The reinvention of an energy hub's planning by considering tidal turbine, bi-facial PV panels, and INVELOX: A unique outlook on the combination performance of novel RERs

Mohammad Shaterabadi[1], Hasan Mehrjerdi[*2], Houshang Karimi[3], Atif Iqbal[1], Mehdi Ahmadi Jirdehi[4]

[1]Department of Electrical Engineering, Qatar University, Doha, Qatar.
[2]Department of Electrical and Computer Engineering, Royal Military College of Canada, Kingston, Ontario, Canada.
[3]Department of Electrical Engineering and Computer Science, York University, Toronto, Ontario, Canada.
[4]Department of Electrical Engineering, Kermanshah University of Technology, Kermanshah, Iran.
Email: hasan.mehrjerdi@rmc-cmr.ca

***Abstract*—New approaches must be taken due to the rapid growth of societies globally and the urgent need for more energy, climate change, and global warming. One of these approaches is supporting and expanding new and efficient renewable energy resources (RERs). Therefore, this paper is dedicated to the energy planning and management of the proposed structure in which novel renewable-based technologies such as INVELOX wind turbines, Bi-facial photovoltaic (PV) panels, and tidal turbines (TT), in addition to the demand response programs (DRP) especially time of use (TOU), are investigated. The purpose is to simultaneously reducing the presented system's overall cost and environmental pollution. The problem is modeled as mixed-integer linear programming (MILP) in GAMS software and solved using a CPLEX solver. The final results show that novel technologies recognized as efficient can significantly reduce contamination, expenses, and greenhouse gas (GHG) emissions while supplying our rapidly growing demand.**

***Index Terms*—Energy management; INVELOX turbines; Photovoltaic systems; Renewable energy sources (RES); Wave energy; Wind energy.**

I. Introduction

A. General survey on the understudy subject

The increasing faith in renewable energy sources' effectiveness and ability to aid nations in reaching their shared objectives has resulted in a heightened focus on their growth and development. In order to harness the benefits of these resources, various solutions have been explored, including microgrids for localized applications and nanogrids for other scenarios, which have been the subject of ongoing discourse in recent times [1, 2]. One of the most versatile and comprehensive solutions for energy supply is the Energy Hub (EH). This system provides a cohesive and adaptable structure that can efficiently convert and store various energy resources to meet consumers' diverse needs, as shown in Figure (1). EH systems' energy planning and management goals include cost and pollution reduction, increased profits, improved network resilience, and integration of green energy resources. Moreover, fuel cells and hydrogen stations are an essential component of this energy planning, garnering increased attention due to the recent advancements in green hydrogen harvesting [3, 4]. The energy hub's planning is a hot topic in which many aspects should be addressed.

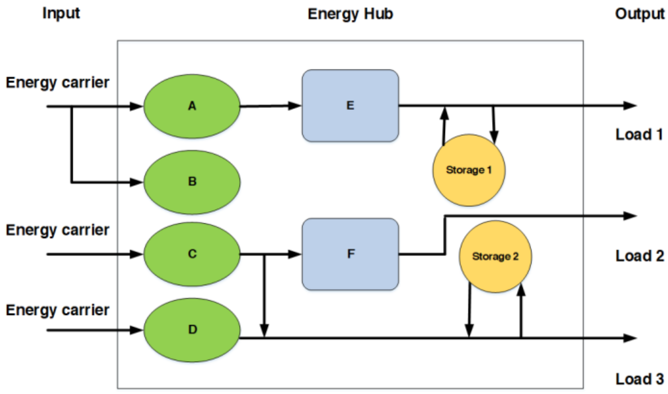

Fig. 1. The overall schematic of the energy hub.

B. Recent research on the understudy issue

Researchers from all over the world have investigated various states and scenarios of EH's planning. For example, Mansouri et al. [5] presented a stochastic model for efficiently planning and operating an energy hub. The primary source of uncertainty in this problem stemmed from the forecast of electric, heating, and cooling load demand and the intermittent output from solar photovoltaic (PV) systems. In order to address these uncertainties, Monte-Carlo simulation (MCS) was utilized to simulate the uncertain parameters, with backward scenario reduction performed to reduce the number of generated scenarios. The study also evaluated the effectiveness of demand response programs (DRP). The research was divided into two stages. In the first stage, particle swarm optimization (PSO) was employed to design the optimal energy hub based on the continuous capacity of the candidate assets. In the second stage, mixed-integer nonlinear programming (MINLP) was utilized to formulate the problem of optimal energy hub operation. In order to validate its effectiveness and efficiency, a typical energy hub was simulated. Outcomes show that utilizing Demand Response Programs (DRPs) can effectively manage electricity consumption during peak hours and shift it to off-peak hours, decreasing costs and capacity requirements for Energy Storage Systems (EES). Furthermore, accounting for uncertainties can enhance the capacity of thermal sources. With the ability to adjust DRPs based on performance, the system can be further optimized. Zadehbagheri et al. [6] proposed an energy planning for the assumed energy hub by considering a tidal turbine as a novel option in addition to demand response programs. The development of the multi-carrier hub involved a comprehensive approach to energy sourcing, utilizing various methods such as PV, tidal turbines, fuel cells, CHP, boilers, micro-turbines, reactors, reformers, and electrolyzers, along with different types of energy storage for both electrical and hydrogen power. Additional inputs included electricity, gas, water, and waste materials. The resulting output was achieved by converting, transmitting, and storing electricity, heat, and hydrogen. The ultimate goal was to minimize overall costs and environmental impact, which was accomplished using the CPLEX solver in the GAMS software. The application of Time-of-Use (TOU) programs resulted in a reduction of 2.72% in pollution, leading to an increase of 9.48% in the hub's total profit. This was achieved by shifting the demand from peak to off-peak hours. In addition, introducing Tidal Stream Turbines (TST) as a reliable way to reduce pollution contributed to a 30% rise in the hub's overall profit and a 9% decrease in overall pollution. The proposed approach has been effective and advantageous in hubs near the ocean, where such cutting-edge technologies have significant investment potential and can benefit. In another research paper, Niazvand et al. [7] investigated energy planning for the assumed hub in which various uncertain parameters such as energy price and renewable energy resources (RERs) output power were considered. Furthermore, carbon capture technology was also exerted as a proper option for utilizing fossil fuel-based units. The energy planning was based on stochastic (more probable) and robust (worst scenario to happen) planning. The Monte-Carlo scenario generation with a decision tree process was used for this purpose. The robust model, which considers the worst-case scenario, resulted in a 1.9% higher cost and a 12.3% increase in pollution compared to the deterministic model. Meanwhile, the stochastic model sees a slight increase in cost but a 3.98% decrease in pollution thanks to the WT surplus generated by the model. By implementing CCUS technology, all planning models can reduce cost and pollution, with a reduction of $775.8 from 10215.2 kg to 1133 kg. The stochastic model further reduces cost and pollution, while the deterministic model achieves the same reduction in both categories. In contrast, the robust model reduces pollution from 11468.7 kg to 1268.5 kg at a higher cost. Despite this, all planning models can achieve a net profit for the EH, with the robust model producing more abundant emissions. It is important to note that the objective function's priority heavily influences the final results of the proposed hub. Despite this, all planning models can utilize CCUS technology effectively to improve the condition of the EH. Several papers have addressed the demand response issues by considering RERs in their construction, such as [8, 9]. Many other papers evaluate the reliability and resiliency of this type of network [10, 11]; the CO2 emission and sharing energy are other issues that have been assessed in [12, 13]; the regulation of the voltage has been another subject which has been under study in [14, 15]; however, there is a vast field of study that need a deeper consideration for further research projects. Therefore, in this article, the most important research gaps are covered. The next section is dedicated to this subject and explains the recent paper's main novelties and key points.

C. The vital hypothesis behind the subject

Based on what has been said and according to recent research, there are gaps in managing the combination of novel renewable technologies and the effect of demand response programs on them. Therefore, this paper presents an energy planning and management of the proposed energy hub in which various renewable and non-renewable energy resources are involved. CHP, boiler, micro-turbine (MT), bi-facial photovoltaic panels (BPV), INVELOX wind turbine (IWT), tidal turbines (TT), fuel cells, reformer, and hydrogen, electrical, and thermal energy storages are assumed and take part in the scheduling. By utilizing the manufacturer's company information, the characteristics of the tidal turbine are explored to make the results more realistic. The time of use (TOU) program is performed to assess this effect on the proposed planning. The proposed study's objective functions are considered total cost and contamination of the structure. The problem is modeled as MILP and solved using the Epsilon constraint method and CPLEX solver in GAMS software.

D. Paper's organizations

The rest of the paper is organized as follows: the renewable-based units mentioned before are explained in Section 2. Furthermore, the most critical constraints and equations which affect the planning are introduced in this section. Section 3 expresses the solving approach and understudy test system characteristics and parameters. Sections 4 and 5 bring numerical results and conclusion, respectively.

II. Novel Renewable-based unit modeling and constraints

A. INVELOX wind turbine (IWT)

The Invelox definition consists of two words, including increase and velocity. In summary, this refers to the system that can increase the wind speed by using a tunnel that works with the Venturi principle. This kind of turbine consists of various sections where the wind enters the structure and uses a funnel-shaped tunnel to the Venturi section, where generators are located. After that, the wind backs to the environment using a diffuser section. This system can harness wind power up to 6 times more than conventional wind turbines [16]. This technology's principle and general diagram, in addition to its modeling equations, are elaborated in Figure (2) and Eq. (1).

Fig. 2. The general shape of the INVELOX technology.

$$P_{IWT}(t)=\begin{pmatrix} 0 & \forall t: V^{Cut-in-IWT} \geq V_t \ and \ V^{Cut-out-IWT} \leq V_t \\ 0.5 \cdot \rho_{IWT} \times A_{IWT} \times \eta^{IWT} \times K_p \times (V_t \times S_R)^3 & \forall t: V^{Cut-in-IWT} \leq V_t \leq V^{Cut-out-IWT} \end{pmatrix} \tag{1}$$

B. Bi-Facial PV panels (BPV)

In the ever-evolving world of renewable energy, pursuing more efficient and sustainable power sources has led to innovations like bi-facial PV panels. These revolutionary panels are reshaping the solar industry, offering a unique approach to harnessing sunlight. Bi-facial PV panels, or photovoltaic panels, are a sophisticated evolution of traditional solar panels. Unlike their conventional counterparts, which capture sunlight on a single side, bi-facial panels can collect energy from both sides. This innovative design enables them to utilize direct sunlight from above and reflected light from the ground, resulting in increased energy production. Eq. (2) and (3) are expressed as the temperature of the cell, and after that by using Eqs. (3) and (4), the output power of the common PV panels and Bi-facial PV panels are calculated.

$$T_j(t)=T_{amp}+\frac{G_T(t)}{G_{T_{STC}}}\times(NOCT-20) \tag{2}$$

All other elements modeling, including reformer, electrolyzer, H_2 tank, demand response programs, Electrical and thermal storage, and fuel cell, are explicated and brought in [6, 17].

$$P_{PV}(t)=\left(\begin{array}{l}\left[P_{PV,STC}\times\frac{G_T(t)}{G_{T_{STC}}}\times(1-\gamma\times(T_j(t)-T_{jstc}))\right]\times \\ N_{PV_S}\times N_{PV_P}\end{array}\right) \tag{3}$$

$$P_{BPV}(t)=P_{PV}(t)+\left(C\times P_{PV}(t)\right) \tag{4}$$

C. Tidal turbine (TT)

Tidal energy is emerging as a promising renewable power source, and at the forefront of this innovation are tidal turbines. Harnessing the relentless power of the tides, these underwater devices have the potential to provide clean and sustainable energy. Tidal turbines operate on the principle of converting the kinetic energy of moving water into electrical power. These turbines are submerged in areas with strong tidal currents, much like how wind turbines harness the wind's energy. As the tides ebb and flow, water flows over the turbines' blades, causing them to rotate. This rotation powers generators, producing electricity. The output power of the tidal turbine is computed using Eq. (5).

$$P_{TST}=\begin{cases}0 & 0\leq V_t\leq V_{cutin} \\ \frac{1}{2}.C_p.\rho.A V_t^3 & V_{cutin}\leq V_t\leq V_{Rated} \\ P_{Rated} & V_{rated}\leq V_t\end{cases} \tag{5}$$

D. The most critical constraints and objective functions

Various constraints and objective functions should be considered based on the operator's planning purposes. Here, the most critical objective functions and constraints are introduced.

$$\mathrm{C_{overall\ Cost}}(t)=\left(\begin{array}{l}\mathrm{C_{TST}+C_{Bi\text{-}PV}+C_{IWT}+C_{Buy}-C_{Sell}+C_{ES}+} \\ \mathrm{C_{Boiler}+C_{CHP}+C_{MT}+C_{Ele}+C_{FC}+C_{Rf}\text{-}R_{H2}}\end{array}\right) \tag{6}$$

$$E_{Emission}(kg/Day)=\sum_{t=1}^{T}(Em_{MT}+Em_{CHP}+Em_{Boiler}+Em_{main}) \tag{7}$$

According to the above, Eqs. (7) and (8) exhibit the proposed energy hub's overall cost and environmental pollution, considered objective functions that should be minimized simultaneously. Eqs. (8) - (10) demonstrate the equality constraints related to the thermal, hydrogen, and electrical demands. The following section explains and illustrates the paper's solving approach and optimization manner of the paper brief and the test system's characteristics.

$$T_{ld}(t)=P_{Boiler}(t)+TF_{CHP}*P_{CHP}(t)+P_{FC}^{H,out}(t) \tag{8}$$

$$H_{ld}(t)=P_{Ele}^{out}(t)+P_{H_2,dch}(t)+P_{H_2,ch}(t)-P_{FC}^{in}(t)+P_{H_2}^{Rf}(t) \tag{9}$$

$$E_{ld}(t)=\begin{pmatrix} P_{TST}(t)+P_{IWT}(t)+P_{Bi-PV}(t)+P_{Buy}(t) \\ -P_{Sell}(t)+P_{E,dech}(t)-P_{E,ch}(t)+P_{MT}(t)+P_{CHP}(t) \\ -P_{Ele}^{in}(t)+P_{FC}^{E,out}(t) \end{pmatrix} \tag{10}$$

III. SOLVING MANNER AND TEST SYSTEM CHARACTERISTICS

A. Solving manner and optimizing approach

In the world of optimization and decision-making, engineers, economists, and researchers often encounter complex problems that require finding the best possible solution from multiple conflicting objectives. The Epsilon Constraint Method is a powerful mathematical approach that helps tackle these multifaceted challenges. This article delves into the intricacies of the Epsilon Constraint Method, explaining its purpose, mechanics, applications, and more. The Epsilon Constraint Method, or ECM, is a mathematical optimization technique for solving multi-objective problems. It is employed when decision-makers need to optimize multiple conflicting objectives simultaneously. These objectives can be anything from maximizing profit while minimizing cost to balancing environmental impacts with economic benefits. The Epsilon Constraint Method offers several advantages, such as Flexibility: It can be tailored to different decision-making scenarios. Transparency: Decision-makers can see the trade-offs. Efficiency: It narrows the solution space, making the decision process more manageable.

B. Understudy energy hub

The proposed energy hub comprises various units such as CHP, boiler, MT, PV, Bi-facial PV, IWT, reformer, electrolyzer, electrical, thermal, and hydrogen storage. Figure (3) depicts the proposed EH diagram. The objective functions include total cost and contamination of the presented system, which should be minimized simultaneously. All needed information, including selling and buying prices, fuel price, units' contamination, energy resources characteristics, tie line capacity, amount of storage details, etc., are expressed in [6, 7]. Also, Figure (4) shows the amount of electrical, thermal, and hydrogen demands.

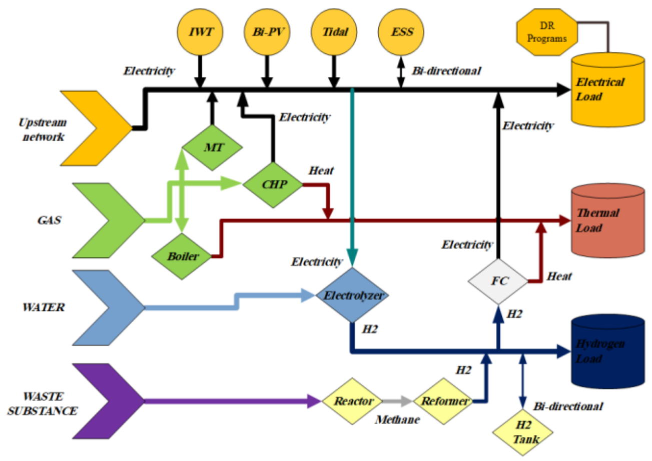

Fig. 3. The overall schematic of the proposed energy hub.

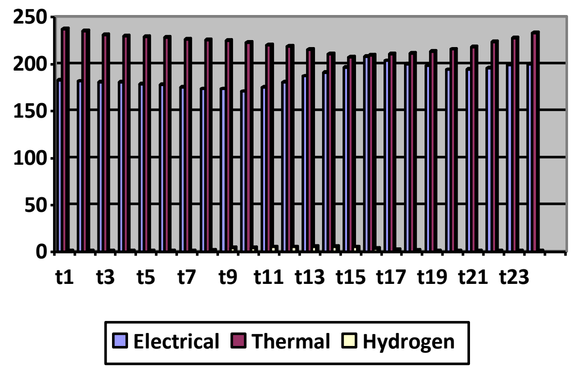

Fig. 4. The amount of various demands during time intervals.

IV. NUMERICAL RESULTS

This section is dedicated to the outcomes of the proposed planning and considering various scenarios, in which the first one is the nominal scenario. The second scenario is where the IWT and Bi-facial PV panels have taken part. In the last scenario, the impact of demand response programs is examined.

A. Scenario without BPV and IWT (First Scene)

This section evaluates the nominal scenario in which none of BPV and IWT have participated in the planning. The exact value of objective functions for total cost and contamination has been calculated and obtained at $745.651 and 4361.865 kg, respectively.

B. Scenario by considering BPV and IWT (Second Scene)

This section assesses the impact of BPV and IWT on the proposed study's objective functions. The total cost and pollution for this scenario have been reached from $745.651 to $442.92 and 4361.865 kg to 4216.009 kg compared to the first scenario. As can be seen, the presence of BPV and IWT has significantly affected the objective functions. The amount of power generated by these types of resources has shown in Figure (5).

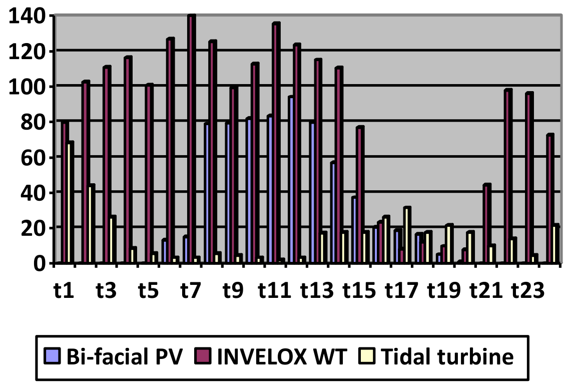

Fig. 5. The output power generated by RERs in 2nd scenario.

C. Scenario by considering BPV and IWT and demand response (Third Scene)

This section evaluates the impact of BPV and IWT plus demand response programs on the objective functions of the proposed study. This scenario's total cost and pollution are $ 512.915 and 4267.147 kg. Compared to the first scenario, it has experienced a reduction in the values. However, it has been growing compared to the second scenario due to changing demands from peak to non-peak hours and the fine and rewards principle. Figure (6) illustrates the load curve before and after implementing DRP. Notably, the amount of DR factor for shifting the loads has been assumed to be 25 %. Furthermore, 5 % of whole demands are supposed to be turned off and assumed as non-critical loads.

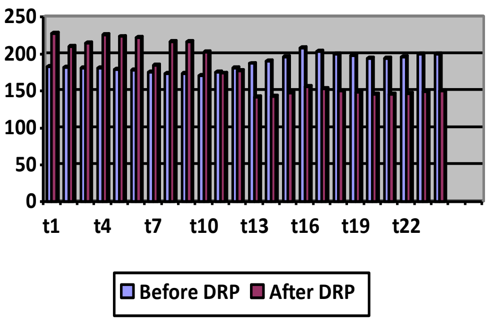

Fig. 6. The load curve before and after DRP.

V. Summary and Conclusion

This paper presents a unique outlook on energy management of the proposed energy hub in which novel renewable-based units, including INVELOX wind turbines, bi-facial PV panels, and tidal turbines, participated. The impact of demand response programs, especially time of use, was evaluated. The problem was modeled as MILP and solved in GAMS software. The final results show that utilizing novel and effective RERs can reduce the cost and pollution of the whole system. In other words, the objective functions were decreased by about 41 % and 4 % for cost and pollution, respectively. In the third scenario and by considering DRP, the objective functions were reduced compared to the first scenario; however, due to the exchangeable demands from peak hours to non-peak hours and fine and rewards principle, compared to the second scenario, the objective functions experienced an increment.

References

[1] M. A. Jirdehi and M. Shaterabadi, "Incentive programs caused by the carbon capture utilization and storage technology profit's effect: optimal configuration and energy planning of hybrid microgrid involving INVELOX turbine," *Energy Technology,* vol. 8, no. 10, p. 2000398, 2020.

[2] M. A. Jirdehi, M. Shaterabadi, V. S. Tabar, and A. R. Jordehi, "Impact of diverse penetration levels of thermal units on a hybrid microgrid energy management considering the time of use and function priority," *Applied Thermal Engineering,* vol. 217, p. 119164, 2022.

[3] J. Hu, X. Liu, M. Shahidehpour, and S. Xia, "Optimal operation of energy hubs with large-scale distributed energy resources for distribution network congestion management," *IEEE Transactions on Sustainable Energy,* vol. 12, no. 3, pp. 1755-1765, 2021.

[4] M. S. Javadi, M. Lotfi, A. E. Nezhad, A. Anvari-Moghaddam, J. M. Guerrero, and J. P. Catalão, "Optimal operation of energy hubs considering uncertainties and different time resolutions," *IEEE Transactions on Industry Applications,* vol. 56, no. 5, pp. 5543-5552, 2020.

[5] S. A. Mansouri, A. Ahmarinejad, M. S. Javadi, and J. P. Catalão, "Two-stage stochastic framework for energy hubs planning considering demand response programs," *Energy,* vol. 206, p. 118124, 2020.

[6] M. Zadehbagheri, M. J. Kiani, S. Pirouzi, M. Movahedpour, and S. Mohammadi, "The impact of sustainable energy technologies and demand response programs on the hub's planning by the practical consideration of tidal turbines as a novel option," *Energy Reports,* vol. 9, pp. 5473-5490, 2023.

[7] F. Niazvand, S. Kharrati, F. Khosravi, and A. Rastgou, "Scenario-based assessment for optimal planning of multi-carrier hub-energy system under dual uncertainties and various scheduling by considering CCUS technology," *Sustainable Energy Technologies and Assessments,* vol. 46, p. 101300, 2021.

[8] M. Movahedpour, M. J. Kiani, M. Zadehbagheri, and S. Mohammadi, "Microgrids operation by considering demand response and supply programs in the presence of IGDT-based reverse risk," *IEEE Access,* vol. 10, pp. 48681-48700, 2022.

[9] S. A. Mansouri, M. S. Javadi, A. Ahmarinejad, E. Nematbakhsh, A. Zare, and J. P. Catalao, "A coordinated energy management framework for industrial, residential and commercial energy hubs considering demand response programs," *Sustainable Energy Technologies and Assessments,* vol. 47, p. 101376, 2021.

[10] W. Huang *et al.*, "Reliability and vulnerability assessment of multi-energy systems: An energy hub based method," *IEEE Transactions on Power Systems,* vol. 36, no. 5, pp. 3948-3959, 2021.

[11] M. Jadidbonab, B. Mohammadi-Ivatloo, M. Marzband, and P. Siano, "Short-term self-scheduling of virtual energy hub plant within thermal energy market," *IEEE Transactions on industrial electronics,* vol. 68, no. 4, pp. 3124-3136, 2020.

[12] A. A. Eladl, M. I. El-Afifi, M. A. Saeed, and M. M. El-Saadawi, "Optimal operation of energy hubs integrated with renewable energy sources and storage devices considering CO2 emissions," *International Journal of Electrical Power & Energy Systems,* vol. 117, p. 105719, 2020.

[13] N. Liu, L. Tan, H. Sun, Z. Zhou, and B. Guo, "Bilevel heat–electricity energy sharing for integrated energy systems with energy hubs and prosumers," *IEEE Transactions on Industrial Informatics,* vol. 18, no. 6, pp. 3754-3765, 2021.

[14] M. S. Javadi, A. E. Nezhad, A. R. Jordehi, M. Gough, S. F. Santos, and J. P. Catalão, "Transactive energy framework in multi-carrier energy hubs: A fully decentralized model," *Energy,* vol. 238, p. 121717, 2022.

[15] P. Zhao *et al.*, "Economic-effective multi-energy management considering voltage regulation networked with energy hubs," *IEEE Transactions on Power Systems,* vol. 36, no. 3, pp. 2503-2515, 2020.

[16] M. Shaterabadi, M. A. Jirdehi, N. Amiri, and S. Omidi, "Enhancement the economical and environmental aspects of plus-zero energy buildings integrated with INVELOX turbines," *Renewable Energy,* vol. 153, pp. 1355-1367, 2020.

[17] M. Shaterabadi, H. Khajeh, H. Firoozi, and H. Laaksonen, "Energy Management Systems of Grid-Connected Active Buildings," in *Active Building Energy Systems: Operation and Control*: Springer, 2022, pp. 251-271.