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# Optimal Stochastic Water-Energy Nexus Management for Cooperative Prosumers in the Modern Multi-Energy Network

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***Abstract*—Nowadays, significant developments of hybrid energy systems have been led to their widespread presence in the energy network's interactions and have made the interdependent analysis of energy networks essential. In this regard, the inextricable role of the water in the production process of various forms of energy has created a great need for innovative water-energy nexus models in modernizing future multi-vector energy grids. To this end, this paper proposes an innovative water-energy nexus model for optimal energy management of prosumers in the modern energy infrastructure. In the proposed model, each prosumer benefits to wind and PV units for generating clean power, storage units for ensuring continuous power and water supply, power-to-X-to-power technology for linking power and water networks, as well as the water well and water desalination units for serving water demand. Due to the essentiality of uncertainty modeling for gaining confident results in the system engaged with a 100% level of renewables, the stochastic assessment is conducted by generating scenarios using an autoregressive integrated moving average approach as well as reducing the number of scenarios by applying fast forward reduction method. The applicability of the proposed model is examined in the IEEE 6-bus power distribution system. The results highlighted the effectiveness of the offered model in optimally managing the energy of prosumers in the water-energy nexus system.**

***Keywords—optimal energy management, prosumers, 100% renewable energy resources, water-energy nexus, grid modernization, power-to-X-to-power (P2X2P) technology***

## I. INTRODUCTION

### A. Motivation and Background

Recent advances in the technology of hybrid energy systems facilitate the transition from traditional power grids towards interconnected energy networks [1]. This transition has been done in response to the call for sustainable and secure energy grids and has made energy structures tighter and more dependable than ever before [2]. However, the sustainability of energy infrastructures has been more challenged when future energy networks are targeted to host 100% renewable energy resources (RERs) [3]. How the related plans can be feasible in the act is a motivation question that has driven the research world to figure out practical solutions for the challenge of fully implementing RERs. In this respect, water is the vital substance of forming diverse carriers of energy enabling the system to simultaneously generate multi-vector energy using energy conversion technologies [4]. Herein, the ever-increasing multi-energy demand alongside the threat of growth rate in climate changes has been led to the appearance of the water-energy nexus concept for ensuring reliable access to sufficient water and energy in the hybrid energy infrastructure [5]. The water-energy nexus models can support the system in improving its overall efficiency, reaching the environmental targets, as well as further intensifying the operational interdependency of integrated energy systems [6]. However, as water-energy nexus frameworks can facilitate the penetration of RERs, their effective role is ignored in addressing the challenge of optimal integration of 100% RERs in the modern interconnected energy grid (MIEG). This is while irreparable environmental damages of conventional energy generation plants reveal the necessity for fully RERs in the energy generation process of the MIEG. For this aim, this paper aims at developing a new water-energy nexus model for optimal energy management of prosumers that benefit 100% RERs in the power production sector and energy conversion technologies for easily handling the fully RERs incorporation in the system.

### B. Relevant Literature

In light of increasing carbon emissions raised from fossil-fuel based units to an alarming level alongside day by day growing demand for multi-carrier energy, prosumers have emerged to ease energy interactions in welcoming to efficient, greener, sustainable, and reliable energy supply [7]. To promote decarbonization in the MIEG structure, researchers have devoted ambitious efforts to optimally manage energy interactions of prosumers in recent years. In this respect, the endeavors of authors in [8] have been resulted in proposing a cooperative game theory-based model for incorporating clustering techniques to manage energy interactions of prosumers as well as develop the nucleolus mechanism for estimating computation times. In [9], the game theory engaged with stochastic programming in energy management of autonomous prosumers with the aim of voltage regulation and uncertainty modeling by adopting the Markov decision process. An innovative blockchain-based mechanism is presented in [10] for incentivizing prosumers to preserve their privacy while saving energy. The proposed mechanism avails the energy management system aiming to allow prosumers for scheduling their power consumption. The authors presented a two-stage energy management framework for prosumers in

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[11] to minimize the storage system's total life-cycle cost in the optimal planning of smart home RERs. Besides the cost-based frameworks and models, a novel two-tier peer-to-peer energy exchanging paradigm is presented in [12] to allow multiregional proactive prosumers for energy sharing in both inter-area and intra-area markets. The same study designed the consensus-based and dual decomposition-based distributed market-clearing mechanisms for the optimal energy management of prosumers.

The recent substantial developments in multi-energy systems alongside high-efficiency energy conversion devices have accelerated the switch from separated and heterogeneous energy systems to the coupled structure of energy networks [13]. In this transition, water plays a critical role as the main input material for forming a variety of energy carriers that has been led to the creation of various water-energy nexus models for maintaining the sustainability of interdependent energy grids in recent literature. The robust-based water-energy nexus operational model is proposed in [14] to cope with the uncertainties of wind power production as well as explore interdependencies among the power and water distribution network. In [15], the water-energy nexus model is proposed to cover energy interactions in the subway and electric vehicles, a microgrid, and a smart energy hub aiming to coordinately supply the electrical and thermal energy demand as well as water load. The authors devised a novel water-energy nexus framework in [16] to not only quantify the resilience of the power system but also examine its interdependent operation with the water distribution network to make the integrated energy structure more sustainable in serving energy. Another developed water-energy nexus model in [17] is concentrated on optimizing the energy flexibility in the day-ahead operation of the interconnected power and water grid. The proposed model enables the systems' operators for calculating and offering feasible flexible energy capacity to the integrated structure. Besides, an innovative water-energy nexus scheme is suggested in [18] for a cyber-secure operation of the system by developing a two-stage risk-averse mitigation strategy for preserving the system from false data injection attacks.

### C. Contributions and Organization

The detailed assessments of recent works in the context of water-energy nexus frameworks reveal the crucial research gaps that need innovative models for procuring effective remedies to guarantee the system's sustainability. All of the proposed frameworks in the literature only focused on the energy management of structures that incorporated with a lower level of RERs. This is while future MIEGs are planned for involving fully RERs in the multi-energy generation sector to harness the irreparable environmental damages of fossil fuel-based units. However, developing a holistic framework for water-energy nexus management of the MIEG is overlooked in the related research area. On the other hand, the current proposed multi-energy structures for the energy management of prosumers cannot support the fully RERs participation in the energy generation process that is required for modernizing future MIEGs. Thus, this issue has created a sense of huge requirement for a novel architecture for cooperative prosumers enabling them to effectively utilize the 100% clean energy production possibility. To address the mentioned challenges, this paper innovates in proposing a novel water-energy nexus management model for prosumers incorporated with 100% RERs in the MIEG. The offered model is empowered by RERs, energy storage systems, power-to-X-to-power (P2X2P) technology, and water production and storage systems for constructing a sustainable and reliable framework aiming to unbroken power and water supply. To model the intrinsic intermittences of RERs, numerous scenarios of their stochastic changes are produced by exerting an autoregressive integrated moving average (ARIMA) approach that their numbers are reduced by benefiting from the application of the fast forward reduction (FFR) method.

The remainder of this article is organized as follows. The problem formulation along with the uncertainty quantification is characterized in Section II. Section III covers the extracted results and their analysis. Section IV includes a conclusion of this work.

## II. Problem Formulation

### A. Prosumer Structure

This work aims at developing a new water-energy nexus management model for 100% renewable-penetrated prosumers for optimally managing energy interactions as well as continuously supplying power and water in the MIEG. Fig. 1 shows the renewable-based structure of prosumers.

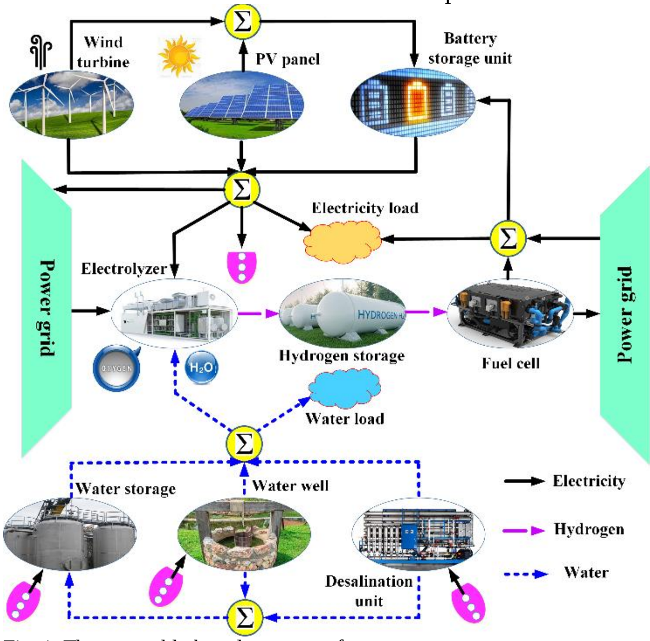

Fig. 1. The renewable-based structure of prosumers

As indicated in Fig. 1, PV and wind systems constitute the clean energy production part of prosumers that make eco-friendly power generation possible in the MIEG. The battery storage unit (BSU) upsurges the assurance of an uninterrupted power supply by detracting the uncontrollable effects of RERs. To increase the flexibility and sustainability of the system in the presence of 100% RERs, the P2X2P technology along with the possibility of power sharing with the main grid is intended for prosumers to optimally manage the produced clean power in the grid. The P2X2P technology consists of an electrolyzer (EL) system to break down the water and produce hydrogen and oxygen molecules. The produced hydrogen is directed to the hydrogen storage unit (HSU) for storage. The stored hydrogen can be used for the reproduction of power by the fuel cell (FC) when the system suffers from an energy production shortage. In the water sector, the water well (WW) and water desalination (WD) units are deployed for generating the required water, and the water storage system (WSS) is also operated for ensuring a continuous water supply.

*B. Objective Function*

Minimizing the overall operation cost of prosumers is the main objective of the optimization problem that conforms to the following formula.

$$F_p^{\Pr} = \sum_{\varpi=1}^{\varpi_T} \varepsilon_{\varpi} . \left[ \sum_{t=1}^{t_T} [(E_{t,p,\varpi}^{BSU} .\eta^{B,L} + P_{t,p,\varpi}^{BSU}).(\Im_p^{BSU})] + \sum_{t=1}^{t_T} \text{Cost}_{t,\varpi}^{DSEM} + \sum_{t=1}^{t_T} \lambda_t^{S,E} .P_{t,p,\varpi}^{TWC} - \sum_{t=1}^{t_T} \lambda_t^{Ex,E} .P_{t,p,\varpi}^{Ex} - \sum_{t=1}^{t_T} \lambda_t^{Ex,W} .Q_{t,p,\varpi}^{Ex,W} - \sum_{t=1}^{t_T}\sum_{i=1}^{i_T} \lambda_t^{S,E} .P_{t,i}^{Load} - \sum_{t=1}^{t_T} \lambda_t^{S,W} .Q_{t,p}^{W,Load} \right] \quad (1)$$

where, $F_p^{\Pr}$ states the objective function of prosumers. $E_{t,p,\varpi}^{BSU}$ and $P_{t,p,\varpi}^{BSU}$ are the energy and power of BSU at time *t*, prosumer *p*, and scenario $\varpi$. $\Im_p^{BSU}$ and $\eta^{B,L}$ denote the degradation cost and leakage loss coefficient of BSU. $\text{Cost}_{t,\varpi}^{DSEM}$ presents the cost of demand-side energy management (DSEM) programs. Electricity (water) selling and exchanging prices are represented by $\lambda_t^{S,E}$ and $\lambda_t^{Ex,E}$ ($\lambda_t^{S,W}$ and $\lambda_t^{Ex,W}$). $P_{t,p,\varpi}^{TWC}$ is the total consumed power by water systems. $Q_{t,p}^{W,Load}$ and $P_{t,i}^{Load}$ indicate the water and power loads. $Q_{t,p,\varpi}^{Ex,W}$ and $P_{t,p,\varpi}^{Ex}$ state the water and power exchanging with the upstream grid. $\varepsilon_{\varpi}$ is the probability of scenario $\varpi$.

In (1), the operation costs of BSU and DSEM programs are modeled by the first and second terms. The third term indicates the power consumption cost by the water units. The fourth and fifth terms state the cost/revenue of power and water exchanging with the main grid. The two last terms denote the revenue of selling power and water to consumers.

*C. Constraints*

*1) Electricity and water balances*

The power and water networks require a dynamic balance between their production and consumption according to the following formulas.

$$\sum_{p=1}^{p_T} \left( P_{t,p}^{BSU} + P_{t,p}^{PV} + P_{t,p}^{FC} + P_{t,p}^{Wind} - P_{t,p}^{Ex} - P_{t,p}^{EL} - P_{t,p}^{TWC} \right) = \sum_{p=1}^{p_T} \left( P_{t,p}^{Load} - P_{t,p}^{CL} \right) \quad (2)$$

$$\sum_{p=1}^{p_T} \left( Q_{t,p}^{WW,Dis} + Q_{t,p}^{WD,O} + Q_{t,p}^{WS,Ch} - Q_{t,p}^{WS,Dis} - Q_{t,p,\varpi}^{Ex,W} \right) = \sum_{p=1}^{p_T} Q_{t,p}^{W,Load} \quad (3)$$

where, $P_{t,p}^{PV}$, $P_{t,p}^{FC}$, and $P_{t,p}^{Wind}$ are the produced power by the PV panels, FCs, and wind turbines. $P_{t,p}^{EL}$ and $P_{t,p}^{CL}$ are the power consumed by the EL and curtailable load. $Q_{t,p}^{WW,Dis}$ and $Q_{t,p}^{WD,O}$ present the produced water by the WW and WD units. $Q_{t,p}^{WS,Ch}$ and $Q_{t,p}^{WS,Dis}$ represent the charging and discharging water in the WSS.

*2) Wind turbine and PV panel*

$$P_{t,p}^{Wind} = \begin{cases} 0 & V_t^W < V_p^{CI}, V_t^W > V_p^{CO} \\ \left( \dfrac{V_t^W - V_p^{CI}}{V_p^{RW} - V_p^{CI}} \right)^3 \times P_p^{RW} & V_p^{CI} \le V_t^W \le V_p^{RW} \\ P_p^{RW} & V_p^{RW} \le V_t^W \le V_p^{CO} \end{cases} \quad (4)$$

$$P_{t,p}^{PV} = (1 - \frac{\tau^A - 25}{200}) \times (A_P^{PV} .\wp_t^{PV} .\eta^{PV}) \quad \forall t, p \quad (5)$$

where, $V_t^W$ and $\wp_t^{PV}$ denote the wind speed and solar radiation at time *t*. The rated, cut-in, and cut-out wind speeds are specified by $V_p^{RW}$, $V_p^{CI}$, and $V_p^{CO}$. $P_p^{RW}$ is the rated wind power. $\eta^{PV}$ and $A_P^{PV}$ indicate the efficiency and area of PV. $\tau^A$ is the ambient temperature.

*3) Battery storage unit (BSU)*

The BSU is recognized as one of the reliable solutions for facilitating the penetration of 100% RERs and harnessing their undesirable changes during the day. The operation of BSU is subject to the following constraints.

$$E_{t+1,p}^{BSU} = E_{t,p}^{BSU} - \left( P_{t,p}^{BSU} - (\vartheta^B + \zeta^B).\eta^{B,C} - E_{t,p}^{BSU} .\eta^{B,L} \right) .\Delta t \quad (6)$$

$$\Im_p^{BSU} = \frac{\text{Cost}_p^{I,BSC}}{E_p^{RC,BSU} .\mathbb{N}_p^{LC,BSU}} \quad (7)$$

$$B_{t,p}^{SOC} = \frac{E_{t,p}^{BSU}}{E_p^{RC,BSU}} \;,\; \vartheta^B = P_{t,p}^{BSU} \;,\; \zeta^B = -P_{t,p}^{BSU} \quad (8)$$

$$\underline{B}_p^{SOC} \le B_{t,p}^{SOC} \le \bar{B}_p^{SOC} \quad (9)$$

$$-\bar{P}_p^{BSU,Ch} \le P_{t,p}^{BSU} \le \bar{P}_p^{BSU,Dis}, \vartheta^B \le \bar{P}_p^{BSU,Dis}, \zeta^B \le \bar{P}_p^{BSU,Ch} \quad (10)$$

$$E_{0,p}^{BSU} = E_{t_I,p}^{BSU} \;;\; E_{t_T,p}^{BSU} \ge E_{End,p}^{BSU} \quad (11)$$

where, $\mathbb{N}_p^{LC,BSU}$ and $E_p^{RC,BSU}$ are the life cycle number and rated energy capacity of the BSU. $\text{Cost}_p^{I,BSC}$ and $\eta^{B,C}$ present the investment cost and charging/discharging loss coefficient of the BSU. The BSU's state of charge and its upper and lower bounds are denoted by $B_{t,p}^{SOC}$, $\bar{B}_p^{SOC}$, and $\underline{B}_p^{SOC}$. The maximum power charging and discharging in the BSU are specified by $\bar{P}_p^{BSU,Ch}$ and $\bar{P}_p^{BSU,Dis}$, respectively.

Equations (6) and (7) state the energy balance and coefficient of the BSU degradation cost. The BSU's state of charge and its limitation are modeled by (8) and (9).

*4) Hydrogen storage unit (HSU)*

$$H_{t,p}^{HSU} = H_{t-1,p}^{HSU} + \left[ (M_{t,p}^{EL,H^2} - M_{t,p}^{FC,H^2}) \times (\frac{\tau^{HSU} .\xi}{\upsilon^{HSU}}) \right] \quad (12)$$

$$\underline{H}_p^{HSU} \le H_{t,p}^{HSU} \le \bar{H}_p^{HSU} \quad (13)$$

$$H_{In,p}^{HSU} = H_{0,p}^{HSU} \quad (14)$$

where, $M_{t,p}^{EL,H^2}$ ($M_{t,p}^{FC,H^2}$) presents the produced (consumed) hydrogen molar by the EL (FC) system. $H_{t,p}^{HSU}$ represents the stored hydrogen in the HSU. The gas constant, overall tank volume, and mean temperature are indicated by $\xi, \upsilon^{HSU}$, and $\tau^{HSU}$. $\bar{H}_p^{HSU}$ and $\underline{H}_p^{HSU}$ are the upper and lower limitations of the HSU. Equation (12) states the hydrogen balance in the HSU and its constraints are modeled by (13) and (14).

*5) Electrolyzer (EL) and Fuel cell (FC) systems*

$$M_{t,p}^{EL,H^2} = \frac{\eta^{EL} .P_{t,p}^{EL}}{LHV^{H^2}} \quad (15)$$

$$P_{t,p}^{FC} = \eta^{FC} .M_{t,p}^{FC,H^2} .LHV^{H^2} \quad (16)$$

$$M_{t,p}^{EL,H^2} \le \bar{M}_p^{EL,H^2} \quad (17)$$

$$M_{t,p}^{FC,H^2} \le \bar{M}_p^{FC,H^2} \quad (18)$$

$$\underline{P}_{p}^{EL} \leq P_{t,p}^{EL} \leq \bar{P}_{p}^{EL} \quad (19)$$

$$\underline{P}_{p}^{FC} \leq P_{t,p}^{FC} \leq \bar{P}_{p}^{FC} \quad (20)$$

where, $\eta^{EL}$ and $\eta^{FC}$ indicate the efficiency of the EL and FC. The lower heating magnitude for the hydrogen is specified by $LHV^{H2}$. Equations (17) and (18) ((19) and (20)) model the limitations for the hydrogen molar (power consumption/production) for the EL and FC units.

*6) Demand-side energy management (DSEM)*

Flexibility is a key for the MIEG that relies on 100% RERs for power production. The DSEM programs can provide a proper degree of flexibility for such a system by effectively utilizing the elasticity property of the dispensible loads. These DSEM schemes can be formulated as follows [19].

$$\text{Cost}_{t}^{DSEM} = CSL_{t} + CCL_{t} \quad (21)$$

$$CSL_{t} = \sum_{i=1}^{i_T} \lambda_{t}^{SL}.(P_{t,i}^{SL+}/2) \quad (22)$$

$$P_{t,i}^{Load} = P_{t,i}^{F,Load} + P_{t,i}^{SL} \quad (23)$$

$$P_{t,i}^{F,Load}.\underline{\kappa} \leq P_{t,i}^{SL} \leq P_{t,i}^{F,Load}.\bar{\kappa} \quad (24)$$

$$\sum_{t=1}^{t_T} P_{t,i}^{SL} = 0 \quad (25)$$

$$CCL_{t} = \sum_{i=1}^{i_T} [\alpha_{1}^{CL}.P_{t,i}^{CL} + \alpha_{2}^{CL}.(P_{t,i}^{CL})^2] \quad (26)$$

$$0 \leq P_{t,i}^{CL} \leq \bar{P}_{i}^{CL} \quad (27)$$

$$\underline{P}_{i}^{CL} \leq P_{t,i}^{Load} - P_{t,i}^{CL} \leq \bar{P}_{i}^{CL} \quad (28)$$

where, $CSL_t$ and $CCL_t$ are the cost of shiftable (SL) and curtailable (CL) loads in (22) and (26). $P_{t,i}^{SL}$ and $\lambda_{t}^{SL}$ present the amount of shifted demand and its price. $P_{t,i}^{F,Load}$ is the forecasted load and $P_{t,i}^{SL+}$ is the positive amount of $P_{t,i}^{SL}$ at all times. $\alpha_{1}^{CL}$ and $\alpha_{2}^{CL}$ are the coefficients for the cost of CL. Equations (24) and (25) ((27) and (28)) denote the limitations of the SL (CL) program.

*7) Electric power system*

$$P_{t,i}^{TPG} - P_{t,i}^{Fl}(\psi_{t,i},\theta_{t,i}) = P_{t,i}^{Load} \quad \forall t,i \quad (29)$$

$$Q_{t,i}^{TPG} - Q_{t,i}^{Fl}(\psi_{t,i},\theta_{t,i}) = Q_{t,i}^{Load} \quad \forall t,i \quad (30)$$

$$\underline{\Gamma}_{i,j} \leq \Gamma_{t,i,j}(\psi_{t,i},\theta_{t,i}) \leq \bar{\Gamma}_{i,j} \quad \forall t,i,j \quad (31)$$

$$\underline{\psi}_{i} \leq \psi_{t,i} \leq \bar{\psi}_{i} \quad \forall t,i \quad (32)$$

$$\underline{\theta}_{i} \leq \theta_{t,i} \leq \hat{\theta}_{i} \quad \forall t,i \quad (33)$$

where, the reactive and active power flow (generation) are presented by $Q_{t,i}^{Fl}$ and $P_{t,i}^{Fl}$ ($Q_{t,i}^{TPG}$ and $P_{t,i}^{TPG}$). The voltage of bus *i* and its phase angle are denoted by $\psi_{t,i}$ and $\theta_{t,i}$. $\Gamma_{t,i,j}$ indicates the complex power.

*8) Water systems*

The proposed water-energy nexus framework comprises the WSS, WW, and WD systems in the water sector. The WSS is exploited for ensuring the dynamic water supply in the grid. The operation of the WSS is subject to the following constraints [20].

$$P_{t,p}^{WS,Ch} = \left[ \left( \frac{Q_{t,p}^{WS,Ch}.G^{W}.D^{W}}{\eta^{wp}.(3.6\times 10^{+6})} \right) \cdot \left( \frac{L_{t,p}^{WS} + L_{t-1,p}^{WS} + L_{p}^{WS,A}}{2} \right) \right] \quad (34)$$

$$L_{t,p}^{WS} = L_{t-1,p}^{WS} + \frac{Q_{t,p}^{WS,Ch} - Q_{t,p}^{WS,Dis}}{\sigma^{WS}} \quad (35)$$

$$0 \leq L_{t,p}^{WS} \leq \bar{L}_{p}^{WS} \quad (36)$$

$$Q_{t,p}^{WS,Ch} \leq \chi_{t,p}^{WS,Ch}.\bar{Q}_{p}^{WS,Ch} \quad (37)$$

$$Q_{t,p}^{WS,Dis} \leq \chi_{t,p}^{WS,Dis}.\bar{Q}_{p}^{WS,Dis} \quad (38)$$

$$\chi_{t,p}^{WS,Ch} + \chi_{t,p}^{WS,Dis} \leq 1 \quad (39)$$

where, $P_{t,p}^{WS,Ch}$ and $L_{t,p}^{WS}$ are the consumed power by the WSS and its water level. $G^{W}$ and $D^{W}$ indicate the gravity and density of water. $\eta^{wp}$ is the efficiency of the water pump. $L_{p}^{WS,A}$ presents the altitude related to the water storage location. $\chi_{t,p}^{WS,Ch}$ and $\chi_{t,p}^{WS,Dis}$ are the binary variables for the charging and discharging states of the WSS. Equation (34) models the consumed power by the WSS. Equations (35) and (36) formulate the water balance in the WSS and its allowable changes. Equations (37) and (38) indicate the permissible range of charging and discharging of the WSS.

The WW and WD units are used for producing the required water for the system, which their operational limitations are given as [20]:

$$P_{t,p}^{WW,Dis} = \left[ \left( \frac{G^{W}.D^{W}}{\eta^{wp}.(3.6\times 10^{+6})} \right) \cdot \left( Q_{t,p}^{WW,Dis}.L_{p}^{WW} \right) \right] \quad \forall t,p \quad (40)$$

$$P_{t,p}^{WD} = \eta_{p}^{WD}.Q_{t,p}^{WD,O} \quad \forall t,p \quad (41)$$

$$0 \leq Q_{t,p}^{WD,O} \leq \bar{Q}_{p}^{WD,O} \quad (42)$$

$$P_{t,p}^{TWC} = P_{t,p}^{WW,Dis} + P_{t,p}^{WS,Ch} + P_{t,p}^{WD} \quad (43)$$

where, $P_{t,p}^{WW,Dis}$ and $L_{p}^{WW}$ are the consumed power by the WW and its water level. $P_{t,p}^{WD}$ and $\eta_{p}^{WD}$ are the consumed power by the WD and its efficiency. Equations (40) and (41) model the consumed power by the WW and WD units. Equation (43) state the total power consumption in the water system.

## *D. Uncertainty Quantification*

Uncertainty modeling is one of the key steps in scrutinizing the MIEG for giving a realistic overview regarding the stochastic changes of uncertain parameters. In this work, due to the operation of 100% RERs, their intermittent outputs are intended as uncertain parameters. As the effective method is required to properly model the probabilities in the power production, the ARIMA method is exerted for the uncertainty quantification. The ARIMA approach pursues the time series-based process in scenario generation and provides a stationary condition for the mean. Since the numerous scenarios are not suitable for practical cases, their numbers should be effectively reduced in stochastic programming. Due to this, the FFR method is applied for scenario reduction. The FFR method is worked based on computing and minimizing the Kantorovich distance of scenarios to overcome the complexity and computational burden of the problem. The full descriptions regarding the ARIMA and FFR processes can be respectively found in [21] and [22].

## III. SIMULATION RESULTS AND DISCUSSION

This research aims at proposing a novel water-energy nexus management model for optimally controlling energy interactions of prosumers that are equipped with 100% RERs. The RERs and BSU are used to allow the system for fully clean energy production [23]. The P2X2P framework with the EL, FC, and HSU is developed for increasing the flexibility of the system in proper usage of the generated clean power [24]. The WW, WD, and WSS are the water systems that have enabled the water sector for a sustainable water supply [20]. Fig. 2 portrayed the prosumers in the IEEE 6-bus test system that is used for investigating the prosumers' energy interactions.

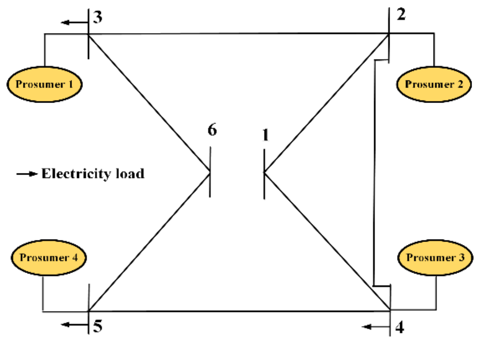


Fig. 2. The structure of the IEEE 6-bus distribution system

In this optimization problem, the general algebraic modeling system (GAMS) software is used for solving the problem. The problem is analyzed in two models in which Model I considers the deterministic version of the problem while Model II is targeted for probabilistic modeling of the system. The amount of objective function is respectively obtained $33,368.6 and $40,353.03 for Models I and II after solving the related problem. Additionally, the detailed financial results for prosumers are listed in Table I.

TABLE I. ENERGY COSTS AND REVENUES FOR PROSUMERS

| | Financial indicators | Prosumers (Pro) | | | |
|---|---|---|---|---|---|
| | | ***Pro 1*** | ***Pro 2*** | ***Pro 3*** | ***Pro 4*** |
| **Model I** | ***Energy Revenue*** | 3,194.49 | 969.08 | 4,383.93 | 2,875.35 |
| | ***Energy Cost*** | 8,224.95 | 12,175.3 | 14,370.4 | 10,020.8 |
| | ***Total cost*** | 5,030.46 | 11,206.22 | 9,986.47 | 7,145.45 |
| **Model II** | **Financial indicators** | ***Pro 1*** | ***Pro 2*** | ***Pro 3*** | ***Pro 4*** |
| | ***Energy Revenue*** | 3,229.98 | 1,290.99 | 4,505.99 | 2,887.7 |
| | ***Energy Cost*** | 11,689.52 | 12,888.66 | 14,726.56 | 12,962.95 |
| | ***Total cost*** | 8,459.54 | 11,597.67 | 10,220.57 | 10,075.25 |

The financial information in Table I indicates that prosumers have been exposed to a high amount of energy costs in Model II than Model I. In other words, considering different states of occurrence for the uncertain parameters in the probabilistic modeling of prosumers' energy interactions in Model II has imposed more energy costs for them in comparison with Model I. The variation profiles for the different units in the electric power system are demonstrated in Fig. 3.

The information in Fig. 3 presents that the system has a more clean energy production by the wind turbine in the initial hours of the day (1 am to 5 am). The surplus produced power in the mentioned time period is used for charging the BSU aiming to keep it as the backup for later times.

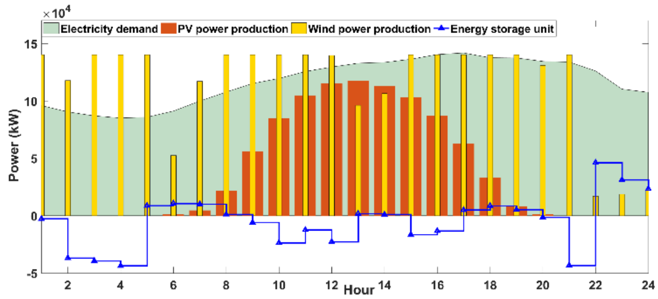


Fig. 3. Outputs of the different electrical energy systems during a day

Following the reduction of the wind turbines' output and due to the minimum power generation by the PV units from 5 am to 8 am, the system has witnessed a remarkable reduction in the energy production and the other supporter choices such as discharging of the BSU and energy trading with the main grid are used for maintaining the stability of the system in energy supply. In the mid-hours of the day, prosumers have advantaged the maximum wind and PV power productions and discharging of the BSU in meeting the power load. This is while they have faced significant energy shortages in the last hours of the day driving them to use the potential of the BSU and energy sharing with the upstream grid for providing the required energy of consumers. In this work, the EL and FC systems along with the DSEM schemes and energy trading possibility are used for upsurging the flexibility of prosumers in the deregulated environment, which their changes during 24-hours are illustrated in Fig. 4.

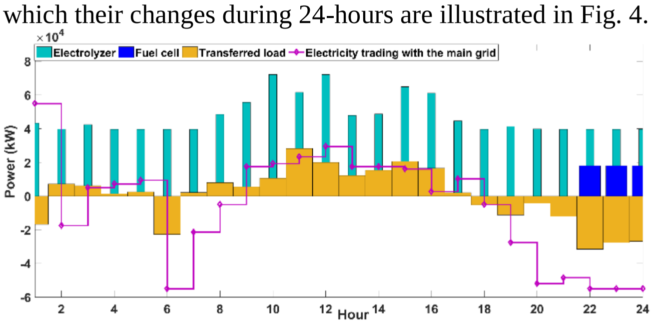


Fig. 4. Optimal set points for the EL, FC, DSEM program, and energy sharing with the main grid

In Fig. 4, the system has been scheduled for a minimum operation of the hydrogen-based systems in the early morning due to the lower energy consumption at this time period. Also, besides prosumers had an opportunity for selling a lower level of surplus energy to the main grid for obtaining benefits, a lower portion of the energy load is transferred to this period for supplying in the DSEM program. By increasing the outputs of RERs in the peak times, a portion of produced power is used by the EL for producing hydrogen molar and storing it in the HSU for later use. Moreover, prosumers have sold more energy to the upstream grid for maximizing their profit and a high portion of their load is also moved to this time period for supplying given a plausible power generation. This is while the maximum purchased power from the main grid as well as shifting load are occurred from 8 pm to 12 pm when the system suffers from the sufficient energy production by RERs. Furthermore, the FC potential is used to support prosumers in dynamically serving power demand. In this study, as another part of the proposed water-energy nexus model, the water systems are also operated for increasing the flexibility of prosumers in the presence of 100% RERs that their outputs are shown in Fig. 5.

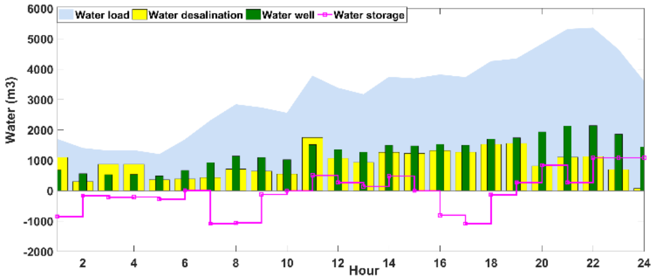

Fig. 5. Outputs of the different water systems during a day

According to Fig. 5, the WW and WD systems have experienced a lower operation level from 1 am to 5 am due to the minimum water demand at these times. The water sector even witnessed to charging of the WSS in the mentioned hours. By sensible increasing the water demand in the mid-hours of the day, the operation of water systems especially the WW unit is increased to properly respond to the load increment. Additionally, the WSS has been accompanied by other water systems in meeting the water demand of the noon hours. However, prosumers have been faced with the maximum water load at night that is resulted in a substantial reaction of the WW, WD, and WSS in upsurging the water production for serving water load.

## IV. Conclusion

This work proposed an innovative water-energy nexus model for optimal energy management of prosumers that are equipped with 100% RERs for fully clean power generation. The P2X2P technology was developed to procure a proper link between water and power systems and increase the sustainability and reliability of the MIEG in continuous water and power supply. The DSEM schemes were also employed for increasing the system's flexibility in the energy management process. Due to the uncontrollability feature of RERs in power production, the uncertainty modeling process was carried out by generating scenarios using the ARIMA method and reducing their numbers by applying the FFR approach. The model validation was done by assessing two models in which Model I was for the deterministic analysis while Model II was for the probabilistic modeling of the system. The extracted results denoted the applicability of the suggested model in providing sustainable conditions for the power and water sectors in the energy supply.

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