigated. Figure 10 shows the state of charging and discharging the battery of 12 EVs during 24 hours.

Figures 11 and 12 respectively show the electricity and gas purchased from the grid in this scenario. As it can be seen, the application of the proposed plan, i.e. the use of EVs at the same time as the application of IDR and the use of storage devices, has reduced the purchase of electricity and thus reduced the cost in hours such as t=11-15 and the amount of electricity purchased in this The hours have reached zero. Figure 13 also shows the SoC of HSS in this scenario. In Table V, the effect of applying the proposed plan when the uncertainties are not taken into account is stated, according to the results, the operating cost has decreased to $36,886.1. In this case, 5 modes have been examined as follows:

- Case 1: With ESS-TSS-GSS
- Case 2: With ESS-TSS-GSS-HSS
- Case 3: With ESS-TSS-GSS-EV
- Case 4: With ESS-TSS-GSS-HSS-EV
- Case 5: With ESS-TSS-GSS-HSS-EV-IDR

Hour	1	2	3	4	5	6	7	8	9	10	11	12
1	22	-16	30	0	10	0	0	10	0	28	10	0
2	0	30	0	30	20	0	0	12	22	0	12	0
3	0	30	22	-29	0	-18	0	0	0	0	0	27
4	0	10	0	30	0	30	26	0	30	0	0	0
5	0	0	0	24	21	30	26	0	0	24	0	0
6	30	0	0	0	0	11	0	30	0	0	30	25
7	0	0	-27	0	-10	0	0	-10	-11	-27	-13	-27
8	0	-12	0	-27	0	0	0	0	13	30	-14	30
9	0	14	30	30	11	0	0	11	0	0	30	0
10	-15	-14	-27	-10	0	0	0	-30	-30	0	0	0
11	0	0	-30	0	-26	-30	-10	0	0	-30	0	0
12	0	0	0	0	-24	-18	-30	-18	0	-27	-10	0
13	-30	0	-10	-30	0	-19	0	0	-10	0	-27	0
14	-10	-30	0	0	-17	0	-27	0	0	0	-30	-12
15	0	-23	0	-27	0	0	0	-19	-27	0	0	-30
16	-12	30	14	30	0	11	29	0	0	0	0	0
17	0	-27	0	-27	0	-10	-27	0	0	-10	0	-25
18	24	11	-12	18	30	0	30	0	0	0	0	0
19	0	0	0	14	0	11	0	30	30	30	0	11
20	0	-10	0	-29	0	-10	0	-27	-10	-17	13	-10
21	-22	0	11	0	-27	0	-27	0	-17	-10	-12	0
22	0	22	-10	0	22	0	0	30	0	23	0	18
23	0	0	22	0	0	22	22	-22	0	-10	11	-16
24	22	0	0	22	0	0	0	16	22	10	11	22

FIGURE 10. State of battery charging and discharging of 12 EVs during 24 hours

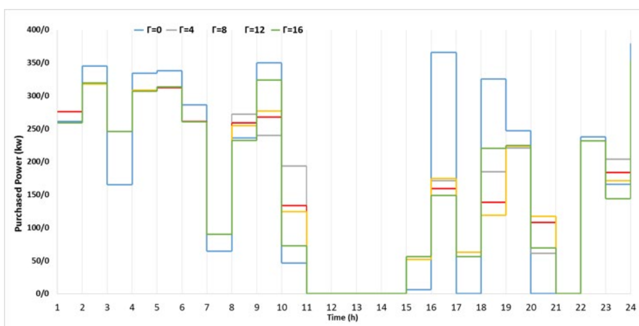

FIGURE 11. Purchased power from grid in proposed scheme

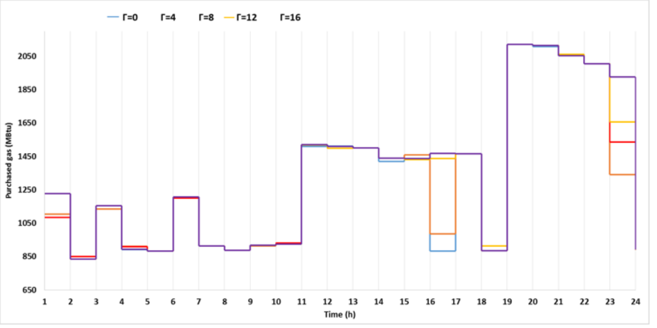

FIGURE 12. Purchased gas from grid in proposed scheme

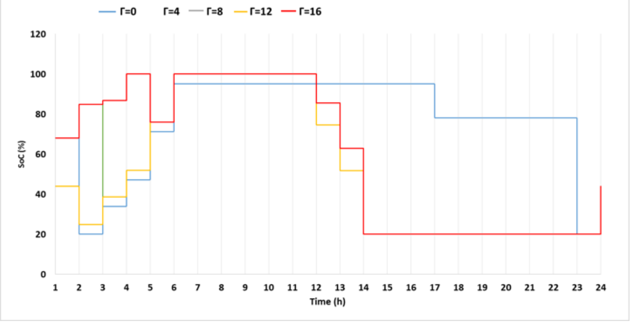

FIGURE 13. The SoC of HSS in the proposed scheme

As can be seen, the presence of a HSS causes a 1.38% reduction, the presence of EVs causes a 10.79 % reduction, the simultaneous presence of EVs and HSS causes a reduction of 11.39%, and finally, by applying the proposed scheme, i.e. applying IDR and using HSS and EVs participation, it causes a 13.89% reduction in total operation costs. Table VI shows the effect of applying the proposed scheme of this paper, considering the uncertainty of the electricity price in four cases, which compared to Scenario 2, the operating cost in the worst case (with the highest uncertainty) is $38,398.2, which is 8.67% decreased.

TABLE V
EXAMINING TOTAL COSTS IN DETERMINISTIC SOLUTION MODE

	TOTAL PURCHASED POWER COST	TOTAL PURCHASED GAS COST	TOTAL OPERATION COST
CASE 1	20237.1	22574.8	42837.6
CASE 2	19903.9	22574.8	42246.1
CASE 3	17605.6	20546.7	38213.8
CASE 4	17649.2	20530.7	37959.0
CASE 5	**17011.0**	**20197.6**	**36886.1**

TABLE VI
THE ECONOMIC IMPACT OF APPLYING THE PROPOSED SCHEME WITH UNCERTAINTIES

UNCERTAINTY LEVEL	SCENARIO 2	SCENARIO 3 (PROPOSED SCHEME)
$\Gamma=4$	41146.7	37397.6
$\Gamma=8$	41553.7	37815.8
$\Gamma=12$	41834.4	38133.7
$\Gamma=16$	42045.3	38398.2

V. CONCLUSION

An EH based on hydrogen is proposed in this paper as a robust method for day-ahead scheduling which is based on a robust algorithm. A HSS can store hydrogen that can be converted into electricity during peak hours or be fed into the hydrogen industry for use during off-peak times. In addition, a transferable and IDR was provided to control the load pattern of consumers in the EH. In the proposed scheme, EVs parking also participates in the IDR program. Electric vehicles (EVs) can provide flexibility to the EH by adjusting their charging patterns according to the supply and demand of electricity. This is known as IDR, and it can help balance the grid, reduce carbon emissions, and lower electricity costs for EV owners and other consumers. The proposed model was formulated as a mixed integer linear programming (MILP) problem. In the case of a deterministic solution, the proposed scheme causes a 13.89% reduction in the total operation costs. Finally, the RO method was used to manage the uncertainty in the price of electricity. Analysis and numerical results showed that the overall cost of operating the proposed hub was reduced by 8.67%. The results guaranteed that the proposed method for hydrogen-based EH scheduling is optimal, economical and robust.

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APPENDIX

TABLE VII TECHNOLOGY CHARACTERISTICS IN DETAIL EMPLOYED IN THIS RESEARCH

	Parameter	Unit	Value		Parameter	Unit	Value
CHP	T_{ON}^{CHP}	H	2	Gas storage	$\eta^{chr,GS}$	%	95
	T_{OFF}^{CHP}	H	2		$\eta^{dischr,GS}$	%	95
	HR^{CHP}	MBtu/kWh	8.53		$\overline{E}^{GS}$	MBtu	300
	R_{up}^{CHP}	kW	60		$\underline{E}^{GS}$	MBtu	15
	R_{dn}^{CHP}	kW	60		$\overline{P}^{chr,GS}$	MBtu	60
Gas Turbine	$\overline{P}^{GT}$	kW	60		$\underline{P}^{chr,GS}$	MBtu	15
	$\underline{P}^{GT}$	kW	20		$\overline{P}^{dischr,GS}$	MBtu	60
	T_{ON}^{GT}	H	2		$\underline{P}^{dischr,GS}$	MBtu	15
	T_{OFF}^{GT}	H	2		RC	$\$$	5000
	HR^{GT}	MBtu/kWh	9.74		$TCDC$		4e6
	R_{up}^{GT}	kW	30	Electrical storage	$\eta^{chr,ES}$	%	95
	R_{dn}^{GT}	kW	30		$\eta^{dischr,ES}$	%	95
					$\overline{E}^{ES}$	kWh	100
Boiler	HR^{B}	MBtu/kWh	4.012		$\underline{E}^{ES}$	kWh	5
Thermal storage	η^{TS}	%	10		$\overline{P}^{chr,ES}$	kW	25
	$\eta^{chr,TS}$	%	90		$\underline{P}^{chr,ES}$	kW	5
	$\eta^{dischr,TS}$	%	90		$\overline{P}^{dischr,ES}$	kW	25
	$\overline{B}^{TS}$	kWh	50		$\underline{P}^{dischr,ES}$	kW	5
	$\underline{B}^{TS}$	kWh	10		RC	$\$$	20000
	$\overline{B}^{chr,TS}$	kWt	10		$TCDC$		4e6
	$\underline{B}^{dischr,TS}$	kWt	10	Electrical Vehicle	$\eta^{chr,EV}$	%	95
	RC	$\$$	5000		$\eta^{dischr,EV}$	%	95
	$TCDC$		4e6		$\overline{E}^{ES}$	kWh	70
Hydrogen storage	$C_t^{chr,hyd}$	$\$$/kWh	0.11		$\underline{E}^{ES}$	kWh	15
	$\overline{P}^{H2P}$	kW	30		$\overline{P}^{chr,ES}$	kW	30
	$\underline{P}^{H2P}$	kW	10		$\underline{P}^{chr,ES}$	kW	10
	$\overline{P}^{P2H}$	kW	30		$\overline{P}^{dischr,ES}$	kW	30
	$\underline{P}^{P2H}$	kW	10		$\underline{P}^{dischr,ES}$	kW	10
	η^{P2H}	%	80		RC	$\$$	20000
	η^{H2P}	%	70		$TCDC$		4e6
	$\overline{A}^{hyd}$	kWh	100	DRP	DRE	%	10
	$\underline{A}^{hyd}$	kWh	20		DRH	%	10
	λ_t^{hyd}	$\$$/kWh	5.5		$C^{E,dn}$	$\$$/kWh	0.25
	RC	$\$$	20000		$C^{E,up}$	$\$$/kWh	0.25
	$TCDC$		4e6		$C^{T,dn}$	$\$$/kWh	0.15
					$C^{T,up}$	$\$$/kWh	0.15

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