The energy management and planning of the proposed Water-Energy nexus concept by considering tidal turbine and INVELOX as novel options

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***Abstract*—The energy and water crisis due to the rapidly growing population and developing societies caused countries and governments to think about novel technologies and ways to respond to this issue. Therefore, this paper is about energy planning and management of the proposed concept for supplying water and energy simultaneously. This approach helps to overcome and supply the dramatic energy need of desalination and distribution systems. This article aims to supply the demands and minimize the total cost at the same time. Various renewable and non-renewable energy resources such as tidal turbines, INVELOX turbines, CHP, micro-turbines, and other elements are utilized in the proposed planning. Real weather conditions are considered to compute the output power of wind and tidal turbines. The presented water-energy nexus structure is modeled as a MINLP concept and solved in GAMS software using various solvers to illustrate the reliability of the optimization answers. The final results show a high improvement in the total cost reduction.**

***Index Terms*—Energy management; INVELOX turbines; Renewable energy sources (RES); Tidal turbines; Water-energy nexus.**

I. Introduction

A. General overview of the proposed issue

In the realm of sustainable energy, a burgeoning confidence in the efficacy and capacity of renewable sources has directed an intensified spotlight on their expansion and evolution. Diverse strategies have been explored to capitalize on the advantages presented by these resources. This exploration spans from microgrids tailored for localized applications to nanogrids addressing other scenarios, topics that have animated ongoing discussions of late [1, 2]. Emerging as a supremely versatile and all-encompassing energy supply solution is the Water-energy nexus. This system embodies a cohesive and adaptable structure adept at efficiently transforming and storing a myriad of energy sources, catering to the multifaceted needs of consumers. Water-energy nexus systems' energy planning and management objectives include reducing costs and pollution, increasing profits, fortifying network resilience, and seamlessly integrating green energy resources. The discourse around the planning of water-energy nexus is a fervent subject demanding comprehensive attention, with numerous facets awaiting scrutiny and consideration [3-5]. In recent years, much attention has been paid to technology and increasing the efficiency of renewable energy resources. The INVELOX wind turbine stands tall as a beacon of innovation and efficiency in the ever-evolving landscape of sustainable energy solutions. Developed to redefine the way we harness wind power, this cutting-edge technology has been making waves in the renewable energy sector [6]. INVELOX, a portmanteau of "In Venturi Effect Wind Turbine," introduces a revolutionary approach to wind power generation. Unlike traditional wind turbines, which rely on large blades to capture wind energy, the INVELOX system utilizes a funnel-shaped structure. This unique design accelerates wind flow, enabling the turbine to harness energy even at lower wind speeds [6-8]. One of the standout features of the INVELOX wind turbine is its increased efficiency. By capturing wind from a broader range of directions, the turbine maximizes energy production. Moreover, the compact design minimizes the impact on local wildlife and reduces the visual footprint, addressing common concerns associated with traditional wind farms [9, 10]. The energy landscape has witnessed a remarkable shift towards sustainable and renewable sources in recent years. Tidal energy, in particular, has gained significant attention as a promising solution. Over the years, a materials revolution has played a pivotal role in enhancing the efficiency and durability of tidal turbines. Advanced composite materials have replaced traditional metals, offering resistance to corrosion and reducing the need for frequent maintenance. This breakthrough has significantly extended the lifespan of tidal turbines, making them a more viable long-term investment [11, 12]. Recent research on the understudy issue is reviewed and evaluates in the following section.

B. Recent research on the proposed issue

Researchers globally have assessed the various states and scenarios of water-energy nexus planning. For instance, Wang et al. in [13] assumed that the bustling industrial park of Jinan City, located in Shandong Province, China, a Comprehensive Heat and Power (CHP) system stands as a beacon of efficiency. This article delved into a comprehensive study of this system, focusing on its hourly water consumption data throughout the year. The goal was to optimize its operation, ensuring a delicate balance between energy production, resource conservation, and profitability. The final results show that integrating the energy-water nexus into the traditional model maximizes efficiency and profitability and safeguards essential water resources. This forward-thinking methodology sets a new standard for sustainable energy practices, ensuring a harmonious balance between economic viability and environmental responsibility. In sustainable energy topics, introducing innovative software can revolutionize the intricate process of determining nominal capacities for an electric-to-water microgrid. Desalination Plant emerges as a groundbreaking solution, addressing the complexity associated with inexhaustible distributed energy resources, decentralized storage systems, and seawater desalination. Therefore, Asensio et al. in [14] delve into the comprehensive modeling of a desalination system linked with a photovoltaic plant, a wind power plant, electrochemical storage, and an electric network connection. The core purpose is to optimize the sizing of distributed renewable resources within the microgrid. The final results illustrate the efficiency of the assumed approach. Understanding the intricate web of water-energy nexuses is paramount. Wang et al. in [15] investigated the multifaceted dimensions, exploring various aspects such as food, greenhouse gases, waste, pollution, and land, with a keen focus on their practical implications. This study was a pivotal stepping stone toward establishing quantified characteristics or components. These benchmarks could serve as eligibility criteria, distinguishing genuine nexus approaches and studies from mere conceptual discussions. The article aims to contribute to a more concrete and applicable framework for understanding water-energy nexuses by quantifying the characteristics. Optimizing efficiency and minimizing water-energy consumption are critical objectives. Thus, Ahmad et.al in [16] assessed and reviewed the scope, objectives, and methodologies related to water-energy nexus studies in urban water systems. A meticulous, systematic review of 94 research papers selected from pertinent literature aims to shed light on strategies leading to enhanced water-energy efficiency in urban water system management. The research focused on dissecting methodologies, models, and influencing factors within the water-energy nexus across various urban water systems. The findings reveal a diverse landscape where studies employ different frameworks and optimization approaches to achieve optimal energy efficiency. Notably, the Integral Theory Framework (ITF) emerges as a key player in identifying interconnectivity among variables within the water-energy nexus, extending beyond technological assessments. Zhao et.al in [17] introduced a cutting-edge, two-stage, distributionally robust operation model. This innovative model incorporated power, gas, and water systems intricately connected with energy hub systems at a distribution level while addressing the challenges of wind uncertainty. The inherent unpredictability of wind power introduces risks into the optimization model, prompting the integration of a coherent risk measure, specifically conditional value-at-risk. This measure is combined with the optimization objective to craft risk-averse operation schemes. In order to address the intricacies of this novel model, Bender's decomposition method was employed. This approach elegantly solves the two-stage mean-risk distributionally robust optimization, ensuring a robust and efficient solution. The numerical results derived from the case studies serve as a robust validation of the proposed model. These results unmistakably showcase the economic effectiveness of Integrated Energy Systems (IES) in optimally coordinating multi-energy infrastructures. By addressing the uncertainties posed by renewable sources, particularly wind power, the proposed model proves its capability to provide system operators with a potent two-stage operation scheme. This scheme, in turn, minimizes operation costs under the water-energy nexus, thus delivering the added benefit of lower utility bills to end consumers. Misrol et al. in [18] developed a mathematical model to optimize the nexus for a centralized facility, which is applicable at the district level. The sources were domestic and industrial wastewater, and multiple contaminants were considered for optimization. The recovery processes were intended to recover biogas, phosphorus, nitrogen, metal, digestate, solid sludge, and microalgae oil from the wastewater streams, while supplying reused and/or reclaimed water for various application options. The model and the techno-economics equations also included connection items and segregation tanks. The model was formulated as mixed-integer non-linear programming (MINLP). A case study was conducted as multiple resources can be recovered in the facility. A total of 3.2 MW of renewable energy can be recovered, and freshwater consumption is reduced by 66%. Supply water selling price, industrial processing fee value, and maximum length of the main transmission pipeline are the important factors affecting the project's economics. As no subsidies are set, the study provides insight into how the tripartite nexus can be symbiotically integrated at the district level. Based on what has been reviewed, the research hypothesis of the presented paper is explained in the following section.

C. The key points hypothesis behind the issue

Based on the explanations and according to recent research papers, it seems that the energy management and planning of the water-energy nexus concept, in addition to the novel technologies such as tidal turbines and INVELOX wind turbines, can be a proper idea for investigation. As the world progresses, utilizing complex concepts to meet consumers' needs looks vital. Because of its application, the water-energy nexus structure is one of these concepts. Using co-product units alongside several renewable and non-renewable resources can help harness power more efficiently. According to the application of various solvers for solving the MINLP model, the responses of the optimization problem are computed by using different solvers to show their performance. The problem is modeled as Mixed Integer Non-linear Programming (MINLP) and solved in GAMS software.

D. Paper's categorization

The remainder of the paper is organized as follows: the modeling and explanation of renewable and non-renewable-based units mentioned before are expressed in Section II. Furthermore, the most important limitations and equations that affect the energy planning of the presented water-energy nexus are described in this section. Section III presents the solving manner and understudy test system characteristics and parameters. Sections IV and V elaborate on the results and conclusion, respectively.

II. Renewable and Non-Renewable Based Unit Modeling and Limitations

A. INVELOX wind turbine (IWT)

Invelox, an amalgamation of the terms' increase' and 'velocity,' encapsulates a sophisticated apparatus designed to augment wind speed. To elucidate, it comprises an intricate system employing the Venturi principle within a tunnel. This turbine, demarcated into diverse segments, facilitates wind ingress into its structure. A funnel-shaped conduit guides the wind to the Venturi section, where generators await. Subsequently, the wind retraces its course, being expelled into the surroundings through a diffuser section. Remarkably, this mechanism can harness wind energy at a magnitude 6 times greater than traditional wind turbines [8]. The general concept, performance, schematic, and modeling equations are demonstrated in Figure (1) and Eq. (1).

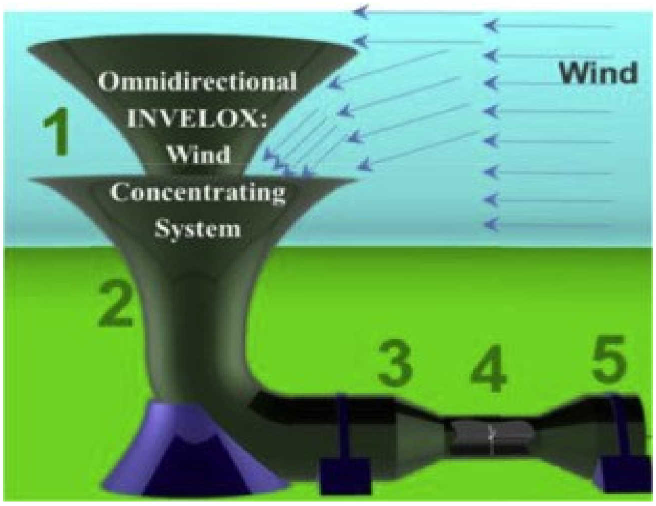

Fig. 1. The overall concept and performance of the INVELOX turbine.

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

B. Tidal turbine (TT)

The ascendancy of tidal energy beckons, prominently propelled by the advent of tidal turbines. These subaquatic contrivances, adept at tapping into the unyielding vigor of the tides, stand as vanguards in the pursuit of cleaner and enduring power sources. The modus operandi of tidal turbines pivots on the transmutation of kinetic energy inherent in the undulating waters into a potent manifestation of electrical power. Strategically submerged in locales characterized by robust tidal currents, these turbines mirror the modality through which their wind-driven counterparts extract energy from the atmospheric currents. As the rhythmic cadence of the tides oscillates, water gracefully traverses the blades of these turbines, instigating a balletic rotation. This rotational choreography, in turn, bequeaths vitality to generators, orchestrating the symphony of electricity production [12]. The output power of the tidal turbine is calculated using Eq. (2).

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

C. The most important limitations and objective function

In order to optimize the assumed objective function, different limitations and restrictions should be considered. Therefore, some of the important ones are brought up in the following.

$$\min_{DV} \text{OF}=\text{TC+CC+WC} \quad (3)$$

$$\text{DV}=\left(P_{g,t},P_{c,t},W_{c,t},W_{w,t}\right) \quad (4)$$

$$\text{CT}=\sum_{g,t} a_g P_{g,t}^2 + b_g P_{g,t} + c_g U_{g,t} \quad (5)$$

$$\text{CC}=\sum_{c,t}\alpha_c P_{c,t}^2+\beta_c P_{c,t}W_{c,t}+\gamma_c W_{c,t}^2+\zeta_c P_{c,t}+\varsigma_c W_{c,t}+\xi_c U_{c,t} \quad (6)$$

$$\text{CW}=\sum_{w,t} a_w w_{w,t}^2 + b_w W_{w,t} + c_w U_{w,t} \quad (7)$$

According to the above, Eqs. (3) demonstrates the objective functions that have been considered the total cost of the water-energy nexus concept. Eqs. (4) – (7) exhibits the elements of the objective function, and Eq (4) shows the various equipment that has been used in the planning. Eq (5) illustrates the cost of thermal units. Eq (6) elaborates on the cost of the co-product units, and Eq(7) shows the total water supply cost. The a_g, b_g, and c_g are the fuel cost coefficients of unit i. The parameters of α_c, β_c, Υ_c, ζ_c, ς_c, and ξ_c are the coefficients of the co-product system. Furthermore, a_w, b_w and c_w are the coefficients related to the water desalination cost.

$$P_g^{\min}U_{g,t}\leq P_{g,t}\leq P_g^{\max}U_{g,t} \quad (8)$$

$$P_c^{\min} U_{c,t} \le P_{c,t} \le P_c^{\max} U_{c,t} \quad (9)$$

$$W_c^{\min} U_{c,t} \le W_{c,t} \le W_c^{\max} U_{c,t} \quad (10)$$

$$W_w^{\min} U_{w,t} \le W_{w,t} \le W_w^{\max} U_{w,t} \quad (11)$$

$$R_c^{\min} \le \frac{P_{c,t}}{W_{c,t}} \le R_c^{\max} \quad (12)$$

$$\sum_g P_{g,t} + \sum_c P_{c,t} = PL_t \quad (13)$$

$$\sum_w W_{w,t} + \sum_c W_{c,t} = WL_t \quad (14)$$

According to above, Eqs. (8) – (12) depict the amount of water, power, and reserve margin of the various units. Ultimately, Eqs. (13) and (14) determine equality and the power and water balance equations [19, 20].

III. SOLVING MANNER AND UNDERSTUDY CHARACTERISTICS

A. Untackle approach and optimization manner

In optimization and decision-making, many objective functions are optimized by planners and engineers. The most common of them is the total cost of the understudy system. Therefore, this paper considers the total expense of renewable and non-renewable resources and co-product units. The GAMS software is used to solve this problem. The problem is modeled as MINLP because of non-linear equations [21-23].

B. Understudy water- energy nexus concept

The presented water-energy nexus comprises different renewable and non-renewable energy resources and electrical and water demands. Figure (2) illustrates the presented water-energy nexus diagram. The objective function is the total cost of all units, including renewable and non-renewable sources, which should be minimized. All other needed information is expressed in [7, 12, 19]. Tables (1) – (3) describe the value of each parameter related to the thermal units, co-product units, and water desalination system.

Table 1. The value of the cost coefficient related to the non-renewable units.

Unit	a_g (\$/MW^2)	b_g (\$/MW)	c_g (\$)	P_g^{max} (MW)	P_g^{min} (MW)
g1	0.0002069	-0.1483	57.11	500	0
g2	0.0003232	-0.1854	57.11	400	0
g3	0.001065	-0.6026	126.8	400	0
g4	0.0004222	-0.2119	57.11	350	0

Table 2. The value of the cost coefficient related to the water desalination system.

Unit	a_w	b_w	c_w	W_w^{max}	W_W^{min}
W_1	0.00182	-0.708	7.374	250	0

Table 3. The value of cost coefficient and characteristics related to co-product units.

Unit	P_c^{max}	P_c^{min}	W_c^{max}	W_c^{min}	R_c^{min}	R_c^{max}	α_c	β_c	Υ_c	ζ_c	ς_c	ξ_c
C1	800	160	200	30	4	9	0.0004433	0.003546	0.007093	-1.106	-4.426	737.4
C2	600	120	150	23	4	9	0.0007881	0.006305	0.01261	-1.475	-5.901	737.4
C3	400	80	100	15	4	9	0.001773	0.01419	0.02837	-2.213	-8.851	737.4

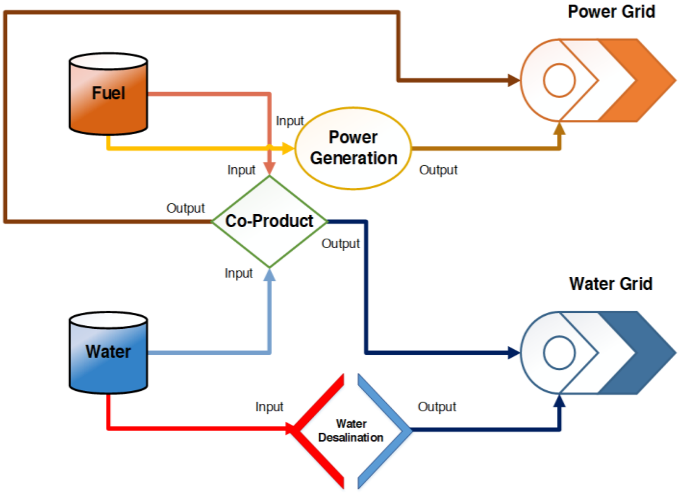

Fig. 2. The overall concept of the presented water-energy nexus.

IV. Numerical Results and Discussion

This section expresses the results of the assumed planning by considering two scenarios. The first one is the nominal scenario (Without INVELOX and Tidal). The second scenario is where the INVELOX wind turbines (IWT) and tidal turbines (TT) have taken part in the planning of the water-energy nexus performance.

A. Scenario without IWT and TT (First Scene)

This section evaluates the nominal scenario where neither TT nor IWT participated in the planning. The accurate value of objective functions for total cost based on various solvers has been computed and illustrated in Table (4). The values have been different because of the nature of the MINLP model. Since the calculation has taken much time, just 2000 iterations for all solvers have been considered.

Table 4. The results of the proposed planning for the first scenario by utilizing various solvers by considering 2000 iterations.

Solvers	Total Cost ($)
KNITRO	31258.065
BARON	23534.265
DICOPT	41561.602

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

This section assesses the impact of TT and IWT on the presented study's objective functions. The total cost for this scenario has been reduced compared to the first scenario. As can be seen in Table (5), the presence of TT and IWT has affected the objective functions. The amount of power generated by these types of resources is shown in Figure (3). Furthermore, the value of the output of various units that participated in the planning is also shown in Figure (4). This reduction has been due to using RERs in the proposed planning. As mentioned earlier, only 2000 iterations have been assumed; therefore, the Baron could not show the accuracy of the objective function compared to other solvers.

Table 5. The results of the proposed planning for the second scenario by utilizing various solvers.

Solvers	Total Cost ($)
KNITRO	29005.162
BARON	23197.836
DICOPT	31924.874

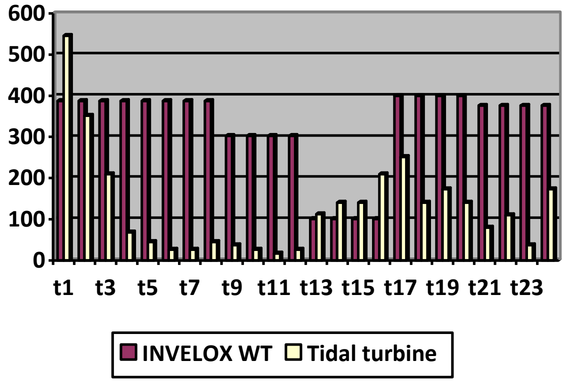

Fig. 3. The output power generated by IWT & TT in the second scenario.

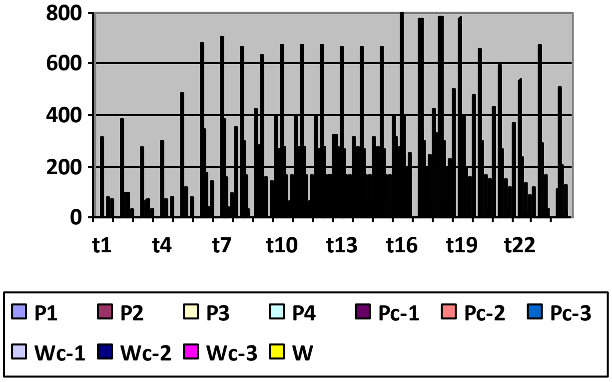

Fig. 4. The output power generated by various units in the second scenario.

V. Summary and Conclusion

This paper investigates a unique outlook on energy management and planning of the presented water–energy nexus concept in which novel renewable-based units, including INVELOX wind turbines (IWT) and tidal turbines (TT), participated. The problem was modeled as mixed integer non-linear programming (MINLP) and solved in GAMS software using diverse solvers such as KNITRO, Baron, and DICOPT. The final results show that utilizing novel and effective RERs can reduce the cost of the whole system by using each solver in particular. The value of the objective function was different because of the MINLP's nature model and local-global optimized response issues. The objective function's value (OF) was reduced from $ 31258.065 to $ 29005.162 using the KNITRO solver. Since only 2000 iterations were assumed for GAMS (to reduce the calculation time to get a response), solvers like Baron could not obtain an accurate answer compared to KNITRO and DICOPT. The results in the MINLP model can vary because of the solvers.

REFERENCES

[1] M. A. Jirdehi and M. Shaterabadi, "A low-carbon strategy using INVELOX turbines in the presence of real-time energy price uncertainty," *Greenhouse Gases: Science and Technology,* vol. 11, no. 3, pp. 461-482, 2021.

[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] A. M. Hamiche, A. B. Stambouli, and S. Flazi, "A review of the water-energy nexus," *Renewable and Sustainable Energy Reviews,* vol. 65, pp. 319-331, 2016.

[4] A. A. Salehi, M. Ghannadi-Maragheh, M. Torab-Mostaedi, R. Torkaman, and M. Asadollahzadeh, "A review on the water-energy nexus for drinking water production from humid air," *Renewable and Sustainable Energy Reviews,* vol. 120, p. 109627, 2020.

[5] M. Shaterabadi, H. Mehrjerdi, and M. A. Jirdehi, "How INVELOX can affect the perspective of renewable energy exploitation: Demand response and multilateral structure planning outlook," *Sustainable Cities and Society,* vol. 91, p. 104421, 2023.

[6] 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.

[7] M. Shaterabadi and M. A. Jirdehi, "Multi-objective stochastic programming energy management for integrated INVELOX turbines in microgrids: A new type of turbines," *Renewable Energy,* vol. 145, pp. 2754-2769, 2020.

[8] 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.

[9] M. Shaterabadi and M. A. Jirdehi, "Smart scheduling of transmission line switching: optimization of multi-objective microgrid's day-ahead energy scheduling with considering high penetration of green energies and INVELOX," *Electrical Engineering,* vol. 103, pp. 1753-1767, 2021.

[10] 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.

[11] F. Jalilian, M. A. Mirzaei, K. Zare, B. Mohammadi-Ivatloo, M. Marzband, and A. Anvari-Moghaddam, "Multi-energy microgrids: An optimal despatch model for water-energy nexus," *Sustainable Cities and Society,* vol. 77, p. 103573, 2022.

[12] 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.

[13] S. Wang, X. Wang, Z. Fu, F. Liu, Y. Xu, and W. Li, "A novel energy-water nexus based CHP operation optimization model under water shortage," *Energy,* vol. 239, p. 121832, 2022.

[14] E. Rosales-Asensio, A.-E. Rosales, and A. Colmenar-Santos, "Surrogate optimization of coupled energy sources in a desalination microgrid based on solar PV and wind energy," *Desalination,* vol. 500, p. 114882, 2021.

[15] X.-C. Wang, P. Jiang, L. Yang, Y. Van Fan, J. J. Klemeš, and Y. Wang, "Extended water-energy nexus contribution to environmentally-related sustainable development goals," *Renewable and Sustainable Energy Reviews,* vol. 150, p. 111485, 2021.

[16] S. Ahmad, H. Jia, Z. Chen, Q. Li, and C. Xu, "Water-energy nexus and energy efficiency: A systematic analysis of urban water systems," *Renewable and Sustainable Energy Reviews,* vol. 134, p. 110381, 2020.

[17] P. Zhao *et al.*, "Water-energy nexus management for power systems," *IEEE Transactions on Power Systems,* vol. 36, no. 3, pp. 2542-2554, 2020.

[18] M. A. Misrol, S. R. W. Alwi, J. S. Lim, and Z. Abd Manan, "Optimization of energy-water-waste nexus at district level: A techno-economic approach," *Renewable and Sustainable Energy Reviews,* vol. 152, p. 111637, 2021.

[19] A. Soroudi, *Power system optimization modeling in GAMS*. Springer, 2017.

[20] M. Hemmati, B. Mohammadi-Ivatloo, and A. Soroudi, "Uncertainty management in decision-making in power system operation," in *Decision making applications in modern power systems*: Elsevier, 2020, pp. 41-62.

[21] H. Mehrjerdi, "Modeling and integration of water desalination units in thermal unit commitment considering energy and water storage," *Desalination,* vol. 483, p. 114411, 2020.

[22] H. Mehrjerdi, "Modeling and optimization of an island water-energy nexus powered by a hybrid solar-wind renewable system," *Energy,* vol. 197, p. 117217, 2020.

[23] M. Shaterabadi, H. Mehrjerdi, N. Amiri, M. A. Jirdehi, and A. Iqbal, "Green roof positive impact on changing a Plus-ZEB to drastic Plus-ZEB: The multi-objective energy planning and audit in real condition outlook," *Energy and Buildings,* vol. 287, p. 112983, 2023.