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# Optimal operation of smart energy hub considering high-temperature heat and power storage

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**Abstract**

Due to the impacts of high intermittent renewable resources, increasing their penetration in the generation sector of energy systems is still challenging. In this regard, the integration of different energy networks can play a key role in dealing with this challenge. This paper focuses on the analysis and optimization of multi-generation energy storage (MGES) system's performance and investigates the role of this type of energy storage in the operation of future smart energy systems by considering 100% green energy goals. Hence, this paper first introduces high-temperature heat and power storage (HTHPS) system, as a novel MGES unit, for a local integrated energy system (IES) with different energy carriers. Then, a novel optimal energy scheduling scheme for this system is presented by considering the energy hub concept. The proposed IES is introduced as a Smart Energy Hub (SEH) which supplies local energy demands through local renewable resources generation, as well as upstream energy networks, by considering a competitive energy market. Finally, the performance of the proposed SEH is investigated by simulating different case studies and its effectiveness is proved in increasing the renewable generation penetration.


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*Keywords:* Energy storage; Smart energy hub; Multi energy carrier; Optimization; Energy market

## 1. Introduction

The integration of different energy infrastructures has a great potential for better utilization of energy resources, increment of renewable energy penetration, as well as reduction of energy losses, operation costs, and environmental emissions [1]. Thus, proposing new technologies and analyzing their performance on IESs are hot topic issues regarding improving the system's energy efficiency and economy to support sustainable energy development

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goals [2]. Researchers have been pursuing new ideas and frameworks to address the optimal energy management of IESs as a result of the trend to integrate energy networks from a conceptual viewpoint. In this regard, smart energy systems and SEH, have been given as possible paradigms for modeling and managing future IESs. Moreover, the challenges of optimizing SEHs under uncertainty factors have recently been explored by [3]. Gu et al. [4] designed an IES optimization method to improve the utilization of wind power energy by considering the thermal inertia of the building and the regional heat network. Kholardi et al. [5] investigated the optimal energy management of the IES consisting of a power, gas, and hydrogen network considering an SEH concept. In Ref. [6], a multi-objective energy management approach has been presented to obtain the optimum performance of an IES based on the solar-powered generation system connected with a thermal storage unit.

From the practical point of view, modeling and analyzing new technologies proposed for IESs could be impressive to smoothen the pathway of these technologies' utilization [7]. Many efforts are being made by research institutes and energy industrial companies to find new solutions and new technologies that can help human achieve the goal of sustainable energy. Although there are many obstacles in the way of all these technologies from different aspects, such as political and economic aspects, it is important to study the integration of these technologies in energy networks. Because this type of studies gives us new windows of a more comprehensive understanding of these technologies, through which the advantages and disadvantages of each of these technologies are better defined. In the meantime, multi-generation energy storage (MGES) technologies have been introduced optimal solutions that provided a basis to increase total system efficiency based on energy networks integration. In fact, this category of energy storage devices has the ability to store a specific energy carrier and deliver different energies in the discharging state. In this way, the efficiency of the whole system will be improved, as different energy networks will be supported by supplying different energy carriers.

As one of the new generations of MGES systems, High-temperature heat and power storage (HTHPS) has received special interest from the research institutes and leading energy firms in Northern Europe [8]. This energy storage can improve IES's operation by storing the excess renewable electricity generation and giving both thermal and electrical energy in the discharging mode. In this regard, Lasemi et al. [9] presented a new model for optimal operation scheduling of HTHPS connected to a wind farm. This paper proposes a new configuration of local IES as an energy hub by considering HTHPS system and the optimal energy scheduling schemes for the proposed energy system will be studied by supposing the owner of the energy hub can participate as a prosumer in the energy market besides supplying the local demand.

## 2. Problem formulation

Fig. 1 illustrates schematic diagram of the proposed SEH. As mentioned before, the proposed problem for optimizing the SEH is given as an optimization problem, in which both the economic and environmental goals are considered as problem objective functions. The economic objective, which demonstrates the system operation cost, includes electricity purchase cost, gas purchase cost, heat purchase cost, and electricity selling income.

### 2.1. Cost function

Eq. (1) shows the daily operation cost of the proposed problem. In which, $\rho_i\,(t)$ is energy price for energy carrier $i$ at hour $t$ and $b_i\,(t)$ is the bonus considered by the market operator to encourage the prosumer for participating in the market.

$$C_1 = \sum_i \sum_t \rho_i\,(t)\,.P_i^{pur}\,(t)\,.\Delta t - \sum_i \sum_t \left(\rho_i\,(t) \times b_i\,(t)\right).P_i^{sel}\,(t)\,.\Delta t \tag{1}$$

The second objective function is environmental objective, which can be divided into two categories containing (*i*) hub inside emissions, regarding producing greenhouse gases during the operation by CHP, and (*ii*) hub outside emissions related to the energy carriers consumed by the hub from upstream networks. Eq. (2) demonstrates the emission cost function of the proposed problem.

$$C_2 = \sum_t \gamma_{chp}.P_g^{chp}\,(t)\,.\Delta t + \sum_i \sum_t \gamma_i.P_i^{pur}\,(t)\,.\Delta t \tag{2}$$

Where, $\gamma_{chp}$ and $\gamma_i$ are $CO_2$ emission coefficients for CHP plant as well as energy carrier $i$ purchased from upstream networks. To reach the optimal operation of the proposed energy hub, a multi-objective optimization problem is

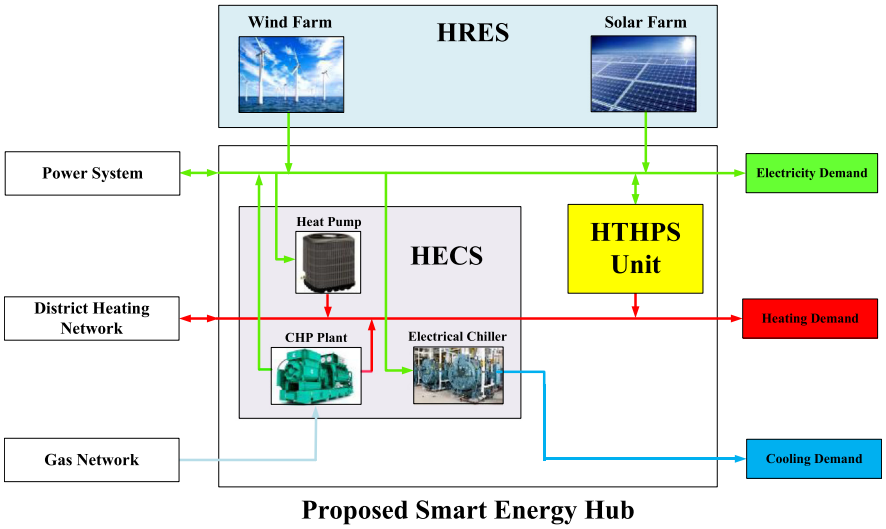


**Fig. 1.** Schematic diagram of the proposed Smart Energy Hub.

defined by (3), considering cost function $C_1$ and $C_2$ and all energy hub constraints. Moreover, in the proposed optimization problem, $X_1$ is considered the vector of the decision variables and $X_2$ is also the vector that represents the dependent variables of the proposed model and for both vectors the upper and lower bound limit is considered. To solve the proposed problem, the Weighted Sum Method (WSM) is firstly employed to convert the problem into a single-objective optimization form and then, the Teaching learning-based optimization (TLBO) method is used to find the best possible solution of the proposed problem.

$$\min_{X_1} C = w_1 \cdot \frac{C_1}{C^*_{1\,min}} - w_2 \cdot \frac{C_2}{C^*_{2\,min}}$$
$$s.t. \quad \text{Eqs. (4)–(20)} \tag{3}$$

### 2.2. Systems' constraints

As mentioned before, in the proposed energy hub, HTHPS is considered for storing surplus power of renewable recourse in this paper. The thermodynamic model of HTHPS could be presented as follows:

$$T_{hx1}(t,j) = T_c(t,j) \times \left[1 + \frac{r_c^{\left(\frac{\mu-1}{\mu}\right)} - 1}{\eta_{s,c}}\right] \tag{4}$$

$$T_c(t,j+1) = T_{hx1}(t,j) \times (1-\varepsilon_{hx1}) + T_{cw} \times \varepsilon_{hx1} \tag{5}$$

$$T_{hx2}(t,j+1) = T_t(t,j) \times \left[1 + \eta_{s,t}\left(r_t^{\left(\frac{\mu-1}{\mu}\right)} - 1\right)\right] \tag{6}$$

$$T_t(t,j+1) = T_{hx2}(t,j) \times (1-\varepsilon_{hx2}) + T_{st} \times \varepsilon_{hx2} \tag{7}$$

Eqs. (4) and (5) represent the relationship between the $T_c$ inlet air temperature of compressor and $T_{hx1}$ inlet air temperature of heat exchangers type 1, located in the compression section. Moreover, the relationship between the inlet air temperature of the system turbines $T_t$ and heat exchangers type 2 $T_{hx2}$ are described by (6) and (7) [9].

$$T_{st}(t+1) = T_{st}(t) + \frac{P_e^{ch}(t) - P_e^{dis}(t) - P_h^{dis}(t)}{\dot{m}_a.c_{p,a}} \tag{8}$$

The thermal storage temperature changes are calculated by (8), in which $\dot{m}$ and $c_{p,a}$ are air mass flow rate and specific thermal capacity in constant pressure. Moreover, $P_e^{ch}$, $P_e^{dis}$, and $P_h^{dis}$ are the charging power, discharging

power, and heat, respectively. $P_e^{ch}$ and $P_e^{dis}$ are the decision variable of the proposed problem and $P_h^{dis}$ is a dependent variable, calculated by (9).

$$P_h^{dis} = \sum_j \dot{m}_a . c_{p,a} (T_{hx1}(t, j) - T_c(t, j+1)) \tag{9}$$

In the proposed energy hub, a CHP unit is employed for the alternative generation of electricity and heat through the gas carrier. For modeling a CHP unit, its input power could be considered as the decision variable, and then, the output powers are calculated by (10)–(12), in which $P_e^{chp}$ and $P_h^{chp}$ are, respectively, electrical, and thermal power generated by CHP unit and $P_g^{chp}$ is the gas power required to produce desired output power.

$$P_e^{chp}(t) = \eta_{e,\text{chp}} \times P_g^{chp}(t) \tag{10}$$

$$P_h^{chp}(t) = \eta_{h,\text{chp}} \times P_g^{chp}(t) \tag{11}$$

$$\underline{P_e^{chp}} \le P_e^{chp}(t) \le \overline{P_e^{chp}} \tag{12}$$

Respectively, to support heat and cold demand, a heat pump and an electrical chiller are considered in the energy hub to produce alternative heat and cold energy through electricity. The relationships between the input and power of these devices are defined by (13) and (14), in which, $COP$ is the coefficient of performance of this equipment.

$$P_h^{hp}(t) = COP^{hp} \times P_e^{hp}(t) \tag{13}$$

$$P_c^{ec}(t) = COP^{ec} \times P_e^{ec}(t) \tag{14}$$

As shown in Fig. 1, wind turbines and PV panels can provide electricity as clean and sustainable energy for the proposed energy hub. Respectively, (15) and (16) present the wind turbines and PV panels model employed in the proposed problem based on [10].

$$P_e^w(t) = \begin{cases} 0 & 0 \le V(t) \le V_{ci}, V_{co} \le V(t) \\ P_r \times \frac{V(t)-V_{ci}}{V_r - V_{ci}} & V_{ci} \le V(t) \le V_r \\ P_r & V_r \le V(t) \le V_{co} \end{cases} \tag{15}$$

$$P_e^{pv}(t) = \eta_{pv} \times S_i \times I_i \times [1 - \alpha . (T_{out}{}^t(t) + 25)] \tag{16}$$

As important constraint in each energy system is the balance between generation and demand. From the energy hub perspective, supplying the demand is a task of the hub operator. Here, there are four energy carriers in the energy hub, so, the electricity, heat, cold, and gas energy balance equations can be written by (17)–(20).

$$\sum_{gen} P_e^{gen}(t) + P_e^{sel}(t) + P_e^{dis}(t) = \sum_{load} P_e^{load}(t) + P_e^{pur}(t) \tag{17}$$

$$\sum_{gen} P_h^{gen}(t) + P_h^{sel}(t) + P_h^{dis}(t) = \sum_{load} P_h^{load}(t) + P_h^{pur}(t) \tag{18}$$

$$P_c^{ec}(t) + P_c^{ac}(t) = P_c^{dem}(t) \tag{19}$$

$$P_g^{sel}(t) = P_g^{chp}(t) \tag{20}$$

## 3. Simulation and results

To accomplish a precise analysis and investigate the proposed energy hub model advantages, in this paper, three different scenarios have been assumed by considering 50%, 75%, and 100% penetration factors for renewable resources. Moreover, four cases are also studied according to Table 1. The sign $\surd$ demonstrates that the proposed energy hub of a case contains which types of equipment as well as the prosumer role, on the contrary, the symbol $\times$ shows that it does not include the equipment or prosumer role in this case. Based on different data mentioned in the literature, this paper provides a special case for study of a IES connected to HTHPS system. The parameters regarding the energy converter devices, the energy demand of the proposed hub, energy prices, and carbon emission coefficient, as well as carbon emission management coefficient, have been considered according to [10]. Moreover, the data for ECSs has been considered according to [11]. The 3-stages HTHPS unit is employed for the case study, and physical and its technical parameters have been considered according to [8].

**Table 1**. Classifications of case studies.

| Case studies | HECS | HRES | HTHPS | Prosumer |
|---|---|---|---|---|
| Case 1 | √ | × | × | × |
| Case 2 | √ | × | × | √ |
| Case 3 | √ | √ | × | √ |
| Case 4 | √ | √ | √ | √ |

The results obtained for different scenarios of cases 3 and 4 regarding the economic and environmental objectives are listed in Table 2. These results show the most optimal solution for the single objective decisions when the energy hub operator only considers one of the objectives of the proposed operation problem. As can be seen from these results, the proposed system can properly support the increment of renewable energy penetration. Respectively, 12.29%, 22.50%, and 12.86% decrement on operation cost is acquired by applying HTHPS unit for scenarios 1, 2, and 3. Moreover, the improvement in the emission cost is observed by reducing 1.21%, 19.98%, and 19.79% for the second cost function in different scenarios for case 4. It is worth mentioning that the negative value obtained for operation cost means the energy hub reaches profit.

**Table 2**. Daily operation and emission cost ($) for cases 3 and 4 in different scenarios.

| Scenario # | *First Cost Function* | | *Second Cost Function* | |
|---|---|---|---|---|
| | Case 3 | Case 4 | Case 3 | Case 4 |
| S1 | −3.1187e+05 | −3.5021e+05 | 1.0286e+04 | 1.0162e+04 |
| S2 | −5.3422e+05 | −6.5440e+05 | 9.8002e+03 | 7.8421e+03 |
| S3 | −7.3679e+05 | −8.3152e+05 | 9.5190e+03 | 7.6350e+03 |

Table 3 demonstrates the results obtained for different cases considering different weighting coefficients for the objective functions. By comparing the results obtained for cases 1 and 2, the energy hub owner, respectively, decreases by 39.5% and 5.0% its operation and environmental cost by participating in the energy market as a prosumer. However, regarding the results obtained for cases 1 and 2 with considering $w_1 = 0$ and $w_2 = 1$, the prosumer role cannot be effective when the hub does not utilize any renewable sources (i.e., case 2). Based on the obtained results for cases 3 and 4, it can be seen that renewable resources can bring profit, which has been calculated as a negative cost, for the hub owner. HTHPS system also improves the system performance by increasing the system profit by 817.8 $ than case 3. Respectively, Figs. 2 and 3 demonstrate the results obtained for Scenario 3 in Case 4 (S3-C4), regarding electrical and heat energy balance. As seen in these figures, the energy balance has been meted for all grids of the energy hub. HTHPS system is on the charging mode from 1 am to 2 pm because of high renewable generation availability and on the discharging mode from 7 pm to 11 pm.

**Table 3**. Total operation and emission cost ($) for different cases considering different weighting coefficients.

| Case # | $w_1 = 1$, $w_2 = 0$ | | $w_1 = 0.5$, $w_2 = 0.5$ | | $w_1 = 0$, $w_2 = 1$ | |
|---|---|---|---|---|---|---|
| | *F1* | *F2* | *F1* | *F2* | *F1* | *F2* |
| C1 | 4654.8 | 766.5 | 5233.7 | 312.1 | 5353.0 | 210.1 |
| C2 | 1183.3 | 798.9 | 3163.4 | 296.3 | 5353.0 | 210.1 |
| C3 | −7367.9 | 560.1 | −5603.8 | 203.7 | −3673.1 | 95.1 |
| C4 | −8315.2 | 554.11 | −6421.6 | 197.4 | −3779.8 | 76.3 |

As can be seen from Figs. 2 and 3, except for bottom hours when the energy hub would be penalized for injecting energy to upstream networks, the heat pump is working on the maximum power for the rest of the hour, due to its high efficiency. Moreover, HTHPS unit supports the energy hub system to balance its energy transaction with upstream energy networks. Hence, the proposed SEH can properly participate in the energy market and manage the renewable energy generation fluctuations.

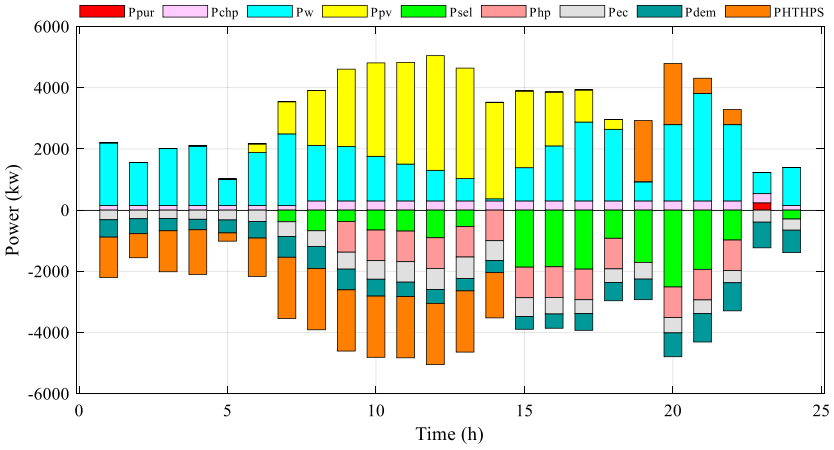


**Fig. 2.** Results obtained for S3-C4 regarding electricity balance.

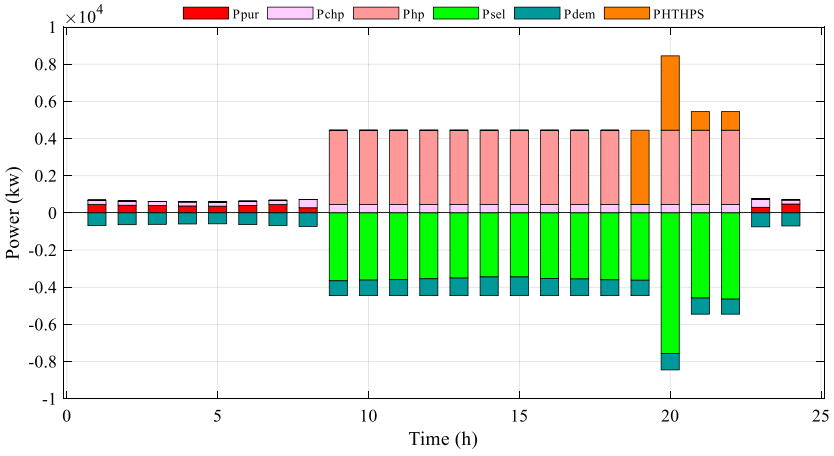


**Fig. 3.** Results obtained for S3-C4 regarding heat energy balance.

## 4. Conclusion

The focus of this paper is on proposing a new structure for an SEH by integrating HTHPS unit as a new technology with the aim of reaching sustainable criteria. Hence, the operation problem of the SEH is modeled as a two-objective optimization problem consisting of the energy hub operation, and the emission pollution costs. Three different scenarios with different renewable energy penetration have been applied to investigate how the proposed system can improve the energy transaction between the energy hub with upstream energy networks. Based on the obtained results for the first scenario, HTHPS unit has decreased the system's daily operation and emission costs by 12.29% and 1.21%, respectively. Moreover, 22.50% and 12.86% decrement on operation cost as well as 19.98% and 19.79% decrement on emission cost have been obtained for the second and third scenarios that it can show HTHPS unit can satisfactorily support the increment of the renewable generation penetration.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mohammad Ali Lasemi reports article publishing charges and travel were provided by Aalborg University. Mohammad Ali Lasemi reports a relationship with Aalborg University that includes: travel reimbursement. The authors declare that they have no more competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

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

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## References

[1] M.A. Lasemi, M. Assili, A. Hajizadeh, Multi-objective hydrothermal generation scheduling and fuel dispatch management considering liquid fuel dispatch network modeling, Electr Power Syst Res 187 (May) (2020) 106436.
[2] V. Davatgaran, M. Saniei, S.S. Mortazavi, Optimal bidding strategy for an energy hub in energy market, Energy 148 (2018) 482–493, http://dx.doi.org/10.1016/j.energy.2018.01.174.
[3] M.A. Lasemi, A. Arabkoohsar, A. Hajizadeh, B. Mohammadi-ivatloo, A comprehensive review on optimization challenges of smart energy hubs under uncertainty factors, Renew Sustain Energy Rev 160 (2022) 112320.
[4] W. Gu, Z. Wang, Z. Wu, Z. Luo, Y. Tang, J. Wang, An online optimal dispatch schedule for CCHP microgrids based on model predictive control, IEEE Trans Smart Grid 8 (5) (2017) 2332–2342.
[5] F. Kholardi, M. Assili, M.A. Lasemi, A. Hajizadeh, Optimal management of energy hub with considering hydrogen network, 2018.
[6] M. Wang, J. Wang, P. Zhao, Y. Dai, Multi-objective optimization of a combined cooling, heating and power system driven by solar energy, Energy Convers Manag 89 (2015) 289–297.
[7] M.A. Lasemi, A. Arabkoohsar, Optimal operating strategy of high-temperature heat and power storage system coupled with a wind farm in energy market, Energy 210 (2020a) 118545.
[8] M.A. Lasemi, A. Arabkoohsar, Participation of high-temperature heat and power storage system coupled with a wind farm in energy market, in: 2020 int. conf. smart energy syst. technol, 2020b, pp. 1–5.
[9] M.A. Lasemi, A. Arabkoohsar, A. Hajizadeh, Stochastic multi-objective scheduling of a wind farm integrated with high-temperature heat and power storage in energy market, Int J Electr Power Energy Syst 132 (May) (2021) 107194.
[10] T. Ma, J. Wu, L. Hao, Energy flow modeling and optimal operation analysis of the micro energy grid based on energy hub, Energy Convers Manag 133 (2017) 292–306.
[11] S. Pazouki, M.R. Haghifam, Optimal planning and scheduling of energy hub in presence of wind, storage and demand response under uncertainty, Int J Electr Power Energy Syst 80 (2016) 219–239.