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Optimal demand management of smart energy hybrid system based on multi-objective optimization problem

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Abstract. This paper presents a multi-objective problem for the energy planning of an energy hybrid system. The problem considers three main objectives: minimizing emission pollution and operation cost on the generation side, addressing consumers' dissatisfaction with the electrical demand, and reducing deviation from optimal levels in the 24 hours ahead to flatten demand profiles. To achieve this, a demand flexibility strategy is implemented, involving the optimal shifting of electrical demand using deferrable loads. The proposed approach utilizes the augmented epsilon-constraint method to identify Pareto solutions for the objectives. Additionally, the TOPSIS decision-making technique is employed to select the optimal solution from the set of Pareto solutions. The effectiveness and robustness of the proposed approach are validated through two case studies. Overall, the paper highlights the importance of considering multiple objectives in the energy scheduling of hybrid systems and demonstrates the effectiveness of the proposed approach in achieving a balance between environmental, economic, and consumer satisfaction goals. The use of demand flexibility strategies and multi-objective optimization techniques can significantly improve the operation of energy systems, paving the way for more efficient energy management practices. The implementation of demand-side management has resulted in a significant reduction of 2.8% and 64.9% in the first and second objectives, respectively, compared to the absence of such management.

Keywords: Consumers' dissatisfaction, Demand profiles, Deferrable loads, Pareto solutions, Multiple objectives.

Nomenclature

Sets and indices

t, T	Time (hour)
de, DE	Diesel engine unit
chp, CHP	Combined heat and power unit

Parameters

a, b, c	Emission coefficients of generation side
D_{E}	Electrical demand
D_{Th}	Thermal demand
D_{G}	Gas demand
$\pi_{\mathrm{p}}^{\mathrm{gas}}$	Price of gas in main energy grids
π_{p}^{E}	Price of electricity in main energy grids
$\pi_{\mathrm{p}}^{\mathrm{Th}}$	Price of thermal in main energy grids
$\pi_{\mathrm{chp}}^{\mathrm{PT}}$	Ratio of the power to thermal in CHP unit
Φ_{E}	Value of the demand shifted
$D_{\mathrm{E}}^{\mathrm{OP}}$	Optimal electrical demand

Variables

f_1, f_2, f_3	Objective functions
C_{chp}	CHP units' operation cost

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C_{de}	Diesel engine units' operation cost
C_{E}	Electrical operation cost in main energy grids
C_{T}	Thermal operation cost in main energy grids
C_{G}	Gas operation cost in main energy grids
E_{chp}	Emission of CHP
E_{de}	Emission of diesel engine
E_{E}	Emission of electrical grid
E_{T}	Emission of thermal grid
E_{G}	Emission of gas grid
P_{chp}	CHP units' power
P_{de}	Diesel engine units' power
P_{E}	Power generation of electrical grid
T_{Th}	Thermal generation of thermal grid
G_{G}	Gas generation of gas grid
$D_{\mathrm{E}}^{\mathrm{ens}}$	Electrical not supplied in demand side
u_{ens}	States of electrical not supplied (Binary variable)

1 Introduction

1.1 Aims and related works

Energy systems are a cutting-edge solution that combines multiple energy sources, such as renewable energy and traditional fossil fuels, to meet the growing electricity demand [1]. Extensive research has been conducted to optimize these systems, taking into account various factors such as cost, environmental impact, and technical limitations [2]. One of the main goals of energy hybrid systems is to supply energy consumers efficiently [3]. By utilizing a combination of energy sources, these systems can ensure a stable and reliable energy supply, even during peak demand periods [4, 5]. This helps to reduce the risk of blackouts and ensures that consumers have access to electricity when they need it most. In addition to improving efficiency, energy hybrid systems also aim to reduce operational costs [6, 7]. By integrating renewable energy sources, operators can take advantage of free and abundant resources, reducing the reliance on expensive fossil fuels [8]. This not only helps to lower energy costs for consumers but also contributes to a more sustainable and environmentally friendly energy sector [9]. Speaking of the environment, minimizing emission pollution is another crucial aspect of energy hybrid systems [10, 11]. By incorporating renewable energy sources, which produce little to no greenhouse gas emissions, these systems can significantly reduce the carbon footprint associated with electricity generation [12]. This is particularly important in the fight against climate change and the transition to a low-carbon economy [13]. Consumer behavior also plays a significant role in the development and optimization of energy hybrid systems [14]. Smart grid technology, which utilizes communication links, allows for the optimization of load profiles and encourages consumer participation in energy management [15, 16]. Through Demand Side Management (DSM) models, consumers can actively contribute to flattening demand curves, managing their energy consumption during peak times, and even influencing generation side management [17, 18]. This not only gives consumers greater control over their energy usage but also provides energy operators with valuable insights and tools to better manage the overall energy system [19]. The energy hybrid systems are a promising solution to address the economic, environmental, and reliability needs of the energy sector [20]. Through extensive research and the integration of smart grid technology, these systems can optimize energy sources, reduce operational costs, minimize emission pollution, and encourage consumer participation in energy management [21]. By doing so, energy hybrid systems are at the forefront of the transition towards a more sustainable and efficient energy future [22–24]. The modifications in the load profile directly influence the most efficient allocation of energy, thereby increasing the adaptability of the system by minimizing the expenses associated with generation, decreasing emissions, and enhancing dependability [25, 26].

Many research investigations have explored different aspects of hybrid energy systems, including scheduling, management, operation, planning, and design. One study [27] specifically delves into the short-term optimal scheduling of a hybrid energy system with a consideration for risk constraints. Another study [28] presents an optimal energy management strategy for micro-scale energy hybrids. This approach considers factors such as resource availability, prices, and demand, and utilizes an iterative algorithm to reduce the cost. The investigation of the scheduling problem in the energy hybrid system, based on multi-step modeling and the DSM through the multiplication approaches is explored in [29]. Chang *et al.* [30] focus on the operation of the energy system via utilizing probabilistic optimization techniques, to maximize the energy hybrid system profit. Lee *et al.* [31] present a scheduling strategy for the energy hybrid system, considering conditional value-at-risk and emphasizing DSM modeling to effectively reduce generation costs. To enhance the security of load supply, a new method for energy management has been presented in [32]. This proposal involves the conversion of power to gas technology. Additionally, Adefarati *et al.* [33] explore the energy flow for the reduction of total energy costs in an energy hybrid system. The investigation of an optimization model for an energy hybrid system that takes into account the peak clipping of thermal as well as cost reduction is presented in [34]. The evaluation of the energy flow in the energy networks of the energy hybrid systems is conducted through load flow analysis to achieve optimal energy hybrid systems, as discussed in [35]. Furthermore, Kilic *et al.* [36] propose a scheduling model for the energy hybrid system that considers the optimization of uncertainties in sources to minimize system investment costs. The multi-methods for energy operation based on quintessential schemes for demand side and aggregation with load forecasts are presented in [37]. The exploration of maximizing expected benefits in an energy hybrid system, considering energy market prices and uncertainties in wind generation, is investigated in [38] through the analysis of stochastic optimization. In [39] a study of stochastic framework in the energy hybrid system with risk modeling approaches is done. Pattnaik *et al.* [40] propose a short-term scheduling framework for an energy hybrid system based on energy pricing by information gap decision theory. Dong *et al.* [41] examine the configuration of an energy hybrid system to obtain resource sizing while considering the uncertainty of energy sources by the Benders algorithm. In [42] a multi-objective problem is evaluated by considering energy efficiency, and economic factors to optimize the system operation.

1.2 Research gaps and contributions

Despite the extensive research conducted in the literature on energy optimization, there are still several research gaps including a lack of consideration of the environment index, demand management in objective functions, demand shifting modeling on the consumption side, and consumers' dissatisfaction in the mentioned research. This paper presents an innovative approach to tackle the energy scheduling problem of an energy hybrid system. By formulating it as a multi-objective problem, the paper aims to address the gaps in the current understanding. The objectives of this problem formulation are twofold: firstly, to minimize emission pollution and operation cost on the generation side, and secondly, to minimize consumers' dissatisfaction in the electrical demand side. Additionally, a third objective is introduced, which focuses on minimizing the deviation between the electrical demands and their optimal levels by utilizing electrical deferrable loads. To effectively find the non-dominated Pareto solutions and select the best solution for these objectives, the paper proposes the augmented epsilon-constraint approach and the TOPSIS decision-making method.

2 Energy hybrid system overview

This part provides an outline of the energy hybrid system, showcasing the scheduling issue proposed in Figure 1. The system consists of different essential parts, such as distributed generation units, primary energy grids (like electrical, thermal, and gas), and the energy demand side. These components are linked through communication links with the energy system operator, allowing for coordination between the generation and demand sides. For example, the operator can inform the demand side about energy pricing, enabling them to react accordingly to the current situation. The energy hybrid system comprises distributed generation units that encompass both electrical and thermal generation units. This includes combined heat and power (CHP) systems as well as diesel engines. These units are powered by fossil fuels, such as gas, to generate energy. The primary energy grids consist of thermal, electrical, and gas grids. These grids actively participate in energy markets, taking into account real-time pricing. On the other hand, the energy demand sides are comprised of end-users or consumers who consume energies like gas, thermal, and electrical.

3 Energy hybrid system modeling

The detailed description of the multi-objective problem in this section models the optimal scheduling of the energy hybrid system.

3.1 First objective

The primary objective is to reduce the operational costs and the environmental impact of emissions on the generation side, which is represented by the following model:

$$\min f_1 = \left(\sum_{t=1}^{T}\left(\sum_{chp=1}^{CHP} C_{\mathrm{chp}}(t, chp) + \sum_{de=1}^{DE} C_{\mathrm{de}}(t, de)\right.\right.$$
$$\left. + C_{\mathrm{E}}(t, de) + C_{\mathrm{T}}(t) + C_{\mathrm{G}}(t)\right)$$
$$+ \sum_{t=1}^{T}\left(\sum_{chp=1}^{CHP} E_{\mathrm{chp}}(t, chp) + \sum_{de=1}^{DE} E_{\mathrm{de}}(t, de) + E_{\mathrm{E}}(t, de)\right.$$
$$\left.\left. + E_{\mathrm{T}}(t) + E_{\mathrm{G}}(t)\right)\right) \tag{1}$$

where

$$C_{\mathrm{chp}}(t, chp) = \{\pi_{\mathrm{p}}^{\mathrm{gas}} \times P_{\mathrm{chp}}(t, chp)\} \quad \forall t,\ chp \tag{2}$$

$$C_{\mathrm{de}}(t, de) = \{\pi_{\mathrm{p}}^{\mathrm{gas}} \times P_{\mathrm{de}}(t, de)\} \quad \forall t,\ de \tag{3}$$

$$C_{\mathrm{E}}(t) = \{\pi_{\mathrm{p}}^{\mathrm{E}} \times P_{\mathrm{E}}(t)\} \quad \forall t \tag{4}$$

$$C_{\mathrm{T}}(t) = \{\pi_{\mathrm{p}}^{\mathrm{Th}} \times T_{\mathrm{Th}}(t)\} \quad \forall t \tag{5}$$

$$C_{\mathrm{G}}(t) = \{\pi_{\mathrm{p}}^{\mathrm{gas}} \times G_{\mathrm{G}}(t)\} \quad \forall t \tag{6}$$

$$E_{\mathrm{chp}}(t, chp) = \{aP_{\mathrm{chp}}^{2}(t, chp) + bP_{\mathrm{chp}}(t, chp) + c\} \quad \forall t,\ chp \tag{7}$$

$$E_{\mathrm{de}}(t, de) = \{aP_{de}^{2}(t, de) + bP_{\mathrm{de}}(t, de) + \mathrm{c}\} \quad \forall t,\ de \tag{8}$$

$$E_{\mathrm{E}}(t) = \{aP_{\mathrm{E}}^{2}(t) + bP_{\mathrm{E}}(t) + c\} \quad \forall t \tag{9}$$

$$E_{\mathrm{T}}(t) = \{aT_{\mathrm{Th}}^{2}(t) + bT_{\mathrm{Th}}(t) + c\} \quad \forall t \tag{10}$$

$$E_{\mathrm{G}}(t) = \{aG_{\mathrm{G}}^{2}(t) + bG_{\mathrm{G}}(t) + c\} \quad \forall t. \tag{11}$$

Equations (2)–(6) are operation costs of the CHP, diesel engine, electrical, thermal, and gas in main energy grids, respectively. On the other hand, equations (7)–(11) are emissions of the CHP, diesel engine, electrical, thermal, and gas in main energy grids, respectively.

3.2 Second objective

In the second objective, the focus is on minimizing the consumers' dissatisfaction, specifically addressing the insufficiency of electrical power generation to meet the demand or energy not supplied on the electrical demand side. The second objective is modeled as follows:

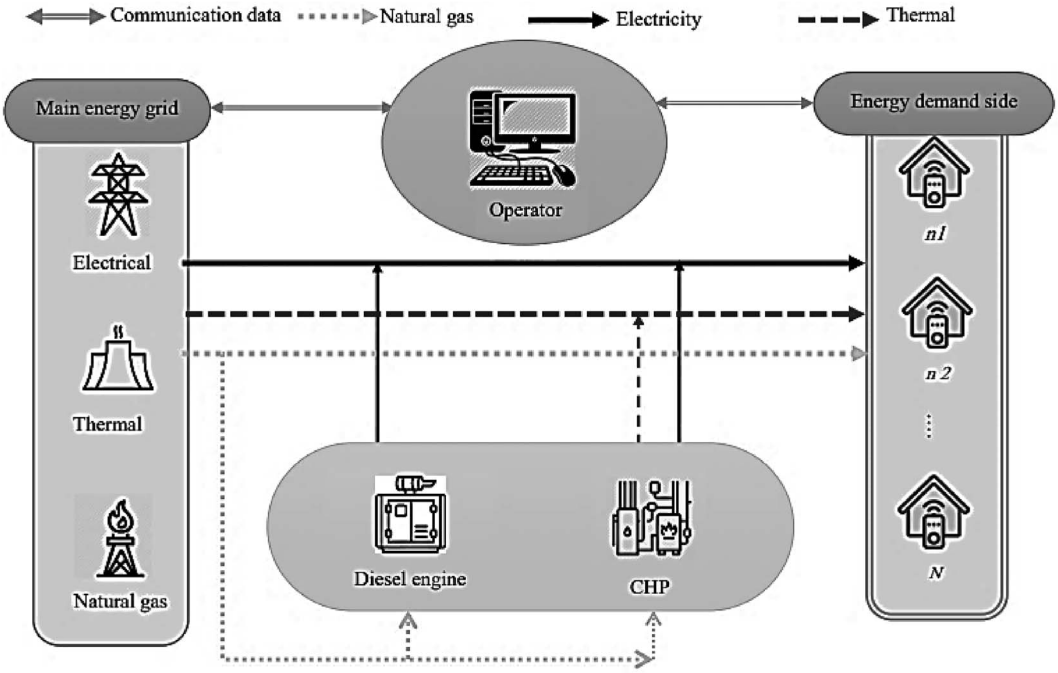

Fig. 1. Energy hybrid system overview.

$$\min f_2\left\{\left(\frac{\sum_{t=1}^{T} D_{\mathrm{E}}^{\mathrm{ens}}(t)}{\sum_{t=1}^{T} D_{\mathrm{E}}(t)}\right)\right\} \tag{11}$$

where

$$0 \leq D_{\mathrm{E}}^{\mathrm{ens}}(t) \leq \left(D_{\mathrm{E}}(t) \times u_{\mathrm{ens}}(t)\right) \quad \forall t \tag{12}$$

$$u_{\mathrm{ens}}(t) = \begin{cases} 1 & D_{\mathrm{E}}(t) > P_{\mathrm{chp}}(t, chp) + P_{\mathrm{de}}(t, de) + P_{\mathrm{E}}(t) \\ 0 & \text{othewise} \end{cases}. \tag{13}$$

Equations (12) and (13) are bound of energy not supplied and the status of the energy not supplied in electrical energy demand, respectively.

3.3 Third objective

The third objective is minimizing the gap between electrical energy demand and optimal demand in the day ahead. This objective is a demand flexibility strategy by an optimal shifting of the electrical demand. The third objective is modeled as follows:

$$\min f_3\left\{\left(\sum_{t=1}^{T} \left|D_{\mathrm{E}}(t) - D_{\mathrm{E}}^{\mathrm{op}}\right|\right)\right\} \tag{14}$$

where

$$D_{\mathrm{E}}(t) = \sum_{t'} D_{\mathrm{E}}(t', t) - \sum_{t'} D_{\mathrm{E}}(t, t') \quad \forall t \tag{15}$$

$$0 \leq \sum_{t'} D_E(t, t') \leq \Phi_{\mathrm{E}} \times \sum_{t=1}^{T} D_E(t) \quad \forall t \tag{16}$$

$$D_{\mathrm{E}}^{\mathrm{op}} = \frac{\sum_{t}^{T} D_E}{T} \quad \forall t. \tag{17}$$

The optimized electrical demand is obtained by equation (15). Equation (16) is the value of the demand shifted by consumers. The optimal electrical demand in the day-ahead is modeled by equation (17).

4 Modeling constraints in energy hybrid system

The energy hybrid system employs various constraints to address the proposed multi-objective optimization problem. These constraints are outlined below:

4.1 Constraint of the energy supply balance

The hybrid energy demands such as thermal, gas, and electrical should be supplied by the generation side each time. Hence, electrical, thermal, and gas energy supply balances are constrained by equations (18)–(20), respectively.

$$\sum_{chp=1}^{CHP} P_{\mathrm{chp}}(t, chp) + \sum_{de=1}^{DE} P_{\mathrm{de}}(t, de) + P_{\mathrm{E}}(t) = D_{\mathrm{E}}(t) - D_{\mathrm{E}}^{\mathrm{ens}}(t) \quad \forall t \tag{18}$$

$$\sum_{chp=1}^{CHP} \left[P_{\mathrm{chp}}(t, chp) \times \kappa_{\mathrm{chp}}^{\mathrm{PT}}\right] + T_{\mathrm{Th}}(t) = D_{\mathrm{Th}}(t) \quad \forall t \tag{19}$$

$$G_{\mathrm{G}}(t) - \sum_{chp=1}^{CHP} P_{\mathrm{chp}}(t, chp) - \sum_{de=1}^{DE} P_{\mathrm{de}}(t, de) = D_{\mathrm{G}}(t) \quad \forall t \tag{20}$$

4.2 Constraint of energy supply bound

The energy productions on the generation side have minimum and maximum bounds in the operation state. Hence, constraints of the energy supply bound on the generation side are modeled as follows:

$$P_{\mathrm{chp}}^{\min} \leq P_{\mathrm{chp}}(t, chp) \leq P_{\mathrm{chp}}^{\max} \quad \forall t, chp \tag{21}$$

$$P_{\mathrm{de}}^{\min} \leq P_{\mathrm{de}}(t, de) \leq P_{\mathrm{de}}^{\max} \quad \forall t, de \tag{22}$$

$$T_{\mathrm{Th}}^{\min} \leq T_{\mathrm{Th}}(t) \leq T_{\mathrm{Th}}^{\max} \quad \forall t \tag{23}$$

$$P_{\mathrm{E}}^{\min} \leq P_{\mathrm{E}}(t) \leq P_{\mathrm{E}}^{\max} \quad \forall t \tag{24}$$

$$G_{\mathrm{G}}^{\min} \leq G_{\mathrm{G}}(t) \leq G_{\mathrm{G}}^{\max} \quad \forall t. \tag{25}$$

The constraints (21)–(25) are energy supply bounds of the CHPs, diesel engines, thermal main grid, electrical main grid, and gas main grid, respectively.

5 Problem-solving method

In order to optimize multiple objective functions simultaneously, a common approach is to create a diverse set of solutions that are not dominated by any other solution (known as the Pareto front). These solutions must adhere to both equality and inequality constraints. However, because of conflicting objectives, it is crucial for the decision maker to carefully assess their performance relative to each other. This study explores the use of the augmented epsilon-constraint method on the Pareto front. The mathematical framework for this method is detailed in the following section [43]:

$$\min \left[f_1(x) - \delta \sum_{n=1}^{N} \frac{s_n}{r_n} \right] \quad 10^{-6} \leq \delta \leq 10^{-3} \tag{26}$$

Subject to:

$$f_n(x) + s_n - \varepsilon_n^z \quad n = 2, 3, \ldots, N; s_n \in R^+$$

where

$$\varepsilon_n^z = f_n^{\max} - \left[\frac{f_n^{\max} - f_n^{\min}}{q_n - 1} \right] \times z \quad z = 0, 1, \ldots, q_n \tag{27}$$

where

x is decision variable.
δ is slack variable.
n is nth objective.
s_n is real number.
ε_n^z is interval of nth objective.
r_n is objectives range.
q_n is equal range zth range.

5.1 Decision-making method

Within this specific section, the operator utilizes the TOPSIS method as a decision-making tool. It is crucial to select the optimal solution from the non-dominated objectives obtained through the augmented epsilon-constraint approach. The TOPSIS technique is carefully applied to address the differences between non-dominated solutions and alternatives. The modeling of TOPSIS involves a series of defined steps [44]:

1. Create a matrix that includes m solutions as alternatives and n goal (objective). The resulting matrix, referred to as g_{ij}, illustrates the connection between each alternative and objective.
2. Ensure that the values of the g_{ij} matrix are appropriately scaled by normalizing it using equation (28).

$$r_{ij} = \frac{g_{ij}}{\sqrt{\sum_{i=1}^{m} g_{ij}^2}} \quad i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n \quad . \tag{28}$$

3. Computing the normalized matrix involves the utilization of the weight sum approach.

$$V = \left(v_{ij}\right)_{m \times n} = \left(w_i r_{ij}\right)_{m \times n}. \tag{29}$$

Subject to:

$$\sum_{j=1}^{n} w_j = 1. \tag{30}$$

4. Determine the options with the greatest and smallest values using equations (31) and (33) respectively.

$$S^+ = \left[\left(\max v_{ij}\right), \left(\min v_{ij}\right)\right]. \tag{31}$$

Subject to:

$$j \in J^+, j \in J^- \left[v_1^+, v_2^+, \ldots, v_m^+\right] = [i = 1, 2, \ldots, m] \tag{32}$$

$$S^- = \left[\left(\max v_{ij}\right), \left(\min v_{ij}\right)\right]. \tag{33}$$

Subject to:

$$j \in J^-, j \in J^+ \left[v_1^-, v_2^-, \ldots, v_m^-\right] = [i = 1, 2, \ldots, m]. \tag{34}$$

5. Assess the gap between the top S^+ option calculated with equation (35) and the lowest S^- option determined by equation (36).

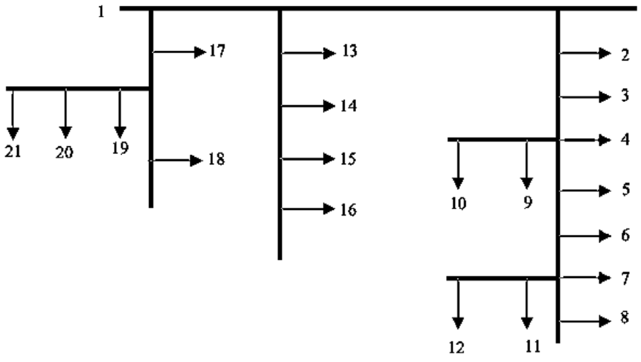

Fig. 2. Energy hybrid test system.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \quad i = 1, 2, \ldots, m \tag{35}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \quad i = 1, 2, \ldots, m. \tag{36}$$

6. Identify the maximum position of the (37) as the optimal solution.

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \quad i = 1, 2, \ldots, m. \tag{37}$$

6 Case studies

The energy optimization problem within the energy hybrid system has been validated through two case studies that involve the demand flexibility strategy of electrical demand shifting by consumers. In this system, there are two diesel engines and two CHP units connected to thermal, electrical, and gas main grids. The power-to-thermal ratio in CHP units is maintained at 60%. The operation of the energy hybrid system is conducted on system test 21-nodes depicted in Figure 2. Moreover, to illustrate the efficiency of the proposed model and its solution approach, case studies are further investigated as follows:

Case A. Operation of the hybrid energy system without demand flexibility strategy.
Case B. Operation of the hybrid energy system with demand flexibility strategy.

The energy prices in primary energy grids like gas, electricity, and thermal are illustrated in Figure 3. The energy consumption of customers is shown in Figure 4. The data of systems such as distributed generation units are extracted from references [45–48]. All consumers participating in the demand flexibility strategy have a maximum participation level of 3% at each node. The execution time for Cases A and B are 456 and 566 seconds, respectively.

6.1 Results and discussion

In this section, each case study's findings are examined and subsequently compared with one another.

Case A

The case study does not include a demand flexibility strategy for the electrical demand side, resulting in the absence of optimal shifting of electrical demand in energy optimization. The first objective focuses on operational costs and the environmental impact of emissions on the generation side, while the second objective addresses consumers' dissatisfaction. By the augmented epsilon-constraint approach, nondominated solutions of the first and second objectives are shown in Figure 5. In the following, the best solution for the first and second objectives is determined by the TOPSIS decision approach in black color. The second and first objectives in the best solution are 0.0115 MW and 286533.3, respectively. Since emission and operation costs are considered in the first objective, the value of the total emission and costs are equal to 176325.4 g and 110207.9$, respectively. The emission of the distributed units, the main grid, the thermal main grid, and gas main grid is equal to 13245.3 g, 62654.5 g, 45645.2 g, and 54780.4g , respectively. Also, the costs of the distributed units, electrical main grid, thermal main grid and the gas main grid are equal to 16543.3$, 33545.6$, 28654.6$, and 31464.4$, respectively. It's clear, that main energy grids such as electrical, gas, and thermal have maximum emission and costs in comparison with distributed generation units, due to high emission pollution factors and high energy prices.

Figures 6 and 7 show energy generation, such as electrical and thermal by main grids and distributed generation units, respectively. In Figure 6, electrical energy generation by the electrical main grid has maximum participation in higher electricity prices in supply demand. Also, energy not supplied is done at hours 18:00 and 19:00, with 1 and 1.41 MW values, respectively. As mentioned before, electrical energy is not supplied due to low generation capacity on the generation side. Also, in Figure 7, most of the thermal demand is supplied by the thermal main grid, and thermal generation by distributed generation units has low participation in meeting demand.

Case B

The demand flexibility strategy in the third objective function for electrical demand is considered in this case study. The solutions of all objectives are presented in Figure 8. The values obtained for the first, second, and third objectives through the TOPSIS decision approach are 278354.5, 0.004, and 315.3 MW, respectively, which are considered the optimal solutions. In Case B, the first and second objectives are minimized by 2.8% and 64.9% in Case A, respectively. The emission and operation costs in the first objective are equal to 176111.2g and 102243.3$, respectively. The operation cost considering the demand flexibility strategy for electrical demand optimization is reduced by 7.2% than Case A. It's clear that; the reduction of the costs is related to the electrical main grid, due to opti-

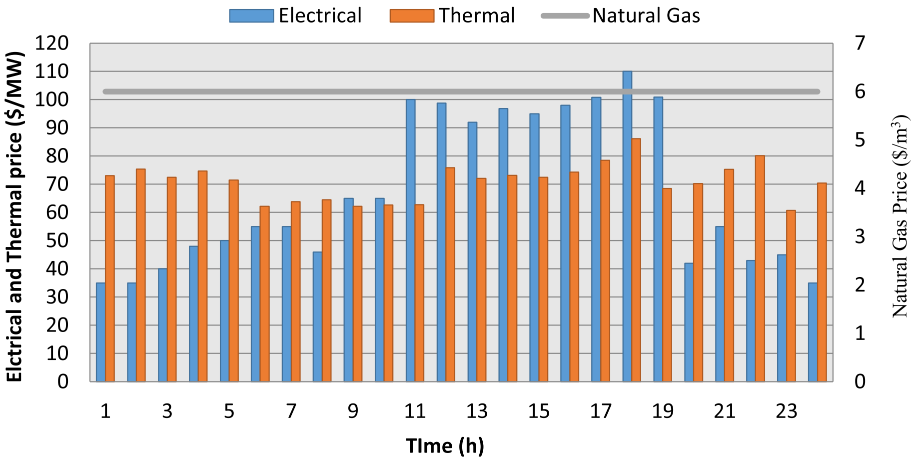

Fig. 3. Energy prices in main energy grid.

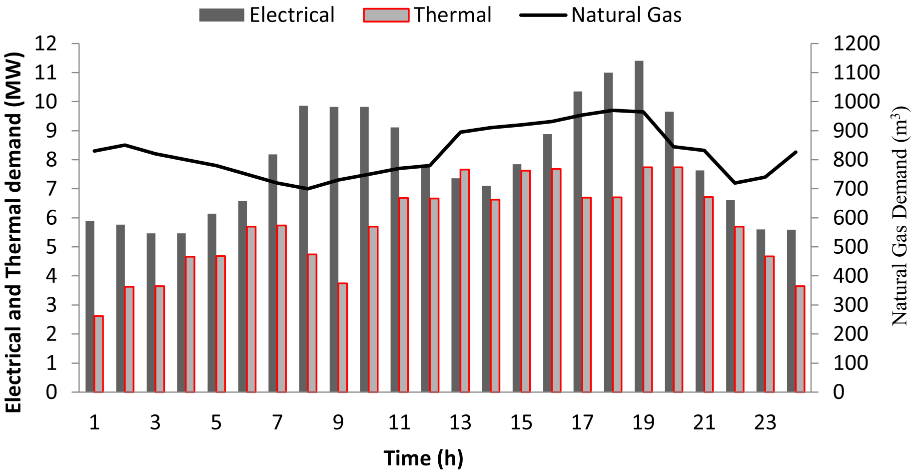

Fig. 4. Energy demand in energy hybrid system.

mal demand shifting from high to low prices by third objective function.

Figures 9 and 10 depict the electrical and thermal energy in Case B. Figure 9 highlights the optimization of electrical demand by employing the third objective function. The demand flexibility strategy involves shifting the electrical demand from high-priced peak hours to lower peaks, resulting in a reduction of energy generation from the main electrical grid at high prices. As a result, the strategy leads to a decrease in the amount of energy not supplied by 1MW when compared to Case A. In the following, thermal generation on the generation side is similar to Case A.

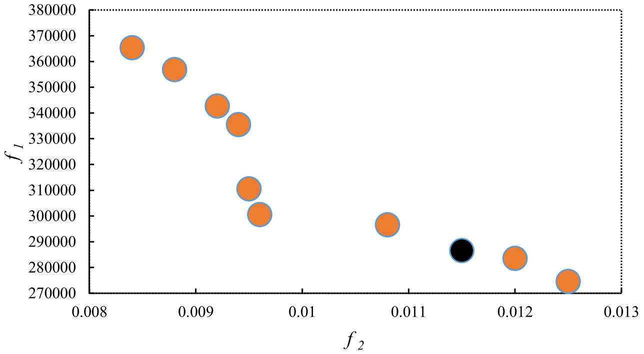

Fig. 5. Non-dominated solutions of the first and second objectives in Case A.

7 Conclusion and future studies

This research delved into the effects of implementing a demand flexibility strategy through optimal energy scheduling in an energy hybrid system using multi-objective optimization. The objective functions were designed to involve both the generation and demand sides in energy scheduling, with goals such as reducing emission pollution and operation costs for the generation side and addressing consumers' dissatisfaction due to electrical energy shortages on the demand side. The study focused on optimizing electrical demand management through day-ahead scheduling,

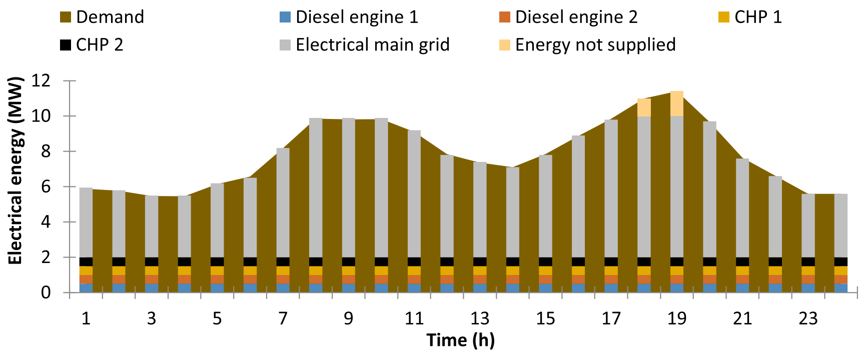

Fig. 6. Electrical energy dispatch in Case A.

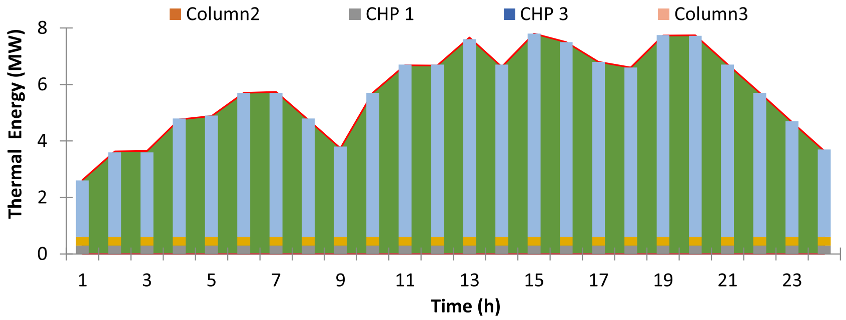

Fig. 7. Thermal energy dispatch in Case A.

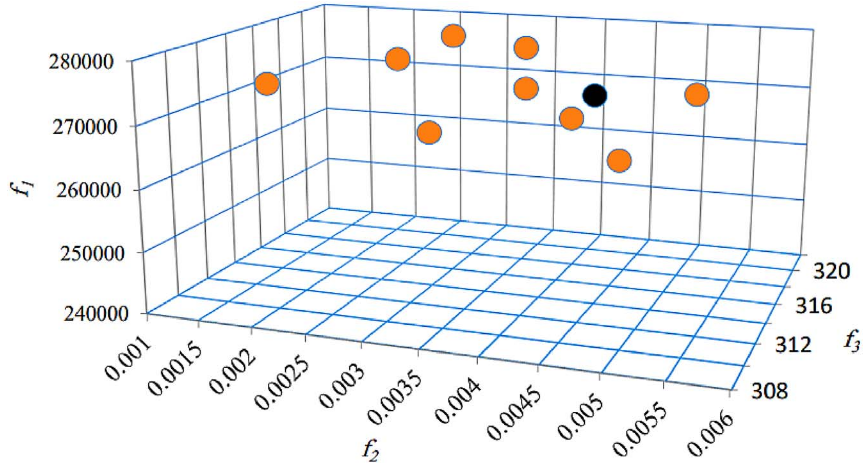

Fig. 8. Non-dominated solutions of all objectives in Case B.

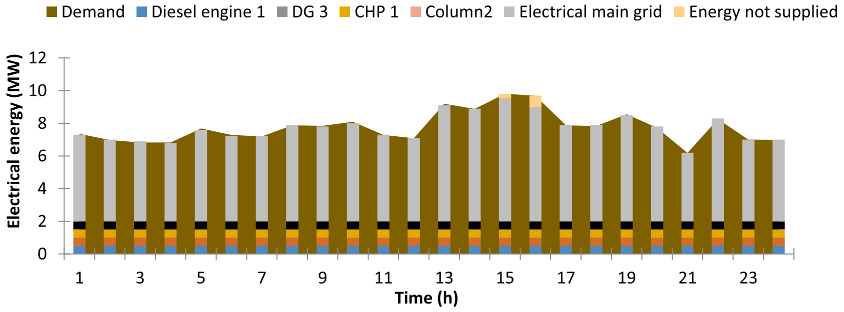

Fig. 9. Electrical energy dispatch in Case B.

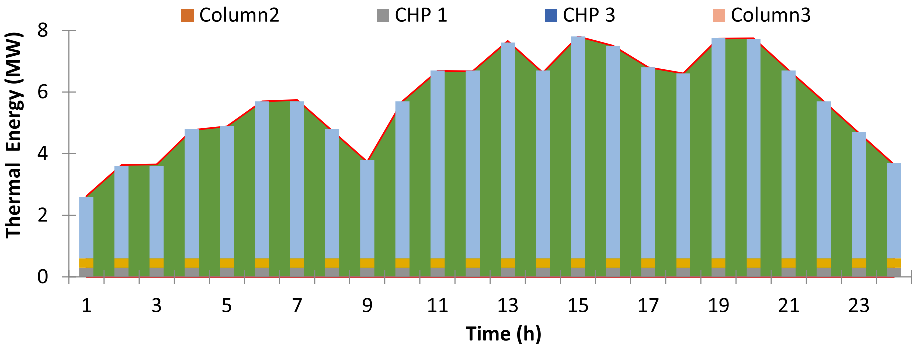

Fig. 10. Thermal energy dispatch in Case B.

utilizing the augmented epsilon-constraint approach and TOPSIS methodology to find the best solutions for multi-objective optimization. Numerical simulations were conducted to validate the proposed modeling, with results from two case studies showing the benefits of implementing the demand flexibility strategy in terms of reducing emission pollution, operation costs, and consumer dissatisfaction.

To expand this study, we can incorporate innovative approaches, different metrics for evaluation, and a wide range of energy systems, such as independent and interconnected modes in the energy markets. Additionally, it is crucial to consider uncertain strategies for both energy demand and generation.

References

1 Kadhim A.A., AL-Jumaili A.M., Hussain K. (2023) Converter for voltage source HVDC links: current status and future challenges, *Edison J. Electr. Electron. Eng.* **1**, 17–23.

2 Hussan B.K., Rashid Z.N., Zeebaree S.R., Zebari R.R. (2023) Optimal deep belief network enabled vulnerability detection on smart environment, *J. Smart IoT* **2023**, 1, 146–162.

3 Al Jasimee K.H., Blanco-Encomienda F.J. (2024) Decoding task uncertainty: moderating effects on participative budgeting and budgetary slack dynamics, *Total Quality Manage. Business Excell.* **35**, 1–9. https://doi.org/10.1080/14783363.2024.2332897.

4 Han L., Yu H.-H. (2023) An empirical study from Chinese energy firms on the relationship between executive compensation and corporate performance, *Nurture* **17**, 3, 378–393. https://doi.org/10.55951/nurture.v17i3.356.

5 Makki M., Mawad J.L., Khalili M. (2023) Impact of oil rents, oil prices, and investment taxes on renewable energy consumption and investment: an investigation, *Int. J. Manage. Sustain.* **12**, 3, 435–447. https://doi.org/10.18488/11.v12i3.3476.

6 Cruz K.P.C.-D., Tolentino L.K.S. (2023) Unlocking the market potential of electric vehicles in the Philippines: a statistical and neural network approach to customer willingness to purchase electric vehicles, *Int. J. Inno. Res. Sci. Stud.* **6**, 4, 888–902. https://doi.org/10.53894/ijirss.v6i4.2088.

7 Li P., Zahedi E., Shi Y., Deng Y., Liu L. (2024) Dynamically tuning and reconfiguring microwave bandpass filters using optical control of switching elements, *Microwave Opt. Tech. Lett.* **66**, 2, e34082.

8 Mozafarjazi M., Rabiee R. (2024) Experimental and numerical study on the load-bearing capacity, ductility and energy absorption of RC shear walls with opening containing zeolite and silica fume, *Eng. Solid Mech.* **12**, 3, 237–246.

9 Keivanimehr M., Chamorro H.R., Zareian-Jahromi M., Segundo-Sevilla F.R., Guerrero J.M., Konstantinou C. (2021) Load shedding frequency management of microgrids using hierarchical fuzzy control, in: *2021 World Automation Congress (WAC)*, Taipei, Taiwan, 01–05 August, IEEE, pp. 216–221.

10 Jahromi M.H.M., Tafti H.D., Hosseini S.M., Jalali A., Keivanimehr M. (2020) Maximum power point tracking of a network-connected photovoltaic system based on gravity search algorithm and fuzzy logic controller, *J. Solar Energy Res. Updates* **7**, 52–63.

11 Rostam-Alilou A.A., Zhang C., Salboukh F., Gunes O. (2022) Potential use of Bayesian Networks for estimating relationship among rotational dynamics of floating offshore wind turbine tower in extreme environmental conditions, *Ocean Eng.* **244**, 110230.

12 Rouhi K., Motlagh M.S., Dalir F., Perez J., Golzary A. (2024) Towards sustainable electricity generation: evaluating carbon footprint in waste-to-energy plants for environmental mitigation in Iran, *Energy Rep.* **11**, 2623–2632.

13 Hajrasouliha A., Ghahfarokhi B.S. (2021) Dynamic geo-based resource selection in LTE-V2V communications using vehicle trajectory prediction, *Comput. Commun.* **177**, 239–254.

14 Esmaili A., Oshanreh M.M., Naderian S., MacKenzie D., Chen C. (2024) Assessing the spatial distributions of public electric vehicle charging stations with emphasis on equity considerations in King County, Washington, *Sustain. Cities Soc.* 107, 105409. https://doi.org/10.1016/j.scs.2024.105409.

15 Hosseini M., Mohammadi V., Jafari F., Bamdad E. (2017) RoboCup 2016 Best Humanoid Award Winner Team Baset Adult-Size, in: Behnke S., Sheh R., Sarıel S., Lee D. (eds), *RoboCup 2016: Robot World Cup XX. RoboCup 2016*, vol. **9776**, Lecture Notes in Computer Science, Springer, Cham, pp. 467–477. https://doi.org/10.1007/978-3-319-68792-6_39.

16 Wang S., Huang X., Liu P., Zhang M., Biljecki F., Hu T., Fu X., Liu L., Liu X., Wang R., Huang Y., Yan J., Jiang J., Chukwu M., Naghedi R., Hemmati M., Shao Y., Jia N., Xiao Z., Bao S. (2024) Mapping the landscape and roadmap of geospatial artificial intelligence (GeoAI) in quantitative human geography: an extensive systematic review, *Int. J. Appl. Earth Obser. Geoinform.* **128**, 103734. https://doi.org/10.1016/j.jag.2024.103734.

17 Hemmati M., Messadi T., Gu H., Seddelmeyer J., Hemmati M. (2024) Comparison of embodied carbon footprint of a mass timber building structure with a steel equivalent, *Buildings* **14**, 5, 1276. https://doi.org/10.3390/buildings14051276.

18 Serajian S., Shamsabadi A.A., Gnani Peer Mohamed S.I., Nejati S., Bavarian M. (2024) MXenes in solid-state batteries: current status and outlook, *J. Power Sources* **610**, 234721. https://doi.org/10.1016/j.jpowsour.2024.234721.

19 Ghorbani M., Wang H., Roberts N. (2024) Analytical and numerical modeling of phase change material and hybrid PCM-heat sinks for high-power wireless EV charging, *Int. Commun. Heat Mass Transfer* **154**, 107460. https://doi.org/10.1016/j.icheatmasstransfer.2024.107460.

20 Ghorbani M., Wang H., Roberts N. (2023) Numerical study of thermal management systems using phase change materials integrated with heat sink for wireless super-fast charging stations of EVs in constant heat flux condition, in: *Heat Transfer Summer Conference*, vol. **87165**, American Society of Mechanical Engineers, p. V001T10A005. https://doi.org/10.1115/HT2023-107128.

21 Fathi M., Moghaddam N.M., Jahromi S.N. (2022) A prognostic model for 1-month mortality in the postoperative intensive care unit, *Surg. Today* **52**, 795–803. https://doi.org/10.1007/s00595-021-02391-6.

22 Farrokhi S., Dargie W., Poellabauer C. (2024) Human activity recognition based on wireless electrocardiogram and inertial sensors, *IEEE Sensors J.* **24**, 5, 6490–6499. https://doi.org/10.1109/JSEN.2023.3348661.

23 Kiani S., Salmanpour A., Hamzeh M., Kebriaei H. (2024) Learning robust model predictive control for voltage control of islanded microgrid, *IEEE Trans. Autom. Sci. Eng.*, 1–12. https://doi.org/10.1109/TASE.2024.3388018.

24 Seifi N., Al-Mamun A. (2024) Optimizing memory access efficiency in CUDA kernel via data layout technique, *J. Comput. Commun.* **12**, 124–139. https://doi.org/10.4236/jcc.2024.125009.

25 Salehi F., Pariafsai F., Dixit M.K. (2024) The impact of different levels of spatial cues on size perception: a spatial perception study of altered conditions, in: Chen J.Y.C., Fragomeni G. (eds), *Virtual, Augmented and Mixed Reality.* HCII 2024, Lecture Notes in Computer Science, vol. **14707**, Springer, Cham, pp. 74–85. https://doi.org/10.1007/978-3-031-61044-8_6.

26 Salehi F., Pariafsai F., Dixit M.K. (2023) How human spatial ability is affected by the misalignment of idiotropic and visual axes, in: Schmorrow D.D., Fidopiastis C.M. (eds), *Augmented Cognition. HCII 2023*, Lecture Notes in Computer Science, vol. **14019**, Springer, Cham. 169–186. https://doi.org/10.1007/978-3-031-35017-7_12.

27 Zhang X., Yu X., Ye X., Pirouzi S. (2023) Economic energy management of networked flexi-renewable energy hubs according to uncertainty modeling by the unscented transformation method, *Energy* **278**, 128054.

28 Ding A., Sun H., Zhang S., Dai X.C., Pan Y., Zhang X., Rahman E., Guo J. (2023) Thermodynamic analysis and parameter optimization of a hybrid system based on SOFC and graphene-collector thermionic energy converter, *Energy Conver. Manage.* **291**, 117327.

29 Ghanjati C., Tnani S. (2023) Optimal sizing and energy management of a stand-alone photovoltaic/pumped storage hydropower/battery hybrid system using genetic algorithm for reducing cost and increasing reliability, *Energy Environ.* **34**, 6, 2186–2203.

30 Chang L., Wu Z., Ghadimi N. (2023) A new biomass-based hybrid energy system integrated with a flue gas condensation process and energy storage option: an effort to mitigate environmental hazards, *Process Safety Environ. Protect.* **177**, 959–975.

31 Lee J., Lin K.Y.A., Jung S., Kwon E.E. (2023) Hybrid renewable energy systems involving thermochemical conversion process for waste-to-energy strategy, *Chem. Eng. J.* **452**, 139218.

32 Cheraghi R., Jahangir M.H. (2023) Multi-objective optimization of a hybrid renewable energy system supplying a residential building using NSGA-II and MOPSO algorithms, *Energy Convers. Manage.* **294**, 117515.

33 Adefarati T., Bansal R.C., Shongwe T., Naidoo R., Bettayeb M., Onaolapo A.K. (2023) Optimal energy management, technical, economic, social, political and environmental benefit analysis of a grid-connected PV/WT/FC hybrid energy system, *Energy Conver, Manage.* **292**, 117390.

34 Li X., Li T., Liu L., Wang Z., Li X., Huang J., Xiong W. (2023) Operation optimization for integrated energy system based on hybrid CSP-CHP considering power-to-gas technology and carbon capture system, *J. Clean. Prod.* **391**, 136119.

35 Almashakbeh A.S., Arfoa A.A., Hrayshat E.S. (2023) Techno-economic evaluation of an off-grid hybrid PV-wind-diesel-battery system with various scenarios of system's renewable energy fraction, *Energy Sources Recovery Util. Environ. Effects* **452**, 6162–6185.

36 Kilic M., Altun A.F. (2023) Dynamic modelling and multi-objective optimization of off-grid hybrid energy systems by using battery or hydrogen storage for different climates, *Int. J. Hydrogen Energy* **48**, 60, 22834–22854.

37 Zhu X., Gui P., Zhang X., Han Z., Li Y. (2023) Multi-objective optimization of a hybrid energy system integrated with solar-wind-PEMFC and energy storage, *J. Energy Stor.* **72**, 108562.

38 Mansouri A., El Magri A., Lajouad R., Giri F., Watil A. (2023) Optimization strategies and nonlinear control for hybrid renewable energy conversion system, *Int. J. Control Autom. Syst.* **21**, 11, 3796–3803.

39 Akarsu B., Genç M.S. (2022) Optimization of electricity and hydrogen production with hybrid renewable energy systems, *Fuel* **324**, 124465.

40 Pattnaik A., Dauda A.K., Panda A. (2023) Optimal utilization of clean energy and its impact on hybrid power systems incorporating STATCOM and pumped hydro storage, *Renew. Sustain. Energy Rev.* **187**, 113713.

41 Dong H., Shan Z., Zhou J., Xu C., Chen W. (2023) Refined modeling and co-optimization of electric-hydrogen-thermal-gas integrated energy system with hybrid energy storage, *Appl. Energy* **351**, 121834.

42 Li J., Chen X., Li G. (2023) Effect of separation wavelength on a novel solar-driven hybrid hydrogen production system (SDHPS) by solar full spectrum energy, *Renew. Energy* **215**, 118969.

43 Chamandoust H., Derakhshan G., Hakimi S.M., Bahramara S. (2019) Tri-objective optimal scheduling of smart energy hub system with schedulable loads, *J. Clean. Prod.* **236**, 117584.

44 Behzadian M., Otaghsara S.K., Yazdani M., Ignatius J. (2012) A state-of the-art survey of TOPSIS applications, *Expert Syst. Appl.* **39**, 17, 13051–13069.

45 Chamandoust H., Hashemi A., Bahramara S. (2021) Energy management of a smart autonomous electrical grid with a

hydrogen storage system, *Int. J. Hydrogen Energy* **46**, 34, 17608–17626.

46 Mohaghegh S., Kondo S., Yemiscioglu G., Muhtaroglu A. (2022) A novel multiplier hardware organization for finite fields defined by all-one polynomials, *IEEE Trans. Circuits Syst. Express Briefs* **69**, 12, 5084–5088. https://doi.org/10.1109/TCSII.2022.3188567.

47 Moradi H.R., Chamandoust H. (2017) Impact of multi-output controller to consider wide area measurement and control system on the power system stability, in: *2017 IEEE 4th International Conference on Knowledge-Based Engineering and Innovation (KBEI),* Tehran, Iran, 22–22 December, IEEE, pp. 280–288.

48 Chamandoust H., Derakhshan G., Hakimi S.M., Bahramara S. (2020) Multi-objectives optimal scheduling in smart energy hub system with electrical and thermal responsive loads, *Environ. Climate Technol.* **24**, 1, 209–232.