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Risk-Oriented Operational Model for Fully Renewable Cooperative Prosumers in a Modern Water-Energy Nexus Structure

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***Abstract*-- The day-by-day increment in the demand for diverse types of energy together with the CO_2-based climate concerns has intensified the need for innovative decarbonization plans leading the energy sector to produce clean, cost-effective, and reliable multi-energy. Herein, inevitable water and power interactions unlock significant benefits for the integrated energy network in the form of water-energy nexus models. In this work, a holistic water-energy nexus model is developed for the operation of cooperative prosumers equipped with 100% renewables in the modern interconnected energy structure. The model is empowered by the transactive energy technology to allow prosumers to cooperatively share multi-energy with each other for reliably serving power and water in a deregulated environment. The proposed model also benefits from hydrogen-based energy conversion units that not only improve the flexibility of prosumers in reliable energy supply but also increase their economic achievements by selling the produced gas to the gas grid. As prosumers are targeted for fully clean energy production, their contributions in the energy interactions are under the high level of risks associated with renewables' intermittences. Due to this, a risk-averse stochastic operational model is proposed that enables the decision-maker to adopt optimal strategies against the uncertain fluctuations in the system. The effectiveness of the proposed model is examined considering prosumers located in Chicago, USA. According to the obtained results, the model can affordably facilitate the realization of Chicago's plans for achieving the goal of equipping with 100% renewable energy sources for a fully clean multi-energy generation.**

***Index Terms*-- Water-energy nexus, transactive energy, 100% renewables integration, grid modernization, risk-oriented operation, integrated power and water grids**

NOMENCLATURE

Indices

p	Index for prosumers
t	Index for times
j,i	Index for the electric power system (EPS)'s buses

Parameters

$\lambda_t^{S,E}, \lambda_t^{S,G}$	Selling price for the electrical and gas energy
$\lambda_t^{Ex,E}, \lambda_t^{Ex,W}$	Power and water exchanging prices
$\lambda_t^{S,W}$	Water selling price for the consumers
Π_p^{BSS}	Degradation cost of the battery storage system (BSS)
$E_{t,i}^{Load}, W_{t,p}^{Load}$	Power and water demand
$\eta_P^{B,C}, \eta_p^{B,L}$	Charging/discharging and leakage loss factors
$\Psi_p^{R,BSS}$	Rated energy capacity for the BSS
$\hat{P}_p^{DE,BSS}$	Maximum level for discharging of the BSS
$\hat{P}_p^{CE,BSS}$	Maximum level for charging of the BSS
$\Psi_{In,p}^{BSS}, \Psi_{End,p}^{BSS}$	The amount of BSS's energy in the first and last hours of the day
$L_p^{NC,B} / IC_p^{BSS}$	Life cycle number/investment cost for the BSS
$\square_t^{SP}, \aleph_t$	Solar radiation and wind speed at time t
$\aleph_p^{Ra}, P_p^{R,WT}$	Rated wind velocity and power for prosumer p
$\eta_p^{SP}, \Im_P^{SP}$	Efficiency of solar panels and number of their cells
$\wp_{SP}^{ST}, \varepsilon^{SP}$	Coefficients for the solar panel modeling
$\wp_{SP}^{AT}, \Omega_p^{HS}$	Ambient and mean temperature values
$\aleph_p^{C-I} / \aleph_p^{C-O}$	Cut-in/cut-out velocities for the wind turbine (WT)
$\ell_a^{WT}, \ell_b^{WT}, \ell_c^{WT}$	Coefficients for modeling the output of the WT
$\varsigma_p^{LR1}, \varsigma_p^{LR2}$	Coefficients for computing the cost of the load response (LR) program
$\lambda_t^{PR}, \square_{t,p}^{F,L}$	Price of the price response (PR) program and the forecasted amount of the power demand
γ^{H2}	Lower heating value for the hydrogen
$\eta_p^{ME} / \eta_P^{EL} / \eta_p^{FC}$	Efficiency of the methanization (ME)/electrolyzer (EL)/fuel cell (FC)
$\tau_{HS}^{G} / \mu_p^{H2}$	Gas constant/volume for the hydrogen storage
ϕ^W, Υ^W	Density and gravity of the water
η_p^{WD}, η_p^W	Efficiency of the water desalination (WD) and water pump in the water distribution network (WDN)
Γ_p^{WW}	Water level of the water well (WW)
$\Gamma_{t,p}^{WS,A}$	Water storage location altitude
ϖ^W, ϖ^E	Upper-level for the water and power trading
$P_{t,i}^{E,De}, \square_{t,i}^{E,De}$	Active and reactive power demands
$\Re_{i,j}^E, X_{i,j}^E$	Resistance and reactance of the line *i-j*

Variables

$\mathrm{Cost}_t^{E,DSEM}$	Cost of the demand-side energy management
$P_{t,p}^{E,BSS}, \Psi_{t,p}^{BSS}$	Charging and discharging power of the BSS and its energy level
$P_{t,p}^{TE,WC}$	Total power consumption in the water network
$P_{t,p}^{G,ME}$	Produced gas by the ME unit
$P_{t,p}^{E,Ex}, Q_{t,p}^{Ex,W}$	Power and water exchanging in the system
$\Upsilon_{t,p}^{BSS}$	State-of-charge level for the BSS
$P_{t,p}^{E,SP}, P_{t,p}^{E,WT}$	Produced power by the PV panel and wind turbine
$\square_{t,p}^{PR,L}, \square_{t,p}^{LR,L}$	The power and water amounts in the PR and LP
$HM_{t,p}^{FC}, HM_{t,p}^{ME}$	Consumed hydrogen molar by the FC and ME

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$P_{t,p}^{E,FC}, P_{t,p}^{G,ME}$	Produced power and gas by the FC and ME units
$P_{t,p}^{E,EL} / HM_{t,p}^{EL}$	Consumed power/produced hydrogen by the EL
$\mathfrak{I}_{t,p}^{HSU}$	Stored hydrogen in the hydrogen storage
$P_{t,p}^{E,LP} / P_{t,p}^{E,PL}$	Received/transmitted power by prosumers from/to the water and power trading local market (WPTLM)
$\Gamma_{t,p}^{WS}$	Water level in the water storage
$Q_{t,p}^{LP,W} / Q_{t,p}^{PL,W}$	Received/transmitted water by prosumers from/to the WPTLM
$U_{t,p}^{E,L2P}, U_{t,p}^{E,P2L}$	Binary variables for the state of power transactions in the WPTLM
$U_{t,p}^{W,L2P}, U_{t,p}^{W,P2L}$	Binary variables for the state of water transactions in the WPTLM
$V_{i}^{PF}, I_{i,j}^{PF}$	Voltage and current flow in line *i-j*
$P_{t,i}^{E,Ge}, □_{t,i}^{E,Ge}$	Active and reactive power generations
$□_{i,j}^{E,Fo}$	Complex power in line *i-j*

I. Introduction

A. Motivation and Literature Survey

RECENT evolutions in the multifarious technologies have caused the born of new energy-dependent systems that face the energy sector with the crisis of energy supply created by ever-increasing energy consumption. Driven by the necessity for curbing global emissions, decarbonization strategies have attracted more popularity in realizing large-scale penetration of renewables around the world. Although zero-marginal cost and carbon-free renewable energy offer tremendous advantages, it brings critical challenges to balancing energy for the grid's operators entailing the necessity of deploying flexibility paradigms in overall system planning, design, and operation to securely accommodate a high or full level of such sources of variability [1]. Herein, the idea of using the energy links and dependencies among different energy networks is flourished for secure accommodating a high level of renewable systems (RSs) by coupling multi-energy grids. In this respect, water-energy nexus frameworks reflect inseparable interactions between power and water networks, making them cornerstones of modern energy community infrastructure [2]. As future modern energy grids (FMEGs) are planned to be a host of 100% RSs, water-energy nexus frameworks cannot be a sufficient option alone for the assurance of reliable and continuous power and water supply. Indeed, FMEGs require a set of innovative flexibility tools that are creatively designed for making the fully carbon-free multi-energy generation feasible in the coupled power and water network (CPWN). However, the system suffers from the lack of a holistic model that is designed in a way to enable CPWNs to confidently benefit from the presence of 100% RSs and supports the realization of net-zero carbon energy infrastructure. Due to this, the present article develops a novel water-energy nexus-based model for cooperative Chicago's prosumers aiming to enable them to use 100% RSs for reliably clean power and water supply in the CPWN.

In the context of CPWNs, recent literature states different water-energy nexus models that are manipulated for solving various challenges by involving diverse techniques in the system assessment. This attention is mostly raised to power and water interactions in reaction to the call for practical solutions for the optimal exploitation of power and water energy systems. For capturing interdependencies in power and water interconnected grids, the authors proposed mathematical formulations and appropriate network models in [3] for optimally controlling unit dispatch considering the operating conditions of both power and water distribution networks. Jointly managing power and water units is also intended in [4] to avoid threats coming from independent modeling of them, which is addressed by proposing an energy-water system simulation methodology to quantify and adapt various modeling assumptions under diverse different weather changes. In [5], the authors proposed a water-energy nexus model for the optimal scheduling of energy hubs by developing a multi-objective optimization methodology aiming to minimize both the total energy cost and extracting the fresh water from the water well. This study also benefited the electricity and thermal energy sharing between energy hubs for achieving more cost savings. Optimizing the energy flexibility is intended in [6] for the water network in the operation of day-ahead power grids by proposing a new model to achieve optimal set points for tanks, pumps, and other devices with the aim of minimizing the operational costs of local water distribution systems. This is while the co-optimization of power and water distribution networks is conducted in [7] by suggesting a two-stage distributionally robust exploitation model for managing water-energy nexus systems considering strong interconnections between them.

As mentioned studies have concentrated on solving different challenges in the optimal operation of CPWNs, the highly penetrated renewable structure of CPWNs is surrounded by uncertainties of RSs as another key challenge of optimally managing CPWNs. Recent efforts in the research world are formed to address the mentioned challenge by developing various uncertain-aware models. For instance, a novel analytic is developed in [8] for the uncertainty-aware day-ahead exploitation optimization of the integrated water and power systems that captures uncertainties of water demand and wind resources using stochastic programming. The authors have tried to provide a reasonable response to major criticisms against 100% RSs in [9] by proposing cost-optimization modeling to access higher shares of solar and wind tended from greater resource availability and energy supply diversification. A holistic vision for the transition to the net-zero carbon economy was the result of this assessment that can confine global warming to 1.5°C based on 100% RSs. Achieving greater economic benefits by interconnecting the power network with 100% RSs is scrutinized in [10] by comparing eight interconnection programs for three regional networks in North America, North-East Asia, and Europe. The economic benefits of a global power network with 100% RSs are assessed in [11], which indicates economic justifications for the energy transition towards full renewables under the 'Net-Zero 2050' goal of the United Nations. To overcome challenges ahead of implementing 100% RSs schemes, five methods are proposed in [12], concentrating on addressing short-term fluctuations of wind power in several balancing areas. This is while solving the mismatch of demand and supply is intended in [13] by presenting a regional renewable assessment method for identifying the best locations of RSs aiming to pave the achievement of 100% RSs. Moreover, long-term planning of the system with

100% RSs is performed in [14] by proposing a new modeling framework combined with robust and stochastic programming to tackle multiple uncertainties.

In CPWNs, the integration of power and water desalination has also found special attention for developing the most efficient water-energy nexus frameworks in recent literature. In this regard, a new model is offered in [15] for decreasing the total cost of desalinated water by coordinated scheduling of water desalination and power production units. The coordinated operation of renewable-rich power grids and water desalination systems is conducted in [16] by suggesting a two-stage co-optimization framework with the aim of maximizing the utilization of RSs as well as minimizing the overall cost of the system. The long-term scheduling of a similar integrated structure is accomplished in [17] by designing a supervisory control system for the optimal energy management of reverse-osmosis water desalination unit and incorporated solar-wind energy production system. In this respect, due to the importance of optimal participation of water desalination units in power regulation and load response markets, a new model is offered in [18] to do this by integrating the available flexibility of water units in the CPWN. Given the considerable uncertainties in the renewable-rich CPWN, the robust exploitation of the water-energy nexus system is accommodated in [19] to provide the required robustness of the integrated network. This is while such uncertainties are modeled by exerting stochastic programming in [20] that pursues the main goal of optimal operating water-energy systems by suggesting a new hard-coupling modelling framework. In such an uncertain environment, the system may face the surplus produced power by RSs that needs to be effectively managed. To do this, the authors suggested a novel framework in [21] to utilize water tanks and pumps for effectively absorbing the extra generated electricity in the power sector. The reliable water and power supply may also be affected by different contingencies that make the resiliency assessment of the CPWN essential. In this regard, the resilient exploitation of the CPWN is taken into account in [22] and [23] by respectively proposing a novel formulation and a new methodology along with new metrics aiming to properly determine the integrated network resilience. Moreover, the optimal exploitation of the CPWN is studied in [24] by proposing a novel optimization model considering various contingencies in the water-power nexus structure.

All of the mentioned studies indicate that 100% RSs will be an inseparable part of FMEGs stating the urgent need for the most comprehensive models supporting the full presence of renewables in the grid. Nevertheless, developing a holistic water-energy nexus model for optimal exploitation of CPWNs with 100% RSs has still remained as a prominent challenge. Indeed, utilizing 100% RSs is undeniable for delivering carbon-free multi-energy in future modern CPWNs that require a plenary model for supporting full usage of renewables, maintaining the sustainability of water and power grids, providing reliable conditions in serving power and water, as well as allowing prosumers for easily satisfying their goals. This paper is structured to provide the aforementioned advantages for cooperative prosumers by developing a novel transactive energy-based water-energy nexus model that enables CPWNs to reliably use 100% RSs as well as realize the goal of reaching technical, environmental, and economic benefits for the incorporated system. Since all prosumers possess 100% RSs for energy generation, the risk of the system's operation is high for the system's operation due to the uncertainties of multifarious uncertain parameters with various stochastic changes. This issue makes the condition more difficult for the decision-maker to make suitable decisions associated with the goals of the system, in which deploying a capable technique is crucial for gaining appropriate solutions. To this end, this work develops a hybrid uncertainty quantification technique that simultaneously benefits the advantages of both Conditional Value at Risk (CVaR) and stochastic programming.

TABLE I: SUPERIORITIES OF THIS ARTICLE IN COMPARISON WITH RECENT STUDIES

Ref.	**CPWN structure**	**Integrated energy management**		**TE-WEN model**	**WPTLM area for energy sharing**	**Uncertainty modeling approach**	**100% RSs**
		Water	**Power**				
[3]	✓	×	×	×	×	×	×
[19]	✓	×	×	×	×	Robust optimization	×
[4]	✓	×	×	×	×	Stochastic programming	×
[5]	✓	×	×	×	×	×	×
[21]	✓	×	×	×	×	×	×
[6]	✓	×	×	×	×	×	×
[8]	✓	✓	✓	×	×	Joint probabilistic constraint	×
[9]	×	×	×	×	×	×	✓
[10]	×	×	×	×	×	×	✓
[25]	×	×	×	×	×	Robust and stochastic programming	✓
[11]	×	×	×	×	×	×	✓
[12]	×	×	×	×	×	×	✓
[13]	×	×	×	×	×	×	✓
[22]	✓	×	×	×	×	×	×
[20]	✓	×	×	×	×	Stochastic programming	×
[7]	✓	×	×	×	×	Distributionally robust optimization	×
[26]	✓	×	×	×	×	×	×
[27]	✓	×	×	×	×	×	×
[28]	✓	✓	✓	×	×	Points estimate method	×
[15]	✓	✓	✓	×	×	×	×
[17]	✓	✓	✓	×	×	×	×
[16]	✓	✓	✓	×	×	Stochastic programming	×
[18]	✓	✓	✓	×	×	×	×
This paper	✓	✓	✓	✓	✓	CVaR stochastic (ARIMA with FFS)	✓

As intending the most suitable scenarios is essential for properly modeling uncertainties, an autoregressive integrated moving average (ARIMA) is employed for scenario generation, whereas the most effective scenarios are selected by the fast forward selection (FFS) technique. Table I effectively poses the superiorities of this work in comparison with recent studies in the field.

B. Research Gaps and Contributions

Despite the fact that recent literature encompasses a variety of water-energy nexus models to cover relevant challenges, some critical challenges have still remained in line with their properness for FMEGs. 1) At first, modernizing CPWNs requires a novel structure that can support the usage of 100% RSs, different energy conversion processes, multi-energy interactions of prosumers, as well as retaining the sustainability of the system. However, such a structure is not offered for CPWNs yet to have elements and processes for bringing the above-mentioned benefits. This is while the development of the renewable-dominant structure is one of the basic and critical requirements for modernizing CPWNs. 2) The second gap is related to the lack of a holistic water-energy nexus model equipped with the capable technologies to make the uninterrupted water and power supply possible in the presence of 100% RSs. Advancing such models is crucial to reach the key goal of generating fully zero-carbon power and water leading to the achievement of great environmental advantages for CPWNs. This is while the recently suggested models have not developed such technologies to not only offer reliable multi-carrier energy supply but also support cooperative prosumers in easily following their environmental, technical, and economical objectives. 3) Another key gap back to not developing an appropriate technique for uncertainty quantification of the CPWN with 100% RSs that faces a high range of uncertainties making optimal decisions difficult to adopt for the decision-maker. Indeed, utilizing 100% RSs in power generation premises significantly increases the risk of optimally exploiting the incorporated grid so that effectively managing such risks is an indispensable step in gaining confident results. Nevertheless, suggesting such a method is overlooked in recent works for prosumers in CPWNs with 100% penetration of RSs. To address the mentioned crucial gaps, this article offers the following contributions.

- This work proposes a novel structure for cooperative prosumers with 100% renewable systems allowing them to produce fully eco-friendly clean multi-energy, reliably serve multi-energy to consumers, share affordable and cooperative water and power in the local area, use energy storage and conversion processes for the flexibility, as well as benefit appropriate schemes for managing energy of the demand-side. The proposed structure is novel for its ability in tightening the interoperability among various devices of the hybrid system leading to purposeful management of multi-energy in the backbone of CPWNs.
- This article develops a new water and power trading local market (WPTLM) based on the transactive energy architecture to procure free energy exchanging for cooperative prosumers. Indeed, transactive energy-based water and power transactions in the local area facilitate the adoption of 100% RSs by increasing the flexibility of prosumers in the system. This transactive paradigm also alleviates the prosumers' reliance on the upstream grid in supplying water and power by localizing the creation of an energy balance.
- To optimally exploit prosumers with 100% RSs in the CPWN, this work proposes a water-energy nexus model that is holistic for its ability in supporting the integration of 100% RSs, retaining the sustainability of the integrated network, offering mixed-integer linear programming (MILP) mathematical formulations, improving the system's flexibility by using energy storage and conversion facilities, establishing energy sharing possibilities, as well as exerting effective schemes for managing energy interactions in the demand-side. The proposed model possesses a practical vision of promoting 100% RSs by relying on developing viable solutions as well as water-energy nexus strategies.
- Given prosumers are exposed to a higher risk of the operation due to equipping with 100% RSs, a CVaR stochastic approach is proposed for the uncertainty quantification by generating scenarios based on the ARIMA method while reducing their number by adopting the FFS. The applied method eases the decision-making for prosumers to make optimal decisions in line with their goals and in the presence of 100% RSs. It also takes the uncertain fluctuations of multifarious random variables into account for effectively assessing the risk of exploiting prosumers with 100% RSs.

The remainder of this article possesses the following organization. Section II describes the water-energy nexus structure for cooperative prosumers. Problem formulations and designing of the WPTLM environment are presented in Section III. Section IV includes the simulation results alongside the relevant discussions. Section V presents the conclusion.

II. Water-Energy Nexus Structure for Prosumers

This work proposes a novel water-energy nexus structure for prosumers to provide a viable solution for reliable usage of 100% RSs in the CPWN. Fig. 1 portrays the schematic of this structure for cooperative prosumers. In the power sector, wind turbines (WTs) and solar panels (SPs) have the responsibility of producing fully net-zero carbon energy for consumers. The main supporting duty from stochastic producers has been assigned to the battery storage system (BSS), whose charging and discharging options let the system effectively store clean energy in energy-rich times. A portion of excess power is delivered to the energy conversion sector, where the electrolyzer (EL) plays a central role in generating hydrogen molars by consuming power and water. The produced hydrogen has three ways to go after leaving the EL. It can be stored in the hydrogen storage unit (HSU) for later use or can be consumed by the fuel cell (FC) and methanization (ME) units for respectively generating power and gas supporting their networks for continuously meeting power and gas demands. The operation of ME is not only to further improve the flexibility of prosumers in the presence of 100% RSs but also to increase their economic benefits by selling the produced gas to the gas network. Indeed, modeling gas systems and network is not the main focus and objective of this work and here, the existence of the natural gas directly depends on operating the ME, which this unit is considered for improving the flexibility and economic benefits of prosumers.

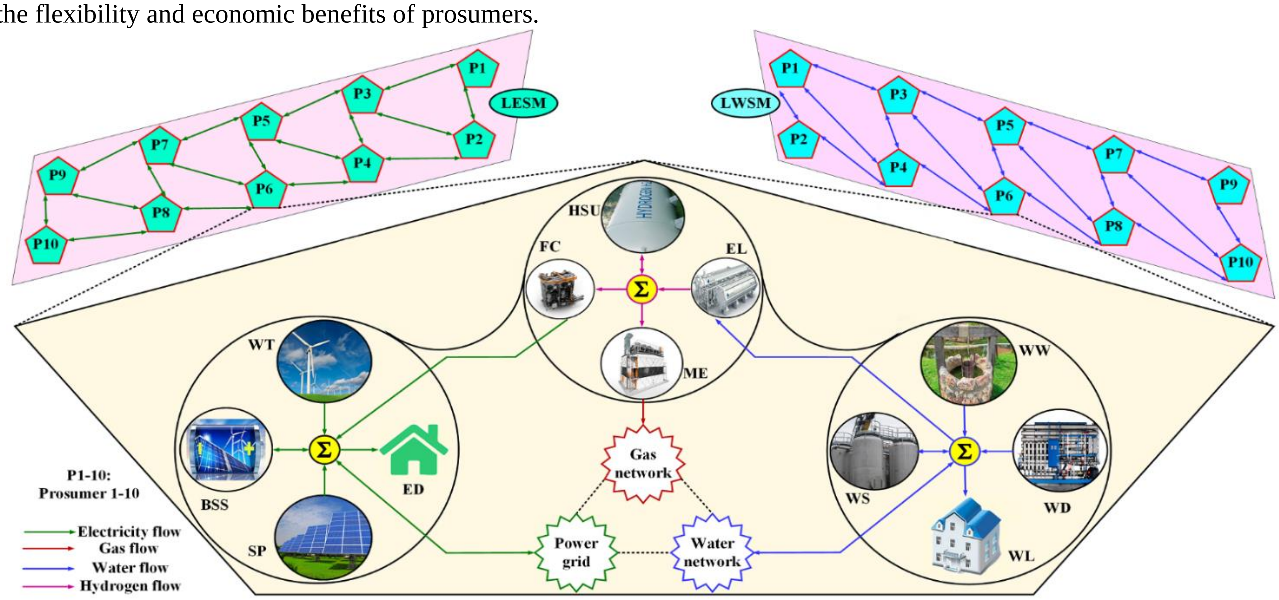

Fig. 1. The proposed structure with 100% RSs for cooperative prosumers.

According to Fig. 1, the water network is another sector that relies on receiving power for operating its devices. In this study, it is assumed that each prosumer is equipped with a water well (WW) and water desalination (WD) units for producing water as well as the water storage (WS) system for upsurging the reliability of the water supply for the water consumers of each prosumer. Indeed, it is assumed that all prosumers benefit from water systems located at the end-use level and the water distribution network is not considered for water interactions at the network level. The WD in producing water, the WW in the discharging mode, and the WS in the charging mode require electricity as the primary energy. As prosumers are empowered by 100% RSs, they need several ways to have enough flexibility for unbroken power and water supply. For this aim, this article develops an innovative WPTLM using the transactive energy paradigm aiming to allow prosumers to cooperatively share water and power with each other at the local level that supports them in reliably meeting their energy demand, keeping the system's sustainability, and achieving their goals in terms of technical, economical, and environmental. In this respect, the WPTLM consists of local water and electricity sharing markets (LWSM and LESM) for creating the possibility of free water and power transactions for prosumers. According to Fig. 1, all prosumers can share water and power with each other based on the transactive energy paradigm in the LWSM and LESM allowing them to sustainably manage multi-energy interactions in the full presence of RSs. In this work, the intended flexibility ways for prosumers are not just limited to the energy storage, conversion, and trading mechanisms, and effective schemes are also adopted for energy management. Following this, the load response (LR) and price response (PR) mechanisms are used to increase prosumers' flexibility by demand-side energy management (DSEM).

III. Optimal Operation of Prosumers

A. Objective Function and Uncertainty Quantification

In this research, minimizing the overall cost of prosumers is the objective function that is as follows.

$$\Xi_p = \Xi^{BSS} + \Xi^{DSEM} + \Xi^{WC} - \Xi^{ME} - \Xi^{E,Ex} - \Xi^{Ex,W} - \Xi^{S,E} - \Xi^{S,W} \quad (1)$$

$$\Xi^{BSS} = \sum_{t=1}^{t_T} [(\Psi_{t,p}^{BSS}.\eta_p^{B,L} + P_{t,p}^{E,BSS+}).(\Pi_p^{BSS})] \; ; \; \Xi^{S,W} = \sum_{t=1}^{t_T} \lambda_t^{S,W}.W_{t,p}^{Load}$$

$$\Xi^{DSEM} = \sum_{t=1}^{t_T} \mathrm{Cost}_t^{E,DSEM} \; ; \; \Xi^{WC} = \sum_{t=1}^{t_T} \lambda_t^{S,E}.P_{t,p}^{TE,WC}$$

$$\Xi^{ME} = \sum_{t=1}^{t_T} \lambda_t^{S,G}.P_{t,p}^{G,ME} \; ; \; \Xi^{E,Ex} = \sum_{t=1}^{t_T} \lambda_t^{Ex,E}.P_{t,p}^{E,Ex}$$

$$\Xi^{Ex,W} = \sum_{t=1}^{t_T} \lambda_t^{Ex,W}.Q_{t,p}^{Ex,W} \; ; \; \Xi^{S,E} = \sum_{t=1}^{t_T} \sum_{i=1}^{i_T} \lambda_t^{S,E}.E_{t,i}^{Load}$$

In (1), Ξ_p is the objective function of prosumers. The first term mathematically describes the operation cost for the BSS. The second term indicates how much the cost is for DSEM. The third term models the power used for water sector consumption. The fourth term models the gas sold to the gas network. The fifth and sixth terms are the revenue/cost of power and water sharing with the main grid. The last two terms denote the revenue of selling power and water to consumers. In these two terms, $E_{t,i}^{Load}$ and $W_{t,p}^{Load}$ are the electricity and water demands that are variables and are defined in equation (21).

In this paper, all prosumers are equipped with 100% RSs that impose huge uncertainties on the system's operation. This issue makes optimal decision-making challenging and under a higher risk of uncertainties. Due to this, the CVaR stochastic method is adopted for risk-based analysis of the system aiming to enable the decision-maker for setting optimal decisions. On the other hand, uncertain parameters such as wind speed can experience stochastic variations in a large deviation range. For modeling uncertain behaviors of such uncertain parameters, considering different states of changes for the uncertain parameter in its deviation horizon along with the state occurrence probability is essential for realistic modeling of the system. For this aim, stochastic programming is applied to take multifarious stochastic changes of RSs into account by generating scenarios using the ARIMA method and selecting the most applicable ones by exerting the FFS technique. Therefore, the CVaR stochastic technique is developed for the uncertainty quantification of prosumers with 100% RSs to enable the system for simultaneously risk-based assessing the optimal exploitation problem while intending the different states of occurrence for uncertain parameters by using scenario-based approaches. In the ARIMA [29], three parameters, including the number of autoregressive parameters (*a*), the number of moving average parameters (*b*), and differentiating order (*c*) are used for its definition as:

$$\left(1-\sum_{\kappa=1}^{a} B^{\kappa}\zeta_{\kappa}\right).\Pi_{t\omega}.(1-B)^{c} = \left(1-\sum_{\kappa=1}^{b} B^{\kappa}\xi_{\kappa}\right)\varphi_{t} \qquad (2)$$

where, φ_t states the error term and B^{κ} is the backshift operator. $\Pi_{t\omega}$ presents the produced scenarios at time *t* and scenario ω. In (2), the right and left sides of the equal denote the moving average and autoregressive parts, respectively. In the SP, selecting candidate scenarios with a high occurrence probability is an urgent step to avoid complexity and computational burden for practical problems. How to effectively select such scenarios has driven us to apply the FFS technique. Indeed, the FFS is designed for scenario reduction that works based on the Kantorovich distance of scenarios [30].

The selected scenarios are considered for the risk-oriented assessment of cooperative prosumers using the CVaR approach. To this end, given the cost minimization as the objective, we develop the mathematical model to find the optimal decision variables that can be resulted in minimizing the worst-case cost for all possible realizations of ρ according to the following equation.

$$\min_{P} \ \max_{\rho} \ \Xi_{p}(P,\rho) \qquad (3)$$

where, ρ and P are a set of random model parameters and decision variables.

In the probabilistic modeling of the system, the robust-based methods can yield the most conservative solutions than stochastic ones due to considering the worst state of occurrence for the uncertain parameter [31]. However, stochastic-based methods consider all the favorable and unfavorable changes of the uncertain parameter along with the related occurrence probability by generating scenarios for the different states of the uncertain parameter that may lead to less conservative solutions [32]. As the CVaR stochastic method is exerted here for the uncertainty quantification, so adopting the related probabilistic framework to this problem may yield less conservative solutions in comparison with robust optimization. Due to this, minimizing the *β*-percentile of the distribution related to $\Xi_p(P,\rho)$ induced by P_{ρ} (probability density function of ρ), *β-VaR*, can offer one possible solution as follows.

$$\beta-VaR \ \square\ \min\left\{\alpha\in\square : \ P\left\{\Xi_p(P,\rho)\le\alpha\right\}\ge\beta\right\}, \ 0\le\beta\le 1. \quad (4)$$

Indeed, *β-VaR* is defined as the smallest cost α for a given confidence level *β*. Although this model is a very popular risk measure in portfolio and finance optimization, subadditivity and lack of convexity are undesirable mathematical attributes that have made VaR an unattractive option and a non-coherent risk measure for practical problems [33]. To address the mentioned problem, CVaR is defined for *β* as follows.

$$\beta-CVaR \ \square\ \square_{\rho}\left\{\Xi_p(P,\rho)\,\middle|\,\Xi_p(P,\rho)\ge\beta-VaR\right\}, \qquad (5)$$

In fact, unlike traditional robust optimization techniques, minimization of CVaR makes the system more flexible in selecting the objective and offers potential performance improvements based on distributional information of the uncertain parameter ρ [32]. By generating samples from the distribution of the uncertain parameter, CVaR can be approximated for the cost function as follows.

$$\beta-CVaR \approx \min_{\alpha}\left(\alpha+\frac{1}{(1-\beta)\Omega}\sum_{\omega=1}^{\omega^T}\left[\Xi_p(P,\rho_\omega)-\alpha\right]^{+}\right), \quad (6)$$

where, ω^T indicates produced samples to approximate the cost distribution, α states the *β-VaR*, $[\Phi]^{+}$ indicates the positive component of P, and ρ_ω is the ωth generated scenario. By replacing $[P]^{+}$ with the auxiliary variable η_ω, we will have:

$$\eta_\omega \ \square \left[\Xi_p(P,\rho_\omega)-\alpha\right]^{+} = \max\left(0,\Xi_p(P,\rho_\omega)-\alpha\right). \qquad (7)$$

Considering these new variables in minimizing *β-CVaR*, the equivalent optimization problem can be formulated as follows.

$$CVaR = \min_{\eta_\omega,\alpha}\left(\alpha+\frac{1}{(1-\beta)}\sum_{\omega=1}^{\omega^t}\eta_\omega\vartheta_\omega\right) \qquad (8)$$

$$\text{subject to:} \quad 0\le\eta_\omega \qquad (9)$$

$$\eta_\omega\ge\Xi_p(P,\rho_\omega)-\alpha. \qquad (10)$$

Finally, by applying the aforementioned formulations to the objective function in (1), the risk-based problem is as:

$$\min(1-\Theta)\sum_{\omega=1}^{\omega^t}(\vartheta_\omega.\Xi_p)+\Theta\left(\alpha+\frac{1}{(1-\beta)}\sum_{\omega=1}^{\omega^t}\eta_\omega\vartheta_\omega\right) \qquad (11)$$

subject to: (9)–(10)

In (11), the risk aversion parameter is denoted by Θ.

B. Electric Power System (EPS) Modeling

In the EPS, optimal exploitation of community prosumers is accomplished based on the operation of diverse distributed energy resources (DERs), including SP, WT, FC, ME, EL, HSU, and BSS, which can be modeled as follows.

$$\Psi_{t+1,p}^{BSS}=\Psi_{t,p}^{BSS}-(\Psi_{t,p}^{BSS}.\eta_p^{B,L}+P_{t,p}^{E,BSS}+(\xi_1^{BSS}+\xi_2^{BSS}).\eta_P^{B,C}).\Delta t \qquad (12)$$

$$\underline{\Upsilon}_p^{BSS}\le(\Upsilon_{t,p}^{BSS}=\Psi_{t,p}^{BSS}/\Psi_p^{R,BSS})\le\overline{\Upsilon}_p^{BSS} \qquad (13)$$

$$\xi_1^{BSS}=-P_{t,p}^{E,BSS},\xi_2^{BSS}=P_{t,p}^{E,BSS}\ ;-\widehat{P}_p^{CE,BSS}\le P_{t,p}^{E,BSS}\le\widehat{P}_p^{DE,BSS} \qquad (14)$$

$$\Psi_{t^T,p}^{BSS}\ge\Psi_{End,p}^{BSS}\ ;\ \Psi_{0,p}^{BSS}=\Psi_{In,p}^{BSS} \qquad (15)$$

$$\Pi_p^{BSS}=IC_P^{BSS}/(L_p^{NC,B}.\Psi_p^{R,BSS}) \qquad (16)$$

$$P_{t,p}^{E,SP}\le\left[1-\left(\wp_{SP}^{AT}-\wp_{SP}^{ST}\right).\varepsilon^{SP}\right].\left[\square_t^{SP}.\Im_P^{SP}.\eta_t^{SP}\right] \qquad (17)$$

$$P_{t,p}^{E,WT}=\begin{cases}0 & 0\le\aleph_t\le\aleph_p^{C-I}\ ,\ \aleph_p^{C-O}\le\aleph_t\\ (\aleph_t^2.(\ell_a^{WT}+\dfrac{\ell_b^{WT}}{\aleph_t})+\ell_c^{WT}).P_p^{R,WT} & \aleph_p^{C-I}\le\aleph_t\le\aleph_p^{Ra}\\ P_p^{R,WT} & \aleph_p^{Ra}\le\aleph_\tau\le\aleph_p^{C-O}\end{cases} \qquad (18)$$

$$\underset{\smile}{P}_p^{E,Ex} \le P_{t,p}^{E,Ex} \le \widehat{P}_p^{E,Ex} \tag{19}$$

$$\mathrm{Cost}_t^{DSEM} = \left(\lambda_t^{PR}.\frac{\square_{t,p}^{PR,L+}}{2}\right) + \left(\varsigma_p^{LR1}\square_{t,p}^{LR,L} + \varsigma_p^{LR2}.(\square_{t,p}^{LR,L})^2\right) \tag{20}$$

$$\square_{t,p}^{Load} = \square_{t,p}^{F,L} + \square_{t,p}^{PR,L} - \square_{t,p}^{LR,L} \quad \square \in \{W, E\} \tag{21}$$

$$\underset{\smile}{\square}_p^{PR,L} \le \square_{t,p}^{PR,L} \le \widehat{\square}_p^{PR,L} \tag{22}$$

$$\sum_{t=1}^{t_T} \square_{t,p}^{PR,L} = 0 \tag{23}$$

$$\underset{\smile}{\square}_p^{LR,L} \le \square_{t,p}^{LR,L} \le \widehat{\square}_p^{LR,L} \tag{24}$$

$$\underset{\smile}{\square}_p^{Load} \le \square_{t,p}^{Load} - \square_{t,p}^{LR,L} \le \widehat{\square}_P^{Load} \tag{25}$$

$$HM_{t,p}^{FC} = P_{t,p}^{E,FC} / \left(\gamma^{H2}.\eta_p^{FC}\right) \tag{26}$$

$$\underset{\smile}{P}_p^{E,FC} \le P_{t,p}^{E,FC} \le \widehat{P}_p^{E,FC} \tag{27}$$

$$P_{t,p}^{G,ME} = HM_{t,p}^{ME}.\gamma^{H2}.\eta_p^{ME} \tag{28}$$

$$\underset{\smile}{P}_p^{G,ME} \le P_{t,p}^{G,ME} \le \widehat{P}_p^{G,ME} \tag{29}$$

$$HM_{t,p}^{EL} = (P_{t,p}^{E,EL}.\eta_P^{EL}) / \gamma^{H2} \tag{30}$$

$$\underset{\smile}{P}_p^{E,EL} \le P_{t,p}^{E,EL} \le \widehat{P}_p^{E,EL} \tag{31}$$

$$\Im_{t,p}^{HSU} = \Im_{t-1,p}^{HSU} + \left[\left(\Omega_p^{HS}.\tau_{HS}^{G} / \mu_p^{H2}\right).\left(HM_{t,p}^{Ch,HS} - HM_{t,p}^{Dis,HS}\right)\right] \tag{32}$$

$$HM_{t,p}^{EL} + HM_{t,p}^{Dis,HS} = HM_{t,p}^{FC} + HM_{t,p}^{ME} + HM_{t,p}^{Ch,HS} \tag{33}$$

$$\underset{\smile}{\Im}_p^{HSU} \le \Im_{t,p}^{HSU} \le \widehat{\Im}_p^{HSU} \quad ; \quad \Im_{0,p}^{HSU} = \Im_{In,p}^{HSU} \tag{34}$$

$$\begin{aligned}&\sum_{p=1}^{p_T}\left(P_{t,p}^{E,LP} + P_{t,p}^{E,BSS} + P_{t,p}^{E,FC} + P_{t,p}^{E,SP} + P_{t,p}^{E,WT}\right) = \\ &\sum_{p=1}^{p_T}\left(P_{t,p}^{E,PL} + P_{t,p}^{E,EL} + P_{t,p}^{E,Ex} + E_{t,p}^{Load}\right) \quad \forall t\end{aligned} \tag{35}$$

Equation (12) is for balancing the energy in the BSS while its state of charge and its charging and discharging limitations, are respectively modeled in (13) and (14). Equation (15) models the limitation of stored energy in the BSS at the initial and end times of the day. Equation (16) formulates the degradation cost of the BSS. According to this equation, the battery degradation depends on the investment cost of the battery, its life cycle number, and the rated energy capacity of the battery that is mathematically modeled similarly to [34] for 24 hours. The outputs of SP and WT can be computed based on (17) and (18). All prosumers can trade energy with the upstream grid according to the limitation in (19).

In this study, DSEM programs are rendered to create another key opportunity for prosumers for their flexible performance in effectively managing water and power interactions. In this respect, the DSEM is taken into account by developing LR and PR programs that rely on benefiting the elasticity property of energy demands. Equation (20) models the implementation cost of DSEM programs, in which the first and second terms are respectively for the cost of PR and LR schemes. Equation (21) is the definition for the updated amount of water and power demands that can be updated based on PR and LR variations. Herein, to avoid repetition, $\square$ is used as the representative of the electricity and water demands as indicated $(\square \in \{W, E\})$ in equation (21). The PR program is for giving the opportunity of load shifting to elastic consumers to support the system in matching the supply and demand while maximizing their economic benefits [35]. Equations (22) and (23) formulate the limitations of this program [35]. Indeed, equation (22) indicates the allowable range of shifting the energy demand, while equation (23) states that the sum of reduced demands (with a negative sign) from energy-poor hours and added demands (with a positive sign) to energy-rich hours should be zero during a day. The LR program is for creating the possibility of emergency control of balancing energy by limited curtailing energy in some required hours [34]. Equation (24) is for bounding the amount of interrupted load in the allowable range [34]. Equation (25) also states the permissible range for curtailing water and power demands [34]. Equations (26) and (27) ((28) and (29)/(30) and (31)) are used for modeling the FC (ME/EL). Equation (32) is for balancing the hydrogen in the HSU. Equation (33) balances the hydrogen molar in the system while the power balance is established using (35).

In this study, the AC power flow formulations are used to model the electricity network's energy interactions and ensure the applicability of the proposed model in practice. As the mathematical model of the AC power flow is nonlinear leading to the MINLP problem, the linearization process is developed to provide the MILP model for the optimization problem as follows [36].

$$\begin{aligned}&\sum_j\left(P_{t,j,i}^{E,Fo+} - P_{t,j,i}^{E,Fo-}\right) + P_{t,i}^{E,Ge} = \\ &\sum_j\left[\left(I_{t,i,j}^{Sq}\Re_{i,j}^{E}\right) + \left(P_{t,i,j}^{E,Fo+} - P_{t,i,j}^{E,Fo-}\right)\right] + P_{t,i}^{E,De} \quad \forall t, \forall i\end{aligned} \tag{36}$$

$$\begin{aligned}&\sum_j\left(\square_{t,j,i}^{E,Fo+} - \square_{t,j,i}^{E,Fo-}\right) + \square_{t,i}^{E,Ge} = \\ &\sum_j\left[\left(I_{t,i,j}^{Sq}X_{i,j}^{E}\right) + \left(\square_{t,i,j}^{E,Fo+} - \square_{t,i,j}^{E,Fo-}\right)\right] + \square_{t,i}^{E,De} \quad \forall t, \forall i\end{aligned} \tag{37}$$

$$0 \le \left(P_{t,i,j}^{E,Fo+} + P_{t,i,j}^{E,Fo-}\right) \le \bar{I}_{i,j}^{PF}V_i^{PF} \tag{38}$$

$$0 \le \left(\square_{t,i,j}^{E,Fo+} + \square_{t,i,j}^{E,Fo-}\right) \le \bar{I}_{i,j}^{PF}V_i^{PF} \tag{39}$$

where, $\square_{t,i,j}^{E,Fo-}$ and $\square_{t,i,j}^{E,Fo+}$ ($P_{t,i,j}^{E,Fo-}$ and $P_{t,i,j}^{E,Fo+}$) are non-negative auxiliary variables in line ***i-j*** that are presented as downstream and upstream directions for the reactive (active) power flow. As two non-negative auxiliary variables are not identical, their difference has led to terming the active and reactive power flows in (36) and (37) as bijections. Engaging half of the quadratic curve by employing auxiliary variables in the power flow modeling reduces the complexity of the linearization process [36]. In order to bound auxiliary variables associated with the active and reactive power, constraints (38) and (39) are used considering the maximum apparent power for them. Moreover, the following formulas are intended due to the necessity of maintaining the voltage changes in the allowable range.

$$\begin{aligned}&V_{t,i}^{Sq} - V_{t,j}^{Sq} - I_{t,i,j}^{Sq}Z_{i,j}^{2} = 2X_{i,j}\left(\square_{t,i,j}^{E,Fo+} - \square_{t,i,j}^{E,Fo-}\right) \\ &+2R_{i,j}\left(P_{t,i,j}^{E,Fo+} - P_{t,i,j}^{E,Fo-}\right)\end{aligned} \tag{40}$$

$$\begin{aligned}&V_{t,i}^{Sq}I_{t,i,j}^{Sq} = \sum_{\gamma^L}\left[\left(\Delta\square_{i,j}^{E,Fo}\Delta P_{t,i,j,\gamma^L}^{E,Fo}\right).\left(2\gamma^L - 1\right)\right] + \\ &\sum_{\gamma^L}\left[\left(\Delta\square_{i,j}^{E,Fo}\Delta\square_{t,i,j,\gamma^L}^{E,Fo}\right).\left(2\gamma^L - 1\right)\right]\end{aligned} \tag{41}$$

In (40), $V_{t,i}^{Sq}$ and $I_{t,i,j}^{Sq}$ state the squared voltage and current flows as new auxiliary variables. Equation (41) is for the linearization of reactive and active power flows. In this respect, the following equations ((42) to (46)) indicate the piecewise linearization modeling of power flow equations. The linearization of the quadratic curve is conducted by intending five blocks to strike the right balance among the computational accuracy and requirements [37].

$$\sum_{\gamma^L} \Delta P^{E,Fo}_{t,i,j,\gamma^L} = P^{E,Fo+}_{t,i,j} + P^{E,Fo-}_{t,i,j} \quad (42)$$

$$\sum_{\gamma^L} \Delta \square^{E,Fo}_{t,i,j,\gamma^L} = \square^{E,Fo+}_{t,i,j} + \square^{E,Fo-}_{t,i,j} \quad (43)$$

$$0 \le \Delta P^{E,Fo}_{t,i,j,\gamma^L} \le \Delta \square^{E,Fo}_{i,j} \quad (44)$$

$$0 \le \Delta \square^{E,Fo}_{t,i,j,\gamma^L} \le \Delta \square^{E,Fo}_{i,j} \quad (45)$$

$$\Delta \square^{E,Fo}_{i,j} = \left(\bar{I}^{PF}_{i,j} V^{PF}_{i} \right) / \gamma^{LT} \quad (46)$$

Moreover, the limitations of the branch voltage and current flow should be intended in the network model based on the following formulas.

$$(\underset{\smile}{V}^{PF}_{i})^2 \le V^{Sq}_{t,i} \le (\bar{V}^{PF}_{i})^2 \quad (47)$$

$$(\underline{I}^{PF}_{i,j})^2 \le I^{Sq}_{t,i,j} \le (\bar{I}^{PF}_{i,j})^2 \quad (48)$$

C. Water Systems Modeling

In multi-carrier energy networks, requiring electricity for exploiting most of the water systems in the WDN has created undeniable dependencies between WDN and EPS that affect the optimal operation of the EPS while some processes and energy conversions in the EPS rely on water for their completion. The WW is one of the water sources that is intended for the water generation cycle of the WDN. Operation of the WW requires power consumption in the discharging mode. In this respect, WW consumes power according to the following formula.

$$P^{Dis,WW}_{t,p} = \left[\left(\frac{\Upsilon^{W} . \phi^{W}}{(3.6 \times 10^{+6}).\eta^{W}_{p}} \right) . \left(\Gamma^{WW}_{p} . Q^{Dis,WW}_{t,p} \right) \right] \quad \forall p,t \quad (49)$$

where, $P^{Dis,WW}_{t,p}$ is the consumed power by the WW and $Q^{Dis,WW}_{t,p}$ is the amount of extracted water from the WW. In the WDN, the WW is not the only source of producing water and the WD is another process supporting the system for meeting water load (WL). The electricity consumption in the WD depends on the amount of its output water and the efficiency of the system as indicated in the following equation.

$$P^{WD}_{t,p} = Q^{G,WD}_{t,p} . \eta^{WD}_{p} \quad \forall p,t \quad (50)$$

$$0 \le Q^{G,WD}_{t,p} \le \hat{Q}^{G,WD}_{p} \quad \forall p,t \quad (51)$$

where, $P^{WD}_{t,p}$ presents the consumed electricity in the WD and $Q^{G,WD}_{t,p}$ represents the generated water in the WD. Similar to the power system, the storage system is also considered for the WDN to enhance the reliability of the system in delivering uninterrupted water. For this aim, the WS system is exploited subject to the following constraints.

$$P^{Ch,WS}_{t,p} = \left[\left(\frac{\Upsilon^{W} . \phi^{W} . Q^{Ch,WS}_{t,p}}{(3.6 \times 10^{+6}).\eta^{W}_{p}} \right) . \left(\frac{\Gamma^{WS,A}_{t,p} + \Gamma^{WS}_{t,p} + \Gamma^{WS}_{t-1,p}}{2} \right) \right] \quad (52)$$

$$\Gamma^{WS}_{t,p} = \Gamma^{WS}_{t-1,p} + \left[\left(Q^{Ch,WS}_{t,p} - Q^{Dis,WS}_{t,p} \right) / \delta^{WS} \right] \quad (53)$$

$$0 \le \Gamma^{WS}_{t,p} \le \hat{\Gamma}^{WS}_{t,p} \quad (54)$$

$$Q^{Dis,WS}_{t,p} \le U^{Dis,WS}_{t,p} . \hat{Q}^{Dis,WS}_{p} \quad (55)$$

$$Q^{Ch,WS}_{t,p} \le U^{Ch,WS}_{t,p} . \hat{Q}^{Ch,WS}_{p} \quad (56)$$

$$U^{Ch,WS}_{t,p} + U^{Dis,WS}_{t,p} \le 1 \quad (57)$$

where, $P^{Ch,WS}_{t,p}$ is the consumed power by the WS. $Q^{Dis,WS}_{t,p}$ and $Q^{Ch,WS}_{t,p}$ are the water discharging and charging in the WS. Equations (52) and (53) model the consumed power by the WS and its water balance. According to the mentioned formulas, the total amount of consumed power in the WDN is as follows.

$$P^{TE,WC}_{t,p} = P^{Dis,WW}_{t,p} + P^{WD}_{t,p} + P^{Ch,WS}_{t,p} \quad \forall p,t \quad (58)$$

In the WDN, the water sharing possibility is accommodated for cooperative prosumers to flexibility act in water management. The below equations denote the water trading limitation along with the water balance constraint.

$$\underset{\smile}{Q}^{Ex,W}_{p} \le Q^{Ex,W}_{t,p} \le \hat{Q}^{Ex,W}_{p} \quad \forall p,t \quad (59)$$

$$\sum_{p}^{p^T} \left(Q^{Dis,WS}_{t,p} + Q^{Dis,WW}_{t,p} + Q^{G,WD}_{t,p} + Q^{LP,W}_{t,p} \right) = \sum_{p}^{p^T} \left(Q^{Ex,W}_{t,p} + Q^{Ch,WS}_{t,p} + Q^{PL,W}_{t,p} + W^{Load}_{t,p} \right) \quad (60)$$

D. Designing WPTLM Environment

One of the overarching objectives of this article is to propose a new reliable way for the effective and optimal integration of 100% RSs in the CPWN. To this end, this work offers a novel WPTLM to provide a free power and water-sharing option for prosumers to manage their energy interactions. The main difference between the proposed transactive energy model here with other transactive energy models is that it develops the WPTLM environment and allows all prosumers to freely share power and water with each other in the WPTLM with the aim of reducing their reliance on the upstream grid, upsurging the confidence in unbroken energy supply, improving their sustainability and flexibility, and facilitating the achievement their technical, environmental, and economical goals. To optimally exploit the newly developed WPTLM, this article proposes new mathematical models as follows.

$$U^{E,L2P}_{t,p} + U^{E,P2L}_{t,p} \le 1 \,;\, U^{W,L2P}_{t,p} + U^{W,P2L}_{t,p} \le 1 \quad \forall p,t \quad (61)$$

$$P^{E,LP}_{t,p} \le U^{E,L2P}_{t,p} . \varpi^{E} \quad ; \quad Q^{LP,W}_{t,p} \le U^{W,L2P}_{t,p} . \varpi^{W} \quad \forall p,t \quad (62)$$

$$P^{E,PL}_{t,p} \le U^{E,P2L}_{t,p} . \varpi^{E} \quad ; \quad Q^{PL,W}_{t,p} \le U^{W,P2L}_{t,p} . \varpi^{W} \quad \forall p,t \quad (63)$$

$$\sum_{p} P^{E,LP}_{t,p} = \sum_{p} P^{E,PL}_{t,p} \quad ; \quad \sum_{p} Q^{LP,W}_{t,p} = \sum_{p} Q^{PL,W}_{t,p} \quad \forall t \quad (64)$$

$$\sum_{t} \left(P^{E,LP}_{t,p} . \lambda^{Ex,E}_{t} \right) = \sum_{t} \left(P^{E,PL}_{t,p} . \lambda^{Ex,E}_{t} \right) \quad \forall p \quad (65)$$

$$\sum_{t} \left(Q^{LP,W}_{t,p} . \lambda^{Ex,W}_{t} \right) = \sum_{t} \left(Q^{PL,W}_{t,p} . \lambda^{Ex,W}_{t} \right) \quad \forall p \quad (66)$$

Equation (61) includes binary variables for modeling the state of power and water sharing in the WPTLM. Equations (62) and (63) limit the received and transmitted power and water by prosumers in the WPTLM. Equation (64) is for balancing power and water in the local area. Equations (65) and (66) are for economically balancing the power and water traded in the WPTLM that provide a fair condition in terms of economics for prosumers who participated in the cooperative power and water exchange. Indeed, allowing free power and water sharing for prosumers by the transactive energy-based WPTLM in the local area increases their flexibility and ability to keep the systems' sustainability in the presence of 100% RSs, which is one of the vital objectives of FMEGs.

IV. Simulation Results

This work proposes a novel risk-oriented water-energy nexus model for optimally exploiting cooperative prosumers with 100% RSs in the modern CPWN. Indeed, in this research, all prosumers are equipped with 100% RSs to meet a high portion of their power load from carbon-free energy units. This does not mean their total energy load is supplied by renewable systems and other ways such as energy transactions with the main grid are also used for balancing energy. All prosumers are equipped with SP and WT as RSs that SP requires solar radiation, the efficiency of SPs, and the number of their cells as input data while WT needs wind speed, rated wind velocity and power, coefficients for modeling the output of the WT, and cut-in/cut-out velocities for the WT all of them can be accessed in [38]. In this respect, Fig. 2 illustrates the amounts of solar radiation and wind speed for 24 hours.

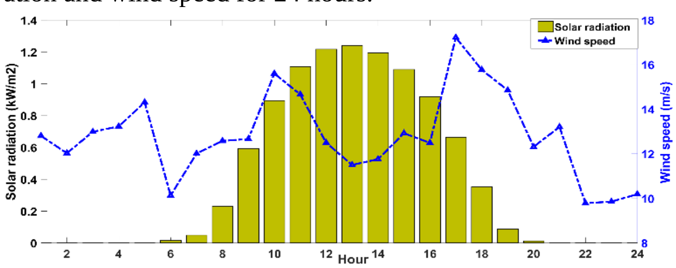

Fig. 2. Solar radiation and wind speed during a day.

BSS is another key unit of the electric sector that the required data for its operation such as charging/discharging and leakage loss factors, rated energy capacity, life cycle number, and investment cost are available in [39]. In this research, EL, FC, HSU, and ME are operated as energy conversion systems that their input data like their efficiency, maximum and minimum outputs, as well as gas constant and volume for the HSU can be found in [40]. The water sector is equipped with WW, WD, and WS requiring the efficiency of the WD and water pump, the water level of the WW, and the water storage location altitude as input data for their exploitation that can be accessed in [5]. The research is accomplished for studying the modernization of prosumers located in Chicago, USA to techno-economic-environmentally analyze how prosumers can be optimally operated when they are equipped with 100% RSs in the CPWN, which their load and price data can be found in [41]. The modified IEEE 33-bus test system is availed for validating the effectiveness of the suggested model. The geographical location of ten prosumers in the mentioned test system is illustrated in Fig. 3. Indeed, for each prosumer, it is assumed that all water systems such as the WS, WW, and WD units along with the water load are located at the end-user level of the prosumer.

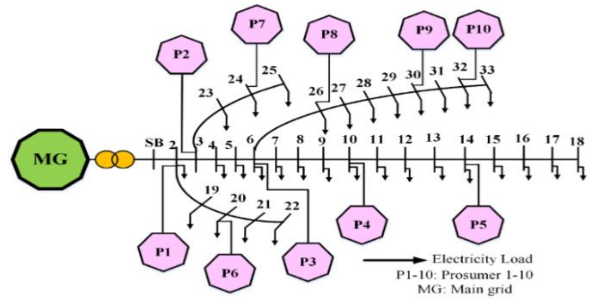

Fig. 3. Water-energy nexus prosumers in the integrated system.

This work presents an innovative mathematical framework for the optimization problem by developing linearized models to benefit the MILP structure and avoid the MINLP problem with optimal solution challenges. Herein, the hybrid CVaR stochastic method is exerted for the uncertainty quantification that is different from those completely stochastic approaches. Assessing the optimization problem is performed by accommodating three cases, in which the first case (Case I) studies the deterministic state of the problem, whereas the second case (Case II) concentrates on the probabilistic examining the problem using the CVaR stochastic approach. To compare the prosumer trading and economic operation without the proposed WPLTM model, Case III is intended without considering the energy trading of prosumers in the WPLTM. Indeed, the only difference between Cases II and III is that the energy sharing in the WPLTM is not accommodated in Case III. In this work, due to the inevitable dependencies between water and power systems, it is assumed that all case studies are performed in the CPWN structure and their independent operation is not intended. The run time of the MILP optimization problem is 51.437 seconds and simulations were conducted by a PC with Intel Core i7-6700HQ CPU @ 2.60 GHz with 16.00 GB RAM. All cases are solved using the CPLEX solver in the GAMS, in which \$57304.03, \$99133.97, and \$108877.67 are respectively reached for the objective function of the first, second, and third cases. In this study, collective results are considered for evaluating the effectiveness of the proposed model for the optimal exploitation of cooperative prosumers. Table II procures detailed information regarding the costs of water and power sectors in Cases I, II, and III.

TABLE II: Exploitation Costs for Water and Power Sectors

Cases	Case I		Case II		Case III	
Sectors	Water	Electric	Water	Electric	Water	Electric
Cost ($)	52340.44	4963.6	50548.68	48585.29	58169.57	50708.1
Total cost ($)	57304.03		99133.97		108877.67	

As obvious from Table II, Case II with uncertainty quantification using the CVaR stochastic method has imposed further costs than Case I with deterministic analysis of the system. In other words, considering uncertainties for real-based modeling of prosumers brings more costs in the operation of the system. In this work, as the electricity generation sector is fully empowered by 100% RSs, the power production process faces a huge level of uncertainties that affect the optimal exploitation of prosumers. In such a circumstance, given the direct dependency of RSs outputs on climate changes, small variations in the wind speed and intensity of solar radiation can result in substantial changes in the amount of total produced power. As the applied uncertainty quantification technique considers such states in the deviation horizon of the uncertain parameter, the generated power under such uncertain changes possesses higher variations in systems with 100% RSs in comparison with other renewable-based systems. In this respect, as the amount of electricity that needs to be provided from other costly ways for energy balance is high for the studied system with 100% RSs, the relevant costs are also substantial amounts according to Table II. The total cost of prosumers in Case III is more than in Case II, which is back to not considering the free energy trading of prosumers in the WPLTM in Case III. In the operation process, the optimal set-points for diverse electric units are depicted in Fig. 4.

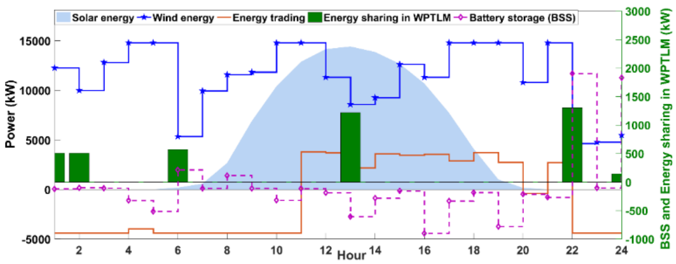

Fig. 4. Optimal set-points for diverse electric units in Case II.

Fig. 4 shows that prosumers properly benefit from the wind power until 6 am while after this hour, the system suffers from low clean energy due to the minimum collective output for the WT and SP. A similar situation occurred in the last two hours of the day due to the lack of solar radiation for the production of the SP and enough wind velocity for the WT. In all the mentioned times, prosumers have effectively used the free power sharing in the WPTLM, power trading with the main grid, and the BSS potential to cover the power shortage and meet power load. Indeed, prosumers benefited from power trading in the WPTLM to affordably balance electrical energy among each other and without heavy reliance on different costly ways that can hinder achieving higher economic advantages. In other time periods, particularly in peak hours, the adequate power production by RSs drives prosumers to not only supply clean energy but also use excess power for charging the BSS as well as selling to the power system for economic goals. In the last times of the day, the BSS is availed to effectively support the system in meeting power load when the output of RSs is at its lowest amount. Indeed, the charging and discharging states of the BSS are determined not only by considering the economic benefits of the system but also by intending the creation of a continuous power balance. Herein, the LR and PR programs as the DSEM along with the energy conversion technology, are also accommodated for supporting prosumers in energy-poor times. In this respect, Fig. 5 demonstrates their behaviors in the energy management of prosumers.

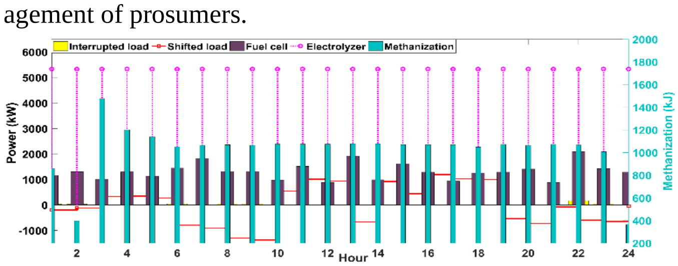

Fig. 5. Optimal set-points for DSEM programs and energy conversion units in Case II.

As seen in Fig. 5, in the time periods with lower power generation, the PR program plays a critical role in transferring a portion of the load to other periods of the day with sufficient available power. Prosumers even have availed the LR program from 6 to 9 am and the last hours of the day that faces power shortage to balance the power supply and demand. In addition to the support of the DSEM programs, prosumers have benefited from the hydrogen-based energy conversion procedure for power management in the presence of 100% RSs. Based on the information in Fig. 5, the EL produced hydrogen molar during the day to support the FC and ME for their exploitation. In this regard, a portion of the produced hydrogen is availed by the ME to generate natural gas not only for upsurging the flexibility and economic achievements of prosumers but also for supporting the natural gas grid in reliably serving gas energy. Indeed, all hydrogen-based systems are operated considering the economic benefits, sufficient flexibility for the system, as well as balancing energy at all hours. The FC has operated at all hours of the day with the maximum degree in the early morning and end of the day to act as the supportive unit for RSs in continuously serving power load. For prosumers, the EL receives its required water from the WDN, while the power sector is responsible for providing the electricity requirement of the water-based systems. Fig. 6 indicates the amount of consumed power by the different units in the WDN.

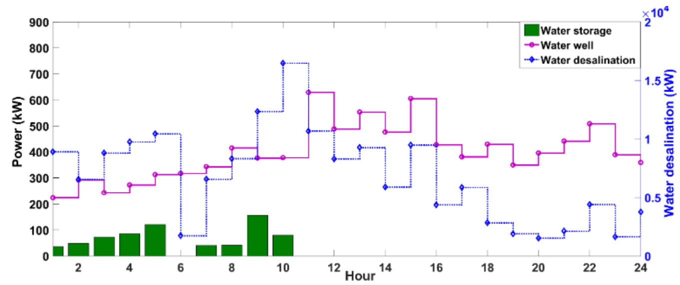

Fig. 6. The amount of consumed power by the different units in the WDN in Case II.

From 1 to 10 am, Fig. 6 indicates that a portion of the produced water by the WD and WW is delivered to the WS unit for charging to enable the WDN to securely supply water to the consumers. With more growing water demand from 10 am, the operation level of WW is increased to allow the system to dynamically balance water. This is while the effective potential of the WD and WS units are also scheduled to be utilized in the balancing process of the water for the WDN. In the evening, declining in the water demand subsequently has been led to a diminution in the outputs of the water production systems as their power consumption is reduced in the mentioned time period. To clearly pursue the application of the water-based units in the WDN, their water-based interactions are shown in Fig. 7.

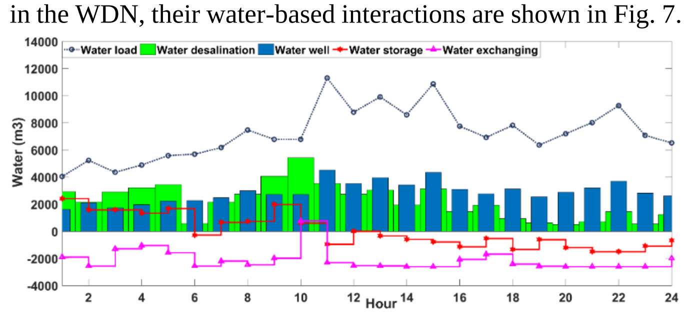

Fig. 7. Water-based interactions of water-based units in the WDN in Case II.

According to Fig. 7, the early morning is the time period with lower water consumption than other times in the WDN. This is why the system has used this trend of water consumption for making the opportunity of charging the BSS. However, increasing the water consumption rate from 10 am has driven prosumers to enhance the range of water production, upsurge water purchasing from the upstream network, and start to use the BSS in the discharging mode for balancing water. By going towards the end of the day and reducing the water demand, the level of exploitation for the water generation systems is alleviated to make the water generation fit with its consumption. Moreover, the last hours of the day were the main time period for transacting water, in which prosumers availed the water trading option as one of the supportive ways for flexibly acting in matching the water demand and supply. Since all prosumers are completely equipped with 100% RSs for water and power supply, the risk for the optimal operation of the integrated grid is high for the decision maker. This critical challenge is addressed by developing the CVaR stochastic method for modeling uncertainties associated with RSs in Case II. In this respect, the proposed water-energy nexus model is examined considering various amounts of the risk aversion parameter (Θ) in the optimal exploitation of cooperative prosumers. Indeed, the mentioned risk aversion parameter is intended in the presented model in Case II with the aim of assessing the effects of risk-based modeling on the objective function of the optimization problem. Such analysis is necessary that enables the decision-maker to effectively adopt decisions in line with the different techno-economic-environmental goals. Fig. 8 portrays the amount of the expected cost and CVaR at different values of Θ.

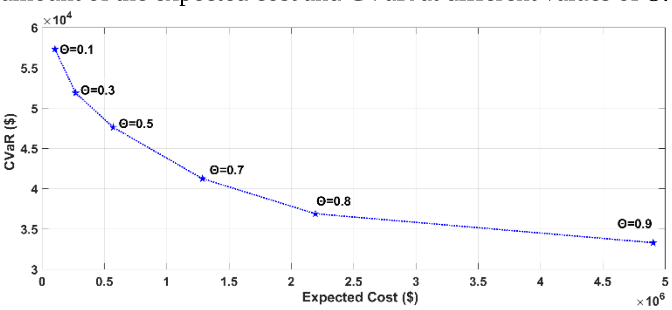

Fig. 8. Changes in the expected cost and CVaR at different values of Θ in Case II.

Fig. 8 denotes that higher operating costs and lower CVaR are in the higher values of the risk aversion parameter. Indeed, when the system is scheduled to be under the lower risk of the 100% RSs, the operation costs will be more than usual states due to the need for deploying costly mechanisms for reducing the risk of the full usage of stochastic producers. On the other hand, operating at lower risks in higher values of the risk aversion parameter has led to lower amounts of CVaR. These changes in the expected cost and CVaR highlight the fact that the system will experience higher costs in its operation if it is targeted to be scheduled at lower risks. Thus, it is up to the decision maker to act on the trade-off point by intending diverse effective factors such as money and robustness. To analyze the effects of energy trading in the WPTLM on the optimal operation of prosumers, Case III is intended without considering the energy sharing of prosumers in the WPTLM. Fig. 9 indicates the optimal set-points for diverse electric units in Case III.

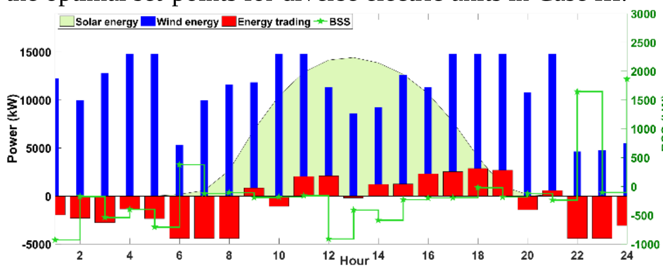

Fig. 9. Optimal set-points for diverse electric units in Case III.

According to Fig. 9, prosumers mostly relied on the produced wind power and received power from the upstream grid in the early morning to meet the power demand. This is while the peak hours benefited both wind and solar power that have resulted in producing extra clean power driving the system to sell a part of the energy to the main grid. By zeroing the output of solar systems and reducing wind power production in the last hours of the day, all prosumers have availed the BSS, wind systems, and purchasing power from the power grid as the dominant sources of energy for matching the power supply and demand. To assess the activity of a specific prosumer, Fig. 10 shows the optimal scheduling of electric systems for Prosumer 3 with the highest amount of power demand than other prosumers.

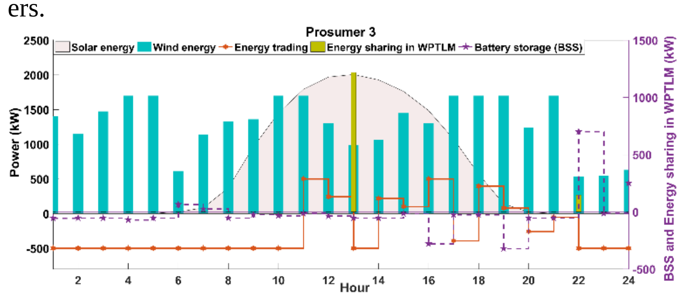

Fig. 10. Optimal set-points for diverse electric units of Prosumer 3 in Case II.

Fig. 10 indicates that Prosumer 3 has mostly benefited from wind power for power serving in the morning hours. It has used the opportunity of power-sharing with the main grid in the peak hours to sell excess produced power to the upstream grid. This was possible for the prosumer due to the maximum power outputs for the WT and SP in noon hours. By declining solar power generation in the last hours of the day, the prosumer has relied on the discharged power from the BSS, WT, and the produced power from the main grid for uninterrupted power supply in the mentioned time period. Moreover, the prosumer has participated in the WPTLM interactions at two hours of the day to effectively balance its produced and consumed electricity. As one of the main goals of proposing the transactive energy-based model for prosumers is to facilitate the adoption of 100% RSs, the total renewable energy production that is the sum of WT and SP outputs is illustrated for each prosumer in Fig. 11.

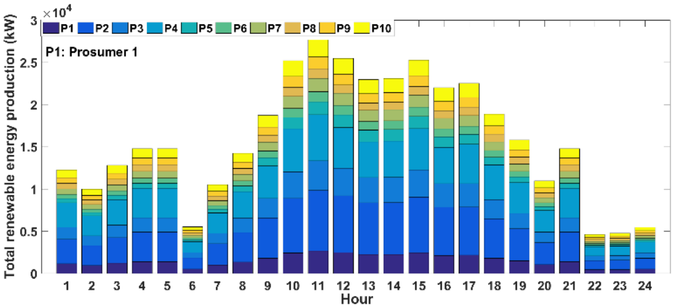

Fig. 11. The total renewable energy production for each prosumer in Case II.

As obvious from Fig. 11, all prosumers have the minimum clean power production at 6 am and 10 to 12 pm due to the zero output for the SP and lowest wind speed for the WT. In the aforementioned time periods, using other proper ways is necessary for prosumers to keep their sustainability in energy serving. In addition to the power-sharing with the main grid, BSS, energy conversion units, and energy management schemes, developing the WPTLM allowed all prosumers to freely trade power with each other for dynamically balancing power while reaching their economic objectives. However, according to Fig. 11, the noon hours state a different situation for prosumers in generating clean electricity. In the mentioned hours, the produced power is more than the power demand for almost all prosumers. The proposed flexibility ways such as transactive energy trading strategy, energy conversion and storage, and energy management schemes enabled all prosumers to effectively manage their power and water interactions by purposefully utilizing each of the mentioned ways.

V. Conclusions

This article addresses the critical challenge of the optimal integration of 100% RSs in CPWNs by proposing a novel water-energy nexus model for optimally exploiting cooperative Chicago's prosumers. The model was empowered by the adoption of transactive energy technology for designing the WPTLM as the new environment for prosumers to freely exchange water and power in line with their purposes. Indeed, the proposed transactive energy-based model procures the indispensable requirements of prosumers with 100% RSs by decreasing their dependencies on the main network, sustainably managing water and power interactions, and raising the flexibility degree by deploying storage and energy conversion units as well as energy sharing mechanisms along with the DSEM programs. To address the risk of the operating prosumers, the CVaR stochastic technique was exerted for easing the adoption of suitable decisions for the decision-maker. The results stated a 42.2% increment in the costs of prosumers when they exploited under the risk-aversion condition created by the CVaR stochastic approach. Indeed, the proposed model not only allows prosumers to reliably manage water and power in the presence of 100% RSs but also it facilitates taking appropriate decisions for the decision-maker. To further analyze the effectiveness of the proposed model, its applicability will be assessed by modeling the water distribution network as well as considering its constraints and various systems, such as the water pump, in future work.

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