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Research paper

Robust Scheduling of Water and Energy Hub Considering CAES, Power-to-Gas Units, and Demand Response Programs

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Abstract

Background and Objectives: The smart energy hub framework encompasses physical assets such as thermal storage, boiler, wind turbine, PV panel, water storage and, water desalination unit to ensure continuity of electricity, water, thermal, and gas provision in the case of unexpected outages in the upstream networks. In this regard, the smart energy hub as an integrated structure provides a suitable platform for energy supply. Considering the drinking water resources in the smart hub structure can cause operational efficiency improvement.
Methods: This paper proposes an integrated scheduling model for energy and water supply. To address the issue of increasing operational flexibility, a set of new technologies such as Compressed Air Energy Storage (CAES) and Power-to-Gas (P2G) system are provided. Also, the energy price is modeled as an uncertain parameter using a robust optimization approach. The proposed model is established as a Mixed Integer Linear Function (MILP). The mentioned model is implemented using the CPLEX solver in GAMS software. The proposed model is simulated in different scenarios in the energy hub and the optimization results are compared with each other to validate the proposed method.
Results: The results show that using CAES technology and the P2G system can lead to reducing the operating costs to a desirable level. Moreover, the impact of the P2G unit on the operation cost is more than the CAES unit.
Conclusion: The energy hub operator should tradeoff between robustness and operation cost of the system. The obtained results ensured that the proposed methodology was robust, optimal, and economical for energy hub schedules.

Introduction

In the last decades, energy system has expanded from isolated energy carrier systems into integrated energy structure [1]. The integrated multi-carrier energy system play an important role in future smart grid power systems [2]. In any urban area, different energy carriers can be managed in an energy hub framework where the operation cost and emission mitigation issues are the main purposes [3]. In this regard, the energy hub system plays an important role in the field of energy conversion, generation, and storage in an efficient manner [4]. Due to the mentioned abilities of energy hub systems, input carriers of the energy hub system have a variety [5] where the electrical, thermal, gas and freshwater are the main energy input into the energy hub system [6].

Furthermore, Demand Response Programs (DRPs) are used in the energy hub system to increase operational efficiency [7]. In this regard, DRPs are categorized into electrical [8] and thermal [9] programs. The operating expenditure of energy systems can be decreased by the demand response programs [10]. The effects of electrical and thermal DRPs on the flexibility and reliability of the energy hub system are evaluated in [11]. Moreover, DRPs can decrease greenhouse gases emission in the energy hub system [12].

Furthermore, considering novel and efficient storage technologies in the energy hub system is caused to decrease in the operation cost [13]. One of the efficient Energy Storage Systems (ESS) technologies is Power-to-Gas (P2G), which is associated with challenges due to environmental problems as well as storage space [14]. The P2G storage system converts the extra electrical power into gas energy in the low electrical price hours and uses the stored gas energy in electrical peak hours [9], [15]–[18].

Researchers have recently been able to store excess energy by compressing air from electricity generated using renewable energy, a technology called Compressed Air Energy Storage (CAES) [19]. The cost of using this method is very low and its efficiency is much higher than power storage batteries [14]. Also, CAES is a low-cost method of energy storage that plays an important role in energy management, improving power quality, etc., and is the cheapest method of energy storage [20]. Some research papers climes that the CAES can cover the energy price uncertainty of the upstream network. In [21] a random optimization method is proposed to cover the uncertainty of energy prices in the electricity market. Profit maximization is the main objective of the mentioned paper.

In optimization problems, there are several ways for dealing with uncertainties, one of which is the robust optimization (RO) method [22]. In [23], the problem of unit commitment due to wind power uncertainty has been solved using the robust optimization method. This method has recently been introduced as an efficient method in mathematical programming in optimization problems for power system decision-makers. The future power grid, with the unprecedented infiltration of renewable energy sources, will face severe uncertainties that may cause problems in the operation of the grid. It is necessary to evaluate the uncertainty of system performance in this network. In [24], the uncertainty of renewable wind energy is investigated using a strong two-stage optimization method. The integrated electricity and heating system has been investigated in [25], [26] and the price uncertainty of electricity has been modeled using a robust optimization method.

In this paper, a novel robust energy and water optimization model is proposed. Also, the CAES unit, as well as P2G, are used to enhance the flexibility of the proposed energy hub system. Mixed-Integer Linear Programming (MILP) method is used to model the optimization of the proposed energy hub. Also, desired results are obtained using the CPLEX solver in the GAMS environment. Summary, the contributions of the paper are as follow:

- ✓ The role of novel energy storage technologies such as CAES and P2G units in the energy hub system is investigated.
- ✓ The water desalination units, as well as water storage, are considered in the energy hub system.
- ✓ The robust optimization method is used to model the upstream electrical price uncertainty.

The remaining of the paper is organized as follows. In section II, the proposed structure is stated. The formulation of the problem is specified in Section III. The case study is presented in Section IV. At the end of this study, the conclusion is given in Section V.

The Proposed Structure

In this paper, a novel Power and Water Robust Optimization (PWRO) framework has been proposed to decrease the effects of the parameter uncertainties in the energy hub structure. Furthermore, the uncertainty of price has been considered as an uncertainty parameter and has been modeled by the robust optimization method. Thermal, electricity, gas, and water carriers are inputs of the system. On the other hand, the demand for the proposed hub system should be satisfied. Furthermore, the boiler unit, thermal storage unit, and partial section of energy outputs of the Combined Heat and Power (CHP) unit are to receive the thermal energy of the energy hub system. Also, the wind turbine and the microturbine unit generate electrical power. The integrated structure of the energy hub test system is shown in Fig. 1.

Mathematical Formulation

The objective function of the proposed energy hub model is as follow:

$$Min\sum_{t=1}^{N_t}\left\{\begin{array}{l}\underbrace{\left(\pi_{net}^{E}(t)P_{net}^{E}(t)+\pi_{wind}^{E}P_{wind}^{E}(t)\right)}_{\text{Electrical Cost}}+\\ \underbrace{\left(\pi_{net}^{G}(t)P_{net}^{G}(t)\right)}_{\text{Gas Cost}}+\underbrace{\left(\pi_{net}^{T}(t)P_{net}^{T}(t)\right)}_{\text{Thermal Cost}}+\\ \underbrace{\left(\begin{array}{l}\pi_{Drink\_water}(t)W_{Drink\_water}(t)+\\ \pi_{Sea\ to\ drink}^{Des}W_{Sea\ to\ drink}^{Des}(t)\end{array}\right)}_{\text{Water Cost}}+\\ \underbrace{\left(\begin{array}{l}\pi_{DRP}^{E}\left(P_{down}^{E}(t)+P_{up}^{E}(t)\right)+\\ \pi_{DRP}^{T}\left(P_{down}^{T}(t)+P_{up}^{T}(t)\right)\end{array}\right)}_{DRP\ \text{Cost}}\end{array}\right\} \quad (1)$$

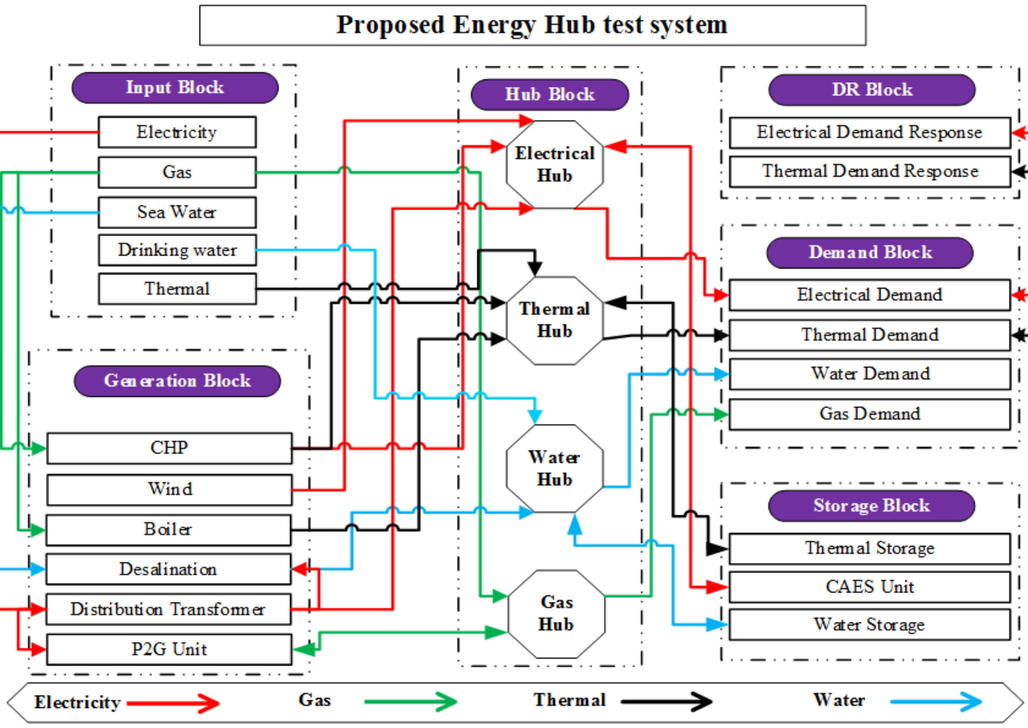

Fig. 1: The water and energy hub system.

The objective function is included different parts such as electrical cost, Gas Cost, Thermal Cost, Water Cost, and DRP Cost respectively.

$$\begin{aligned}&\left[\eta^{EE}_{Trans} P^{E}_{net}(t)\right]+\left[\eta^{GE}_{CHP} P^{G}_{netCHP}(t)\right]+\left[\eta^{EE}_{Conv} P^{E}_{wind}(t)\right]+\\&\left[P^{E}_{dis}(t)-P^{E}_{ch}(t)\right]+\left[P^{E}_{down}(t)-P^{E}_{up}(t)\right]+\\&W^{Des}_{Sea\ to\ drink}(t)\sigma_{P2W}+P_{C,S}(t)-P_{CAES}(t)\\&+P_{P2G}(t)-P_{G2P}(t)=P^{E}_{demand}(t)\end{aligned} \tag{2}$$

$$P^{G}_{net}(t)-P^{G}_{netCHP}(t)-P^{G}_{netboil}(t)=P^{G}_{demand}(t) \tag{3}$$

$$\begin{aligned}&\left[\eta^{GT}_{CHP} P^{G}_{netCHP}(t)\right]+\left[\eta^{GT}_{Boil} P^{G}_{netBoil}(t)\right]+P^{T}_{net}(t)+\\&\left[P^{T}_{dis}(t)-P^{T}_{ch}(t)\right]+\left[P^{T}_{down}(t)-P^{T}_{up}(t)\right]=P^{T}_{demand}(t)\end{aligned} \tag{4}$$

$$\begin{aligned}&W^{Des}_{Sea\ to\ drink}(t)+W_{Drink_{water}}(t)+W_{dis}(t)\\&-W_{Ch}(t)=p^{water}_{demand}(t)\end{aligned} \tag{5}$$

The input electrical power and the wind turbine operation are considered as the electrical cost of the proposed system. The thermal, as well as gas cost, are the cost of input thermal and gas energy to the energy hub respectively. The water cost in the objective function consists of two parts namely: input drinking water from the upstream water network and the water desalination operation cost. Furthermore, the final part of the objective function is the cost of electrical and thermal demand response programs.

The balance limits of electric, thermal, gas, and water energy are as follows (2)-(5):

The input power, thermal, gas, and drinking water from the upstream network are limited by (6)-(9) respectively [27]:

$$0\le P^{E}_{net}(t)\le P^{E}_{net-max} \tag{6}$$

$$0\le P^{T}_{net}(t)\le P^{T}_{net-max} \tag{7}$$

$$0\le P^{G}_{net}(t)\le P^{G}_{net-max} \tag{8}$$

$$0\le W_{Drink_{water}}(t)\le W_{DW-max} \tag{9}$$

In addition, the input power of the distribution transformer is limited by (10) [28]:

$$0\le P^{E}_{net}(t)\le \mathrm{P}^{\mathrm{input}}_{\mathrm{trans}} \tag{10}$$

Moreover, the input gas of CHP and boiler has been addressed as (11) and (12):

$$0\le P^{G}_{netCHP}(t)\le \mathrm{P}^{\mathrm{input}}_{\mathrm{CHP}} \tag{11}$$

$$0\le P^{G}_{netB}(t)\le \mathrm{P}^{\mathrm{input}}_{\mathrm{boiler}} \tag{12}$$

In the following, (13)-(19) models the operation of the CAES technology.

$$V^{inj}(t)=\alpha^{inj}P_{CAES}(t) \tag{13}$$

$$P_{C,S}(t)=\alpha^{P}V^{P}(t) \tag{14}$$

$$V_{min}^{inj}u^{inj}(t)\le V^{inj}(t)\le V_{max}^{inj}u^{inj}(t) \tag{15}$$

$$V_{min}^{P}u^{P}(t)\le V^{P}(t)\le V_{max}^{P}u^{P}(t) \tag{16}$$

$$u^{inj}(t)+u^{P}(t)\le 1 \tag{17}$$

$$A(t+1)=A(t)+V^{inj}(t)-V^{P}(t) \tag{18}$$

$$A^{min}\le A(t)\le A^{max} \tag{19}$$

Equations (13) and (14) indicate the energy import and export in the CAES unit. The imported and exported energy in the CAES unit is limited by (15) and (16) respectively. The energy level of the CAES unit is obtained by (18). Furthermore, the capacity of the CAES unit is limited by (19). The thermal storage operation constraints have been provided in (20)-(25).

$$P_{s}^{T}(t)=P_{s}^{T}(t-1)+P_{ch}^{T}(t)-P_{dis}^{T}(t)-P_{loss}^{T}(t) \tag{20}$$

$$P_{loss}^{T}(t)=\vartheta_{loss}^{T}P_{s}^{T}(t) \tag{21}$$

$$\alpha_{min}^{T}P_{CAPA}^{T}\le P_{s}^{T}(t)\le\alpha_{max}^{T}P_{CAPA}^{T} \tag{22}$$

$$\beta_{min}^{T}P_{CAPA}^{T}I_{ch}^{T}(t)\le P_{ch}^{T}(t)\le\beta_{max}^{T}P_{CAPA}^{T}I_{ch}^{T}(t) \tag{23}$$

$$\beta_{min}^{T}P_{CAPA}^{T}I_{dis}^{T}(t)\le P_{dis}^{T}(t)\le\beta_{max}^{T}P_{CAPA}^{T}I_{dis}^{T}(t) \tag{24}$$

$$0\le I_{dis}^{T}(t)+I_{ch}^{T}(t)\le 1 \tag{25}$$

Equation (20) indicates the thermal storage status. Moreover, the loss of energy storage unit is modeled by (21). The capacity of the thermal storage is shown by (22). Charging and discharging of thermal storage are limited by (23) and (24). The status of the thermal energy storage unit in each hour is determined by (25).

The mathematical formulations of the water storage are as follow:

$$W_{storage}(t)=W_{storage}(t-1)+W_{ch}(t)-W_{dis}(t) \tag{26}$$

$$0\le W_{storage}(t)\le W_{storage-max} \tag{27}$$

$$0\le W_{ch}(t)\le W_{max-ch}I_{ch}^{W}(t) \tag{28}$$

$$0\le W_{dis}(t)\le W_{max-dis}I_{dis}^{W}(t) \tag{29}$$

$$0\le I_{ch}^{W}(t)+I_{dis}^{W}(t))\le 1 \tag{30}$$

The desalination unit has an efficiency coefficient that has been considered in (31):

$$W_{Sea\,to\,drink}^{Des}(t)=\eta_{sea\,to\,drink}W_{sea}(t) \tag{31}$$

In (32)-(35) and (36)-(40) the mathematical limitations of electrical and thermal energy storage are expressed [29].

$$\sum_{t=1}^{24}P_{down}^{E}(t)=\sum_{t=1}^{24}P_{up}^{E}(t) \tag{32}$$

$$0\le P_{up}^{E}(t)\le LPF_{up}^{E}P_{demand}^{E}(t)I_{up}^{E}(t) \tag{33}$$

$$0\le P_{down}^{E}(t)\le LPF_{down}^{E}P_{demand}^{E}(t)I_{down}^{E}(t) \tag{34}$$

$$0\le I_{down}^{E}(t)+I_{up}^{E}(t)\le 1 \tag{35}$$

$$\sum_{t=1}^{24}P_{down}^{T}(t)=\sum_{t=1}^{24}P_{up}^{T}(t) \tag{36}$$

$$0\le P_{up}^{T}(t)\le LPF_{up}^{T}P_{demand}^{T}(t)I_{up}^{T}(t) \tag{37}$$

$$0\le P_{down}^{T}(t)\le LPF_{down}^{T}P_{demand}^{T}(t)I_{down}^{T}(t) \tag{38}$$

$$0\le I_{down}^{T}(t)+I_{up}^{T}(t)\le 1 \tag{39}$$

Equations (32) and (36) indicate that the sum of downward and upward demand in a day should be equal (load shifting). Also, (33) and (34) as well as (37) and (38) show that the upward and downward DRP is limited to the partial loads. Equations (35) and (39) indicate that in each hour only one DRP strategy can be implemented (Upward or Downward). The P2G system is modeled as follow:

$$GS(t)=GS(t-1)+G_{P2G}^{ch}(t)-G_{P2G}^{dis}(t) \tag{40}$$

$$GS^{\min}\le GS(t)\le GS^{\max} \tag{41}$$

$$G_{P2G}^{ch,\min}\le G_{P2G}^{ch}(t)\le G_{P2G}^{ch,\max} \tag{42}$$

$$G_{P2G}^{dis,\min}\le G_{P2G}^{dis}(t)\le G_{P2G}^{dis,\max} \tag{43}$$

$$G_{P2G}^{ch}(t)=\eta_{P2G}P_{P2G}(t) \tag{44}$$

$$G_{P2G}^{dis}(t)=\eta_{G2P}P_{G2P}(t) \tag{45}$$

$$0\le P_{G2P}(t)\le P_{G2P}^{\max} \tag{46}$$

$$0 \le P_{P2G}(t) \le P_{P2G}^{\max} \quad (47)$$

Constraint (40) shows the charge level of the P2G system. The charge level of the P2G system is limited by (41). Charging and discharging the P2G system are limited by (42) and (43) respectively. Moreover, the energy conversion in the P2G system is modeled by (44) and (47).

A. Robust Optimization Modeling

The RO approach paves the way for system operators to act risk-aversely by changing the uncertainty budget. In this regard, the energy hub operator should tradeoff between operation cost and system robustness. It is clear that if the more uncertainty budget increases, the more risk-averse manner adopted.

The robust optimization approach compared with stochastic approaches has two main advantages:

- First, the implementation of robust optimization is simpler than the scenario-based approaches. This approach only requires the predicted values of the upper limit and the lower limit of the target variable.
- Second, unlike stochastic methods that use probabilistic guarantees to satisfy constraints, the proposed method is followed by optimal solutions that are safe against all changes in random variables.

In the following, the objective function of the energy hub problem is modeled based on the robust optimization approach that is proposed in [30]. The objective function of the deterministic problem can be rewritten as follow:

$$\sum_{t=1}^{24}[(\pi_{net}^{E}(t)\,P_{net}^{E}(t)] + \text{Other Costs} \quad (48)$$

In the above objective function, the electricity cost is separated from other operating costs to implement uncertainty. The other costs are gas, thermal, water, and demand response cost which were shown in (1).

Base on [30], the target of the operator is obtained to the worst solution and find a way to minimize the effects of the worst case. Therefore, the objective function can be rewritten as follow:

$$min \quad max\sum_{t=1}^{N_t}[(\pi_{net}^{RO,E}(t)\,P_{net}^{E}(t)] + \text{Other Costs} \quad (49)$$

where $\pi_{net}^{RO,E}(t)$ is the main grid price of electricity. The second term of objective function should be considered in solving the problem using the dual process. To model the price uncertainty, the uncertain price is modeled by forecasted value and deviation from forecasted value as follow:

$$max\sum_{t=1}^{N_t}[(\pi_{net}^{E,forecasted}(t)(1+Z(t))P_{net}^{E}(t)]$$

$$\begin{aligned} &s.t\\ &Z(t) \le 1 \qquad :\beta_t \\ &\sum_{t=1}^{N_t} Z(t) \le \Gamma \qquad :\alpha \\ &Z(t) \ge 0 \end{aligned} \quad (50)$$

In the above formulation, α and β_t are the dual variables of constraints. Moreover, Γ is the uncertainty budget of the price of electricity. The objective function of the main problem is rewritten by considering the KKT condition as follow:

$$min \begin{Bmatrix} \sum_{t=1}^{N_t}[(\pi_{net}^{E,forecasted}(t)\,P_{net}^{E}(t)]+ \\ \sum_{t=1}^{N_t}[\beta_t]+\alpha+\text{Other Costs} \end{Bmatrix} \quad (51)$$

$$\alpha+\beta_t \ge dev\,\pi_{net}^{E,forecasted}(t)\,P_{net}^{E}(t) \quad (52)$$

$$\beta_t \ge 0 \quad (53)$$

$$\alpha \ge 0 \quad (54)$$

$$constraints(2)-(47)$$

Fig. 2 shows the robust optimization algorithm in the energy hub framework.

In the first step, the uncertainty budget and the iteration index are considered equal to 0 and 1 respectively. In the second step, the proposed optimization problem will be solved and the energy hub variables are obtained. In the following, the uncertainty budget is updated and so, if the uncertainty budget is equal to 24 the obtained results are displayed.

Case Study

The energy management horizon time is considered 24 hours. Also, the electrical, thermal, gas, and water demands of the energy hub test system are shown in Fig. 3. The maximum and minimum electrical prices are shown in Fig. 4. Also, the thermal price of the energy hub test system is shown in Fig. 5. Furthermore, the input parameters of the energy hub test system are used from [18]. The effects of CAES and P2G units on the operation cost of the proposed energy hub system are shown in Table. 1.

In the base case scenario (scenario 1), the CAES and P2G units are neglected in the energy scheduling problem. In the second scenario, the CAES unit is considered and the P2G unit is neglected and vice versa in the third scenario. The simultaneity operation of the CAES unit and the P2G unit is considered in the fourth scenario.

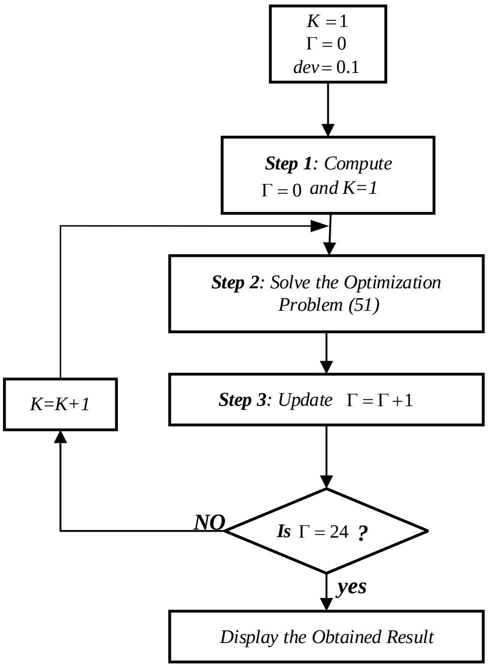

Fig. 2: The Proposed Robust optimization Algorithm.

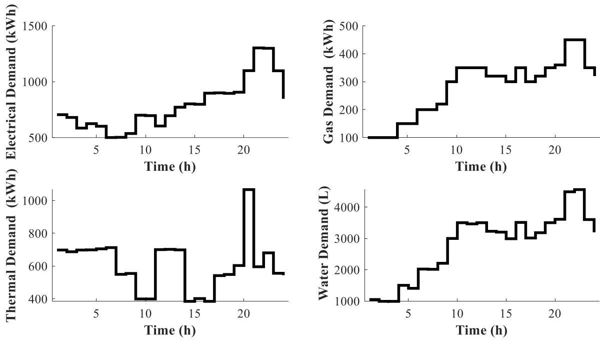

Fig. 3: Energy demands of the energy hub system.

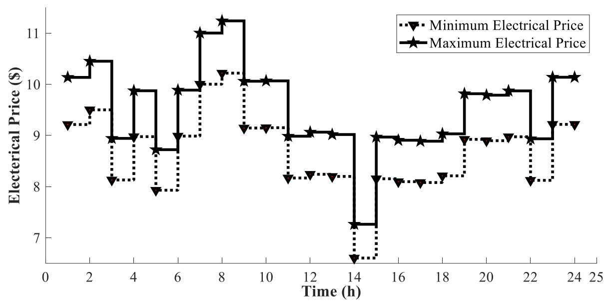

Fig. 4: The minimum and maximum upstream electrical market.

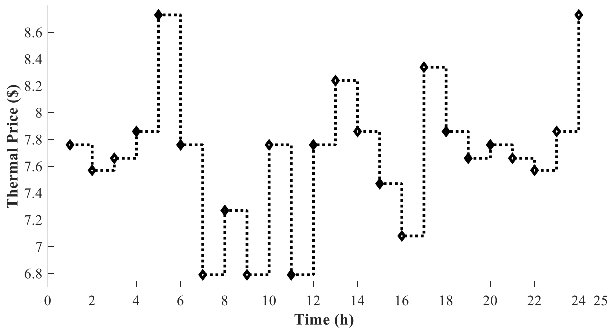

Fig. 5: Thermal price of energy hub test system.

Results show that the CAES unit can be used for operating cost reduction in the energy hub test system. however, the P2G unit is a more efficient device than the CAES unit. The final scenario is the best and the operation cost decreases 1.32% compared with the base scenario (scenario 1).

Table 1: The operation cost energy hub system

	CAES	P2G	Operation Cost ($)	Percentage (%)
Scenario 1	✕	✕	622039	-
Scenario 2	✓	✕	620861	-0.18
Scenario 3	✕	✓	614662	-1.18
Scenario 4	✓	✓	613801	-1.32

Fig. 6 and Fig. 7 show the operation of the CAES unit and P2G system. The results show that the CAES unit and P2G are appropriate for energy arbitrage between hours. In this regard, the system operator imports energy in the P2G and CAES units at the high energy price hours and exports the stored energy at the lower price hours.

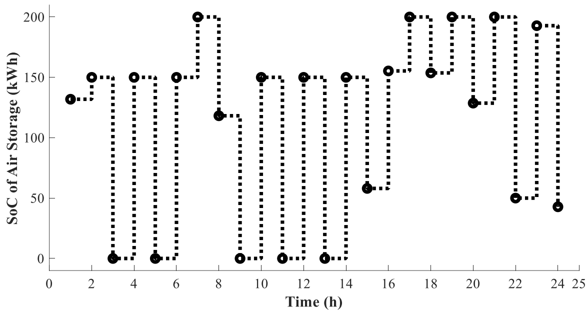

Fig. 6: The SOC of the CAES unit.

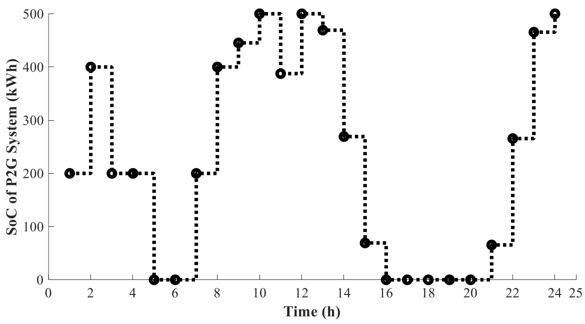

Fig. 7: The SOC of the P2G unit.

The results of electrical and thermal load shifting DRP are shown in Fig. 8 and Fig. 9 respectively. The positive values in the mentioned Figures are referred to the load decrement and vice versa. Results show that the electrical demand in the high price hours 1-2 and 7-10 is shifted down. Moreover, the electrical demand peak reduction in high peak hours 21-24 is more than other hours. Because the high electrical peak price and high electrical peak demand simultaneously occur. The thermal DRP works the same as the electrical one. For example, the thermal load is shifted down in high thermal price hours 12-14. Moreover, the thermal demand is shifted up in the low price and low thermal demand hour 11.

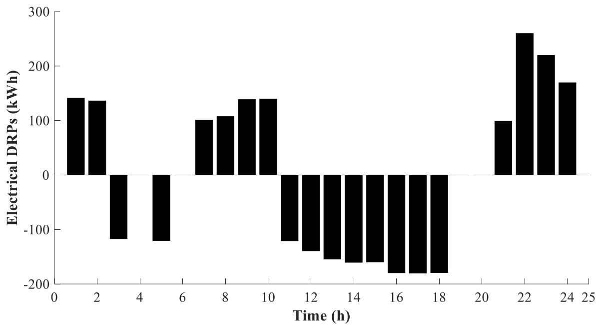

Fig. 8: The load shifting of the electrical DRP.

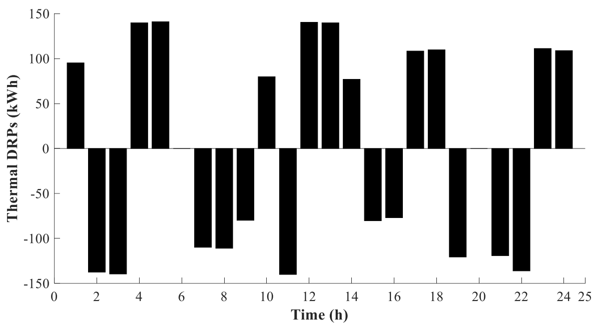

Fig. 9: The load shifting of the thermal DRP.

The effect of the uncertainty budget on the operational cost is presented in Fig. 10. By increasing the robust uncertainty budget, the total operation cost increases.

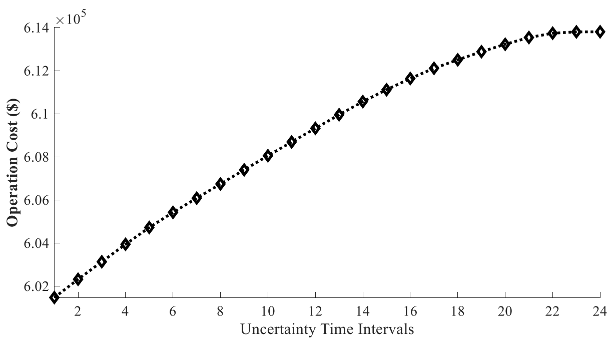

Fig. 10: The operation cost of the energy hub.

Conclusion

This paper proposes a novel robust energy nexus water optimization problem. The effects of uncertainty budget on the results of energy hub schedules were evaluated. The proposed approach was formulated as a Mixed Integer linear programming problem. The effects of the P2G unit and CAES units are evaluated on the operation cost. Results show that novel energy storage technologies such as P2G and CAES units can significantly decrease the daily operation cost (i.e., 1.32 %). However, the impact of the P2G unit (i.e., 0.18 %)is more than the CAES unit (i.e., 1.18 %). The robust optimization method was implemented to evaluate the uncertainty of upstream electricity prices. The results showed that the operation cost of the proposed system increased by increasing the robust uncertainty budget. However, the robustness of the proposed energy hub system was increased by considering a robust strategy (increasing the uncertainty budget). The energy hub operator should tradeoff between robustness and operation cost of the system. The obtained results ensured that the proposed methodology was robust, optimal, and economical for energy hub schedules. In future research, the electrical, thermal, water, and heating networks will be considered in the model.

Author Contributions

S. Dorahaki and S. S Zadsar proposed and designed the structure of the energy hub. Also, the optimization code has been implemented by S. Dorahaki. S. S Zadsar wrote the original draft of the manuscript. M. Rashidinejad and M. R. Salehizadeh reviewed the data analysis and results as well as reviewed and edited the manuscript.

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This work is completely self-supporting, thereby no financial agency's role is available.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

CAES	Compressed Air Energy Storage
P2G	Power-to-Gas
MILP	Mixed Integer Linear Function
PWRO	power and water robust optimization
CHP	Combined Heat and Power
DRP	Demand Response Program

Sets and indices

t	Index of time.
$\boldsymbol{N_t}$	The number of the time periods.

Parameters

π_{net}^{E}	Electrical price.

π_{wind}^{E}	The operation cost of wind unit.
π_{net}^{G}	Gas price.
π_{net}^{T}	Thermal price.
π_{Drink_water}	Drinking water price.
$\pi_{Sea\ to\ drink}^{Des}$	The operation cost of the desalination unit.
η_{Boil}^{GT}	The efficiency of gas to thermal in Boiler.
$\eta_{sea\ to\ drink}$	The efficiency of the desalination unit.
η_{Trans}^{EE}	The efficiency of the transformer unit.
η_{CHP}^{GE}	The efficiency of the CHP unit.
η_{Conv}^{EE}	The efficiency of the converter unit.
η_{CHP}^{GT}	The efficiency of gas to thermal in CHP.
$\eta_{HS}^{ch}, \eta_{HS}^{dis}$	The charge/discharge efficiency of thermal storage.
η_{G2P}, η_{P2G}	The energy conversion efficiency of the P2G unit.
$\beta_{max}^{H}, \beta_{min}^{H}$	Maximum/Minimum ratio of thermal charge.
ϑ_{loss}^{H}	The ratio of thermal storage loss.
$\alpha_{min}^{H}, \alpha_{max}^{H}$	The min/max ratio of thermal storage.
α^{inj}, α^{P}	Imported/exported efficiency to/from CAES.
$GS^{\min}, GS^{\max}$	Minimum/Maximum SOC of the P2G unit.
$G_{P2G}^{ch,\min}, G_{P2G}^{ch,\max}$	Minimum/Maximum charge of the P2G unit.
$G_{P2G}^{dis,\min}, G_{P2G}^{dis,\max}$	Minimum/Maximum discharge of the P2G unit.
$V_{min}^{inj}, V_{max}^{inj}$	Minimum/Maximum energy imported to CAES.
V_{min}^{P}, V_{max}^{P}	Minimum/Maximum energy exported to CAES.
$P_{net-max}^{E}$	Maximum input electrical power.
$P_{net-max}^{T}$	Maximum input thermal energy.
$P_{net-max}^{G}$	Maximum input gas energy.
$W_{net-max}^{E}$	Maximum input drinking water.
W_{DW-max}	Maximum output water of desalination unit.
$\mathrm{P}_{\mathrm{trans}}^{\mathrm{input}}$	Input electrical power to the transformer.
$\mathrm{P}_{\mathrm{CHP}}^{\mathrm{input}}$	Input energy to CHP.
$\mathrm{P}_{\mathrm{Boiler}}^{\mathrm{input}}$	Input energy to the boiler.
$W_{storage-max}$	Maximum state of water storage.
$W_{max-ch}, W_{max-dis}$	Maximum charge/discharge water.
$LPF_{up}^{E}, LPF_{down}^{E}$	Shifted up/down electrical Demand.
P_{CAPA}^{H}	The thermal storage capacity.
P_{demand}^{E}	Electrical demand.
P_{demand}^{G}	Gas demand.
P_{demand}^{T}	Thermal demand.
P_{demand}^{water}	Water demand.

Variables

P_{net}^{E}	Input electrical power.
P_{wind}^{E}	Wind power.
P_{net}^{G}	Input gas power.
P_{net}^{T}	Input thermal power.
W_{Drink_water}	Input drinking water.
$W_{Sea\ to\ drink}^{Des}$	Output water of desalination unit.
P_{up}^{E}, P_{down}^{E}	Electrical demand response up/down demand.
P_{up}^{T}, P_{down}^{T}	Thermal up/down demand response.
$P_{CAES}(t), P_{C,S}(t)$	Imported/exported power to/from CAES.
$P_{P2G}(t), P_{G2P}(t)$	Energy conversion power of P2G unit.
P_{ch}^{T}	Thermal charge.
P_{dis}^{T}	Thermal discharge.
$W_{storage}$	State of water storage.
W_{sea}	Seawater.
$V^{inj}(t), V^{P}(t)$	Imported/exported energy to/from CAES.
$GS(t)$	The SOC of Gas energy in the P2G unit.
$G_{P2G}^{ch}(t), G_{P2G}^{dis}(t)$	Charging/discharging energy from the P2G unit.
dev	The upstream price deviation from the forecasted value.
W_{ch}, W_{dis}	Charge/Discharge water from water storage.
P_{netCHP}^{G}	Input gas to CHP unit.
$P_{netboil}^{G}$	Input gas to Boiler unit.

Binary Variables

I_{ch}^{H}, I_{dis}^{H}	The binary variable of thermal charge/discharge.
I_{up}^{E}, I_{down}^{E}	The binary variable of shifted up/down DRPs.
I_{ch}^{W}, I_{dis}^{W}	The binary variable of water charge/discharge.
$u^{inj}(t), u^{P}(t)$	Binary variables of imported and exported energy to the CAES.

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