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Risk-Aware Stochastic Scheduling of Hybrid Integrated Energy Systems with 100% Renewables

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***Abstract*—Recently, ambitious endeavors have been carried out to facilitate the transition from traditional grids to hybrid interconnected energy networks in the form of grid modernization. Align to such efforts, this article aims at developing a novel framework for satisfying techno-economic-environmental goals in the grid modernization process. To this end, a detailed examination is conducted for the optimal exploitation of energy hubs (EHs) equipped with 100% renewables to pursue the environmental goal alongside intending technical and economic constraints. The energy conversion technology is adopted to enable the power-to-gas system for establishing multi-energy interactions among electricity and gas networks. Fully benefiting from renewable units has exposed the system to uncertain fluctuations that necessitate the modeling of uncertainties to achieve near-reality results. Hence, risk-averse and seeker strategies are developed based on robustness and opportunistic modes of the information gap decision theory (IGDT) method to deal with stochastic fluctuations of uncertain parameters. The integrated electricity and gas test system is considered to analyze the applicability of the proposed framework in modeling efficient multi-energy interactions. Given the obtained results, 43.68% more energy cost is reached for EHs when they adopted a robust strategy against uncertainties under the risk-averse strategy. Moreover, the proposed framework procured a rational decision-making model for balancing multi-energy in the hybrid energy grid with 100% renewables.**

***Index Terms*—Risk-aware framework, multi-carrier energy systems, grid modernization, power-to-gas technology, 100% renewable energy sources, energy management decision-making.**

NOMENCLATURE

Abbreviations

BSS	Battery storage system
ED/GD	Electrical/Gas demand
EHs	Energy hubs
EL	Electrolyzer
FC	Fuel cell
FFS	Fast forward selection
GAMS	General algebraic modeling system
GS	Gas storage
HS	Hydrogen storage
IGDT	Information gap decision theory
IL	Interrupted load
LHS	Latin hyperbolic sampling
LR/ PR	Load/Price response program
ME	Methanization
MINLP	Mixed-integer nonlinear programming
PG/NG	Power/Gas grid
P2G	Power to gas
RESs	Renewable energy sources
SP	Stochastic programming

I. INTRODUCTION

A. Motivation and Background

IN recent years, co- and tri-generation processes are empowered by developed cutting-edge technologies to pave the quick transition toward multi-vector energy units [1]. Such a transformation is intended in response to the need for applying effective energy management schemes as well as efficient and clean energy processes by mushrooming renewable energy sources (RESs) in the interconnected energy structure [2]. Increasing the adoption of RESs in the energy structure has affected the sustainability of multi-vector energy grids due to facing high intermittences in energy production [3]. In this regard, as interconnection points of multifarious components and energy networks, energy hubs (EHs) are introduced to enhance the system's ability for multi-energy collection, conversion, and storage in a sustainable manner [4]. In other words, EHs ease multi-energy interactions making the energy network susceptible to the uttermost usage of RESs, which is the key objective of future modern energy grids [5]. The realization of reaching 100% clean energy generation goals in EHs directly relies on the flexibility ways like energy conversion units [6]. In this regard, the coupled structure of gas and power networks procures appropriate conditions for exploiting carbon-zero EHs to cost-effectively meet both the thermal and electrical energy demands. Thus, co-optimization of power and gas grids is the necessary step for obtaining confident results. On the other hand, the risk of the system operation in the presence of fully renewable units needs to be analyzed by developing innovative strategies to give an appropriate overview for decision-makers enabling them to taking affordable decisions. Therefore, the optimal risk-aware stochastic operation of cooperative EHs is intended as the main target of this article that scrutinizes EHs scheduling in the cooperation of 100% RESs under the co-optimization of gas and power networks.

B. Relevant Literature

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In recent decades, the rapid transformation in energy systems has created the undeniable need for multi-vector energy in modernizing the energy customer side [7]. This evolution has been accompanied by the basic development in clean energy production technologies and hybrid energy systems challenging the energy management of cooperative EHs. This trend has made the consensus for switching from uni-dimension electric power grids to modern multi-dimensional energy networks stronger aiming to the cost-effective energy management of the system. Due to this, examining the optimal operation of EHs has been conducted from various perspectives in recent literature. For example, the chance-constrained programming is intended in [8] to solve the optimal energy flow for the optimal energy management of adjacent EHs by innovatively modeling the power and gas flows considering intermittences of uncertain parameters. The main finding of this work is a novel optimization model that defers or reduces network investment as well as ensures system security. In [9], a distributionally robust optimization model is proposed to innovatively deal with uncertainties of RESs by concentrating on multimodal forecast errors of solar PV systems with the aim of improving the energy efficiency of EHs. Indeed, the mentioned study innovates in developing a new model that not only results in overcoming the conservatism of multimodal distribution uncertainties but also decreases operation costs for EHs. A two-stage approach is presented in [10] to enable energy trading in the local energy market by introducing the state-of-the-art optimization process to minimize/maximize costs/revenues within the district energy grid. The main achievement of this research is the comprehensive framework in the optimization process that includes the energy-exchanging possibilities along with locally producing energy for prosumers. The new optimization method and intelligent modeling paradigm are proposed in [11] to set up the smart EH model for its optimal operation based on the computerized algorithm. The overarching finding of this work is the holistic paradigm guaranteeing global optimal exploitation decisions and significantly reducing the computational burden. References [12] and [13] were targeted for the techno-economic energy management of renewable-based EHs in which a cooperative decision-making strategy was used in [12] while the authors of [13] proposed a distributionally robust day-ahead management framework for the operation strategy of the system. Indeed, reference [12] innovates in developing a cooperative strategy to obtain a minimum operational cost through effective energy management whereas the main achievement of reference [13] is the energy management scheme that enables the system for gaining robust optimal results. Furthermore, a decentralized energy management framework was offered in [14] to allow EHs for achieving Nash equilibrium by designing an online distributed algorithm using the potential game technique. The overarching finding of this research is the optimization algorithm that increases the average payoff for EHs as well as improves the technical performance of energy grids by declining the peak-to-average ratio in gas and electricity.

In the modern energy structure, the indispensability of transiting toward the multi-vector energy network for benefiting high-quality and clean energy synergies has made grid decarbonization as a pioneering effort [15]. The outcomes of decarbonization endeavors are more sensed by the exploitation of 100% RESs as attractive schemes enabling the carbon-free environment to appear in the modern energy landscape [16, 17]. Herein, recent literature encompasses several studies with substantial attention on the fully RESs usage under multifarious clean energy production technologies. For example, a novel decomposition-based strategy is intended in [18] to make the model of manifold uncertainties possible in the coordinated planning of electricity networks with full renewables. The main finding of this study is a novel modeling framework that allows for the long-term planning of the highly renewable penetrated system under huge uncertainties. The authors in [19] scrutinized the possibility of sustainably exploiting the power system with 100% RESs given the presence of multi-carrier energy units. The results denoted the effectiveness of increasing the flexibility of the whole network on the electrification process through the integration of energy networks. Furthermore, the overarching achievement of this research is a sector-coupling model that terminates in lower energy supply costs for the renewable-based system. For raising the flexibility of hybrid energy networks, reference [20] presented a fundamental linear optimization model with the aim of assessing the applicability of storage units in balancing energy by enhancing the system’s flexibility in the presence of full renewables. In other words, this work has an innovative finding in developing an optimization model to quantify the distributional effects and system cost changes for different stakeholder groups. Moreover, a location-optimized hybrid energy system is developed in [21] for realizing the 100% renewable grid aiming to reduce optimal systems’ capacities using a distributed power system approach. The main achievement of this work is a multi-objective optimization methodology that reduces the size of RESs in both with and without an energy storage system.

C. Contributions and Organization

The evaluated studies in the prior subsection highlight important study gaps addressing them is critical for modern energy networks. In recent works, the lack of a holistic model for the multi-energy management of cooperative EHs hinders the optimal exploitation of the integrated system with 100% RESs. The development of the sustainable model with manifold applicability is overlooked for simultaneously procuring green power and gas energy in the coupled multi-energy grid. On the other hand, the hybrid energy network with full exploitation of RESs faces substantial uncertain changes in the energy generation sector that makes the reliable and affordable operation of the grid at great risk. As a techno-economic analysis of hybrid energy systems with 100% renewables is assessed in [22] for the optimal scheduling of EHs, it cannot effectively address the challenge of stochastic changes associated with huge RESs uncertainties due to the lack of developing a comprehensive model and applying a capable method for the risk-aware evaluation. Indeed, the risk-aware assessment of hybrid networks is necessary for properly tackling stochastic volatilities of uncertain parameters for realistic modeling of the grid while enabling decision-makers to adopt risk-based strategies considering the favorable and undesirable fluctuations of RESs. Due to this, the hybrid system requires innovative risk-seeker and risk-averse strategies that lack of them hinder the optimal operation of EHs with a full/high level of RESs. Therefore, this article targets to bridge the aforementioned gaps by proposing a novel techno-economic-environmental risk-aware model for energy management of multi-carrier EHs with fully eco-friendly power production units. Indeed, this work develops an innovative model of operation for the co-optimization of gas and power networks enabling the system for coordinated multi-energy management given operational restrictions. To ensure the sustainability of the interconnected system with 100% RESs, hybrid energy devices are availed in community EHs with sufficient flexibility. The multi-energy synergies are established across the hybrid grid by advancing the power-to-gas technology in designing the offered model. As the model renders the possibility of full usage of RESs in energy production that is targeted for modern grids, the stochastic fluctuations are the inevitable part of the system modeling affecting the accuracy of extracted results. Hence, the opportunity and robustness functions of the information gap decision theory (IGDT) technique are availed for procuring a risk-constrained framework to cope with intrinsic intermittences of RESs. In this process, designing a risk-averse strategy is intended for modeling undesirable variations of RESs aiming to develop a promising way for providing sufficient robustness of the system. This is while the main motivation for proposing a risk-seeker strategy is to assess the system under the desirable volatilities of RESs outputs. Additionally, this work is benefited from stochastic programming to procure an effective remedy for uncertainties of multi-vector energy price by generating multifarious scenarios using the LHS while reducing scenarios by employing the FFS method. The state of the art of the current work briefly stands on the following contributions:

- The optimal energy management decision-making of EHs with 100% RESs is carried out by proposing a novel techno-economic-environmental risk-aware framework in integrated power and gas networks considering all their interactions and limitations (technical aspects) for maximizing economic benefits of EHs (economic aspects) as well as fully producing clean energy in the system (environmental aspects).
- The risk-averse and risk-seeker strategies are developed relying on the robustness and opportunistic functions of the IGDT technique for quantifying uncertainties aiming to propose a holistic decision-making strategy for adopting effective decisions against the undesirable and describe fluctuations of RESs. An uncertainty quantification scheme is also empowered using the LHS and FFS approaches for modeling intermittences in the multi-carrier energy price by scenario production and reduction.
- The hybrid multi-vector energy architecture is proposed for EHs enabling the integrated system for reliable and sustainable operation and effective usage of produced clean energy by exploiting diverse energy conversion and storage systems as well as energy trading possibilities.

The remainder of this article pursues the following structure. Section II characterizes the problem formulation as well as the uncertainty modeling process. Section III provides the results and their associated discussions. Ultimately, the conclusions of the current research are described in Section IV.

II. Optimal Energy Management Decision-Making for EHs

A. EHs Architecture

This study targets to render a comprehensive operating model for co-optimizing power and gas grids to provide a viable solution for the optimal coordinated multi-energy management of cooperative EHs with 100% RESs as the main goal of grid modernization. Fig. 1 clarifies the structure of EHs.

According to Fig. 1, solar PV systems and wind units are two popular types of RESs that are used for fully pollutant-free power production accompanied by the battery storage system (BSS) as one of confident ways for ensuring the security of energy supply. The possibility of effectively utilizing the excess of generated electricity is intended by operating the electrolyzer (EL) to generate hydrogen molar storing in the hydrogen storage (HS). On the other hand, the fuel cell (FC) is exploited to allow the system to the reproduction of electricity using hydrogen energy when EHs require more energy for stability. On the other hand, as the part of P2G cycle, the stored hydrogen can be used by the methanization (ME) system to deliver the gas energy to the natural gas network making the power and gas serving process more flexible.

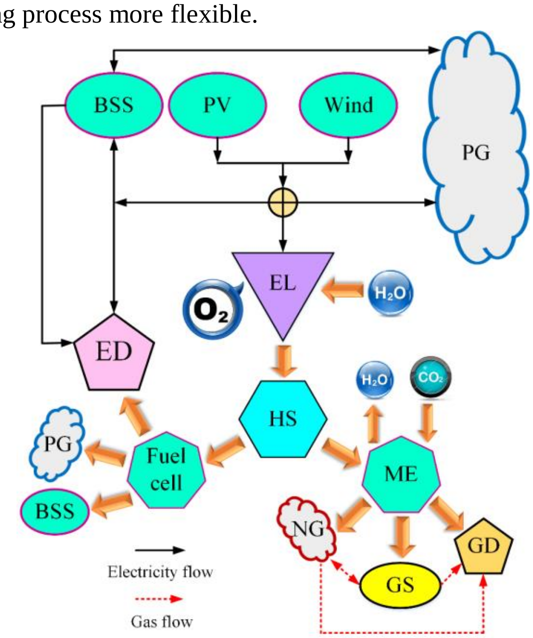

Fig. 1. EHs structure with 100% RESs.

B. Objective Function

This work considers the minimization of total costs as the main objective in the risk-aware operation of EHs according to the following formula.

$$OF_h^B = \sum_{s=1}^{N_s}\psi_s.[\sum_{t=1}^{N_t}(\xi_h^{P2G}.\rho_{CO_2}^{P2G}.\eta^{P2G}.E_{h,t,s}^{ME}) + \sum_{t=1}^{N_t}\rho_t^{S,G}.E_{h,t,s}^{S,G}.\Delta t + \sum_{t=1}^{N_t}[(\Phi_h^{BSS}.\Delta t).(E_{h,t,s}^{BSS} + \Theta_{h,t,s}^{BSS}.\eta^{Lc})] - \sum_{t=1}^{N_t}\rho_t^{T,E}.E_{h,t,s}^{T,E}.\Delta t - \sum_{t=1}^{N_t}\rho_t^{T,G}.E_{h,t,s}^{T,G}.\Delta t - \sum_{t=1}^{N_t}\sum_{i=1}^{N_b}\rho_t^{S,E}.D_{i,t}^{E}.\Delta t - \sum_{t=1}^{N_t}\sum_{g=1}^{N_g}\rho_t^{S,G}.D_{g,t}^{G}.\Delta t + \sum_{t=1}^{N_t}\text{Cost}_{t,s}^{LR} + \sum_{t=1}^{N_t}\text{Cost}_{t,s}^{PR}] \quad (1)$$

where, the objective function is presented by OF_h^B for hub *h*. The probability of scenario is stated by ψ_s for scenario *s*. ξ_h^{P2G} and $\rho_{CO_2}^{P2G}$ indicate the CO_2 consumption per unit in gas generation and its price. $E_{h,t,s}^{ME}$ and η^{P2G} are the power used by the P2G and its efficiency. The supplied gas and its price are denoted by $E_{h,t,s}^{S,G}$ and $\rho_t^{S,G}$ at time *t*. The lifetime degradation cost is stated by Φ_h^{BSS} for the BSS. The energy and power of BSS are indicated by $\Theta_{h,t,s}^{BSS}$ and $E_{h,t,s}^{BSS}$. η^{Lc} presents the self-discharge rate. The gas and power sharing prices (amounts) are presented by $\rho_t^{T,G}$ and $\rho_t^{T,E}$ ($E_{h,t,s}^{T,G}$ and $E_{h,t,s}^{T,E}$). The gas and power selling prices are also represented by $\rho_t^{S,G}$ and $\rho_t^{S,E}$. The gas and power loads are denoted by $D_{g,t}^{G}$ and $D_{i,t}^{E}$. In (1), the exploitation cost of P2G and BSS are respectively intended in the first and third terms. The cost of purchased gas from gas suppliers is presented in the second term. The costs/revenues of power and gas trading with the main grid are represented in the fourth and fifth terms. The revenues of selling power and gas to end-users are formulated in the sixth and seventh terms. The costs of demand response programs including load response (LR) and price response (PR) are modeled in the last two terms.

C. Constraints

1) Power balance

$$E_{h,t}^{Wind} + E_{h,t}^{PV} + E_{h,t}^{BSS} + E_{h,t}^{FC} = E_{h,t}^{T,E} + E_{h,t}^{EL} + D_{h,t}^{E} - E_{h,t}^{LR} \quad (2)$$

where, $E_{h,t}^{EL}$ and $E_{h,t}^{FC}$ are the respective indicators of the consumed power by the EL and generated power by the FC. The produced wind and solar power are presented by $E_{h,t}^{Wind}$ and $E_{h,t}^{PV}$. The interrupted load (IL) is denoted by $E_{h,t}^{LR}$. Equation (2) establishes the power balance that is necessary for the stability of the power grid.

2) Solar PV system

As one of RESs, the solar PV system is intended for EHs to support the system in producing clean energy and its mathematical model can be formulated as follows [23].

$$E_{h,t}^{PV} = \eta^{PV}.\kappa_t^{PV}.A_h^{PV}.(1-0.005.(T^a - 25)) \quad \forall h,t \quad (3)$$

where, the efficiency of the solar PV system is indicated by η^{PV}. The area of solar panels, solar radiation, and ambient temperature are respectively indicated by A_h^{PV}, κ_t^{PV}, and T^a. Equation (3) models the produced solar power by PV panels of hub *h* at time *t*.

3) Battery storage system (BSS)

Energy grids with 100% RESs require reliable ways to effectively cope with the uncertain nature of RESs outputs. One of the promising ways is to exploit a sufficient capacity of BSS that adds more flexibility to the EHs operation. In this study, the Lead-acid battery is used that can be mathematically modeled as follows [24]. It is worth noting that a similar modeling approach can be applied to other types of storage systems.

$$\Theta_{h,t+1}^{BSS} = \Theta_{h,t}^{BSS} - E_{h,t}^{BSS}.\Delta t - (\mu^B + \gamma^B)\eta^{Cc}.\Delta t - \Theta_{h,t}^{BSS}.\eta^{Lc}.\Delta t \quad \forall h,t \quad (4)$$

$$SOC_{h,t} = \frac{\Theta_{h,t}^{BSS}}{\Theta_{RC}^{BSS}}, \quad \gamma^B = E_{h,t}^{BSS}, \quad \mu^B = -E_{h,t}^{BSS} \quad (5)$$

$$SOC_{h,t}^{\min} \le SOC_{h,t} \le SOC_{h,t}^{\max} \quad (6)$$

$$-\bar{E}_{h,t}^{Ch,BSS} \le E_{h,t}^{BSS} \le \bar{E}_{h,t}^{Dis,BSS}, \quad \gamma^B \le \bar{E}_{h,t}^{Dis,BSS}, \quad \mu^B \le \bar{E}_{h,t}^{Ch,BSS} \quad (7)$$

$$\Theta_{h,0}^{BSS} = \Theta_{h,I}^{BSS} \quad ; \quad \Theta_{h,T}^{BSS} \ge \Theta_{h,End}^{BSS} \quad (8)$$

$$\Phi_h^{BSS} = \frac{IC_h^{BSS}}{\Theta_{RC}^{BSS}.LCN_h^{BSS}} \quad (9)$$

where, the loss factor of BSS and its state of charge are presented by η^{Cc} and $SOC_{h,t}$. The rated energy capacity of the battery is represented by Θ_{RC}^{BSS}. $\bar{E}_{h,t}^{Ch,BSS}$ and $\bar{E}_{h,t}^{Dis,BSS}$ are the maximum amounts of power charging and discharging in the BSS. IC_h^{BSS} and LCN_h^{BSS} are for indicating the investment cost and life cycle number of BSS. The power balance of BSS is formulated by (4) while its state of charge is modeled by (5). Equation (6) limits the amount of the state of charge in its allowable range. Equation (7) formulates the permissible bound for the charging and discharging of BSS. Equation (8) models the initial and final energy stored in BSS. The BSS's degradation cost is also computed by (9).

4) Wind unit

$$E_{h,t}^{Wind} = \begin{cases} 0 & 0 \le \varpi_t \le \varpi_h^{Cut-In} \\ (\alpha_1 + \alpha_2\varpi_t + \alpha_3\varpi_t^2)E_h^{W,R} & \varpi_h^{Cut-In} \le \varpi_t \le \varpi_h^{Rated} \\ E_h^{W,R} & \varpi_h^{Rated} \le \varpi_t \le \varpi_h^{Cut-Out} \\ 0 & \varpi_h^{Cut-Out} \le \varpi_t \end{cases} \quad (10)$$

$$E_{h,t}^{Wind} / \sqrt{(E_{h,t}^{Wind})^2 + (Q_{h,t}^{Wind})^2} = \text{Constant} \quad (11)$$

where, $Q_{h,t}^{Wind}$ is the reactive generated power of the wind turbine in *h*th EH. The rated wind power is shown by $E_h^{W,R}$ while $\varpi_h^{Rated}, \varpi_h^{Cut-Out}$, and ϖ_h^{Cut-In} are for illustrating the rated, cut-out, and cut-in wind speeds. The wind speed at time *t* is also denoted by ϖ_t. The modeling of the wind power production requires additional coefficients that are indicated by α_1, α_2, and

α_3. Equation (10) models the power output of wind turbines and its amount is limited by constraint (11).

5) Demand-side management

As the key type of engineering management schemes, demand-side energy management programs have appeared in the energy sector that are usually undertaken to enhance the flexibility in dynamically balancing energy [25]. In this respect, the LR and PR are intended as supportive programs for assisting interconnected EHs in fully feeding the demand-side with clean energy according to the following formulas.

a) LR program

$$\mathrm{Cost}_t^{LR} = \sum_{i=1}^{N_b} [\gamma_1^{LR}.E_{i,t}^{LR} + \gamma_2^{LR}.(E_{i,t}^{LR})^2] \tag{12}$$

$$0 \le E_{i,t}^{LR} \le E_{\max,t}^{LR} \tag{13}$$

$$\underline{E}_i^{LR} \le D_{i,t}^{E} - E_{i,t}^{LR} \le \overline{E}_i^{LR} \tag{14}$$

where, γ_1^{LR} and γ_2^{LR} are the coefficients for IL cost. Equation (12) models the total cost of the LR program. Constraint (13) limits the amount of curtailed load in the allowable range. Constraint (14) also is for ensuring admissible changes of load shedding.

b) LR program

$$\mathrm{Cost}_t^{PR} = \sum_{i=1}^{N_b} \rho_t^{PR}.(E_{i,t}^{PR+}/2) \tag{15}$$

$$D_{i,t}^{E} = D_{i,t}^{E,F} + E_{i,t}^{PR} \tag{16}$$

$$\underline{\varphi}.D_i^{E,F} \le E_{i,t}^{PR} \le \overline{\varphi}.D_i^{E,F} \tag{17}$$

$$\sum_{t=1}^{N_t} E_{i,t}^{PR} = 0 \tag{18}$$

where, the price for incentivizing consumers is denoted by ρ_t^{PR}. The shifted power demand and its forecasted amount are shown by $E_{i,t}^{PR}$ and $D_{i,t}^{E,F}$. The positive value of $E_{i,t}^{PR}$ is stated by $E_{i,t}^{PR+}$ in all times. Equation (15) models the total cost of the PR program. Equation (16) indicates the amount of power load after applying the PR program. Constraint (17) limits the amount of shifted load in the allowable range. Constraint (18) is for ensuring the sum of the reduced load at certain hours is equal to the sum of the added load in other hours during a day.

6) Power grid

$$E_{i,t}^{flow}(V_{i,t},\delta_{i,t}) = E_{i,t}^{E,Gen} - D_{i,t}^{E} \quad \forall i,t \tag{19}$$

$$Q_{i,t}^{flow}(V_{i,t},\delta_{i,t}) = Q_{i,t}^{E,Gen} - Q_{i,t}^{E} \quad \forall i,t \tag{20}$$

$$C_{i,j}^{\min} \le C_{i,j,t}(V_{i,t},\delta_{i,t}) \le C_{i,j}^{\max} \quad \forall i,j,t \tag{21}$$

$$V_i^{min} \le V_{i,t} \le V_i^{max} \quad \forall i,t \tag{22}$$

$$\delta_i^{min} \le \delta_{i,t} \le \delta_i^{max} \quad \forall i,t \tag{23}$$

where, $Q_{i,t}^{flow}$ and $E_{i,t}^{flow}$ are the reactive and active power flow while $Q_{i,t}^{E,Gen}$ and $E_{i,t}^{E,Gen}$ are their produced amounts. $C_{i,j,t}$ states the complex power and $V_{i,t}$ and $\delta_{i,t}$ are the voltage and phase angle variables. Equations (19) and (20) are for establishing active and reactive power balance. Constraint (21) denotes the permissible bound for the complex power while constraints (22) and (23) keep the voltage and its phase angle in the allowable range.

7) Electrolyzer unit

$$N_{h,t}^{EL,H2} = (E_{h,t}^{EL}.\eta^{EL})/(LHV^{H2}) \tag{24}$$

$$N_{h,t}^{EL,H2} \le \overline{N}_{h,t}^{EL,H2} \tag{25}$$

$$\underline{E}_h^{EL} \le E_{h,t}^{EL} \le \overline{E}_h^{EL} \tag{26}$$

where, the produced hydrogen molar in EL is presented by $N_{h,t}^{EL,H2}$. The lower heating value of hydrogen and the efficiency of EL are represented by LHV^{H2} and η^{EL}. Equation (24) models the hydrogen production by the EL. Constraints (25) and (26) maintain the amounts of produced hydrogen and consumed power by the EL in the permissible range, respectively.

8) Fuel cell unit

$$E_{h,t}^{FC} = N_{h,t}^{FC,H2}.\eta^{FC}.LHV^{H2} \tag{27}$$

$$N_{h,t}^{FC,H2} \le \overline{N}_{h,t}^{FC,H2} \tag{28}$$

$$\underline{E}_h^{FC} \le E_{h,t}^{FC} \le \overline{E}_h^{FC} \tag{29}$$

where, the consumed hydrogen molar by FC and its efficiency are indicated by $N_{h,t}^{FC,H2}$ and η^{FC}. Equation (27) models the power production by the FC. Constraints (28) and (29) maintain the amounts of consumed hydrogen and produced power by the FC in the permissible range, respectively.

9) Methanization unit

$$G_{h,t}^{ME} = N_{h,t}^{ME,H2}.\eta^{ME}.LHV^{H2} \tag{30}$$

$$N_{h,t}^{ME,H2} \le \overline{N}_{h,t}^{ME,H2} \tag{31}$$

$$\underline{G}_h^{ME} \le G_{h,t}^{ME} \le \overline{G}_h^{ME} \tag{32}$$

where, the produced gas and the consumed hydrogen molar by ME are shown by $G_{h,t}^{ME}$ and $N_{h,t}^{ME,H2}$. Equation (30) models the gas production by the ME. Constraints (31) and (32) maintain the amounts of consumed hydrogen and produced gas by the ME in the permissible range, respectively.

10) Hydrogen storage unit

$$E_{h,t}^{HS} = E_{h,t-1}^{HS} + (\frac{T^{H2}\Re}{V^{H2}}).(N_{h,t}^{HS,C} - N_{h,t}^{HS,D}) \tag{33}$$

$$N_{h,t}^{EL,H2} + N_{h,t}^{HS,D} = N_{h,t}^{ME,H2} + N_{h,t}^{FC,H2} + N_{h,t}^{HS,C} \tag{34}$$

$$\underline{E}_h^{HS} \le E_{h,t}^{HS} \le \overline{E}_h^{HS} \tag{35}$$

$$E_{h,0}^{HS} = E_{h,In}^{HS} \tag{36}$$

where, the stored hydrogen in HS is stated by $E_{h,t}^{HS}$. $N_{h,t}^{HS,D}$ and $N_{h,t}^{HS,C}$ are the hydrogen discharging and charging in HS. The overall tank volume, mean temperature, and gas constant are respectively denoted by V^{H2}, T^{H2}, and $\Re$. Equation (33) models the balance of stored hydrogen in the HS. Equation (34) indicates the balance of produced and consumed hydrogen molars in the system. Constraints (35) and (36) formulate the permissible changes of stored hydrogen in the HS and its initial amount, respectively.

11) Natural gas grid

This work focuses on the co-optimization of power and gas grids for the optimal multi-energy management of EHs that the gas sector of the integrated energy structure is exploited subject to the following limitations [26, 27].

$$\begin{aligned}&(A^{SG}.E^{S,G}_{g,t})+(A^{ME}.E^{ME}_{g,t})+[A^{GS}.(E^{GS}_{g,t-1}-E^{GS}_{g,t})]=\\&D^{G}_{g,t}+E^{T,G}_{g,t}+\sum_{l=1}^{N_n} f^{Gas}_{g,l,t} \quad \forall g,t\end{aligned} \tag{37}$$

$$f^{Gas}_{g,l,t}=\mathrm{sgn}(\Upsilon_{g,t},\Upsilon_{l,t}).\Gamma_{g,l}.\sqrt{\left|\Upsilon^2_{g,t}-\Upsilon^2_{l,t}\right|} \tag{38}$$

$$\mathrm{sgn}(\Upsilon_{g,t},\Upsilon_{l,t})=\begin{cases}1 & \Upsilon_{g,t}\ge\Upsilon_{l,t}\\-1 & \Upsilon_{g,t}<\Upsilon_{l,t}\end{cases} \tag{39}$$

$$\underline{\Upsilon}_g \le \Upsilon_{g,t} \le \overline{\Upsilon}_g \tag{40}$$

$$\underline{E}^{GS}_g \le E^{GS}_{g,t} \le \overline{E}^{GS}_g \tag{41}$$

$$\underline{E}^{S,G}_{g,t} \le E^{S,G}_{g,t} \le \overline{E}^{S,G}_g \tag{42}$$

where, A^{ME}, A^{GS}, and A^{SG} denote the incidence matrix for the ME, gas storage, and gas supplier. The gas pressure is indicated by $\Upsilon_{g,t}$ in node *g*. The gas flow in line *g-l* and the gas storage energy are shown by $f^{Gas}_{g,l,t}$ and $E^{GS}_{g,t}$. The coefficient of the Weymouth equation is stated by $\Gamma_{g,l}$. Balancing the gas energy is modeled by (37). The gas flow and related directions are formulated by (38) and (39) in the pipeline *g-l*. Constraint (40) keeps the gas pressure in the allowable range while constraints (41) and (42) are for bounding the stored gas and gas supplier output in the permissible range.

D. Uncertainty Modeling

Fully equipped renewable energy structures face great stochastic changes in their energy production sector. Employing an appropriate method for scrutinizing uncertain changes of RESs allows for extracting near-reality outcomes. In this regard, the IGDT is one of the non-fuzzy approaches that more information is not required for its uncertainty modeling process, unlike other techniques [28]. It comprises robustness and opportunistic functions that engage positive and negative violations of uncertain parameters for designing competent risk-averse and seeker strategies for the decision-maker.

1) Risk-averse strategy

This strategy offers a robustness condition for the system by considering the worst state of RESs changes that guarantee the attainment of desirable economic advantages. To this end, the risk-averse strategy pursues the maximization of the horizon of uncertainty under the following mathematical process.

$$\mathrm{Max}\ \Psi^{Ro} \tag{43}$$

Subject to:

$$OF_h \le OF_h^{Ro}=(1+\phi)OF^0 \tag{44}$$

$$\begin{aligned}&\zeta_t=\hat{\zeta}_t+\Delta\zeta_t \quad \zeta_t\in\left\{\varpi_t,\kappa_t^{PV}\right\}\\&(2)-(42)\end{aligned} \tag{45}$$

$$OF_h=\max_{\Delta\zeta_t} OF_h^B(\Delta\zeta_t) \tag{46}$$

$$-\Psi^{Ro}\hat{\zeta}_t \le \Delta\zeta_t \le \Psi^{Ro}\hat{\zeta}_t \tag{47}$$

where, Ψ^{Ro} is the renewables deviation from their forecasted amounts that its maximization is the main objective of the risk-averse strategy. $\Delta\zeta_t$ is the deviation from the renewables forecasted amounts ($\hat{\zeta}_t$). OF_h^{Ro} denotes the anticipated amount of the objective function in the robustness function. Given (46), the optimization problem has gotten the bi-level state that needs to be converted to the single-level for analyzing the risk-averse strategy. Due to this, the worst state of renewables can be intended for procuring a sufficient level of robustness according to the following constraints.

$$\Delta\zeta_t=-\Psi^{Ro}\hat{\zeta}_t \tag{48}$$

$$(\Delta\zeta_t+\Psi^{Ro}\hat{\zeta}_t).\zeta_t\le 0 \tag{49}$$

Equations (48) and (49) are the limitations for ensuring that the worst states of RESs changes are considered in the problem.

2) Risk-seeker strategy

This strategy relies on the opportunistic function of the IGDT method in converting desirable variations of RESs to opportunities for maximizing economic benefits. For this aim, the risk-seeker strategy is aimed to minimize the horizon of uncertainty according to the following formulas.

$$\begin{aligned}&\mathrm{Min}\ \Psi^{Op}\\&\text{Subject to:}\end{aligned} \tag{50}$$

$$\begin{aligned}&OF_h \le OF_h^{Op}=(1-\phi)OF^0\\&(2)-(42),\ (45)\end{aligned} \tag{51}$$

$$OF_h=\min_{\Delta\zeta_t} OF_h^B(\Delta\zeta_t) \tag{52}$$

$$-\Psi^{Op}\hat{\zeta}_t \le \Delta\zeta_t \le \Psi^{Op}\hat{\zeta}_t \tag{53}$$

where, Ψ^{Op} is the renewables deviation from their forecasted amounts that is targeted to be minimized in the risk-seeker strategy. OF_h^{Op} presents the anticipated amount of opportunistic function. Equation (52) states the optimization problem type is changed from the single-level to the bi-level optimization problem. To get back to the single-level problem, the most desirable deviations of RESs can be considered based on the opportunistic function as follows.

$$\Delta\zeta_t=\Psi^{Ro}\hat{\zeta}_t \tag{54}$$

$$(\Delta\zeta_t+\Psi^{Ro}\hat{\zeta}_t).\zeta_t\ge 0 \tag{55}$$

Equations (54) and (55) are for assurance from taking the best occurrence state of RESs into account in the risk-seeker strategy.

3) LHS and FFS methods in the stochastic programming

The stochastic programming (SP) approach is one of the famous uncertainty quantification techniques for its applicability in modeling uncertain fluctuations of random parameters via considering a sample from different states of uncertainty set [29]. As the SP method, LHS relies on the scenario generation process that explores the whole sample space by intending it's all elements as well as their corresponding probability. After dividing the cumulative distribution function to S (number of scenarios) intervals in the LHS, the midpoint of each interval is chosen as the scenario for the stochastic analysis. More information regarding the LHS can be reached in [30].

Computational burden and complexity are the disadvantages that come from considering numerous scenarios for probabilistic assessment of the optimization problem. To avoid the aforementioned drawbacks, the SP techniques benefit from scenario reduction methods for intending a logical number of scenarios in the uncertainty modeling process. The FFS is one of the scenario reduction ways that relies on minimizing the Kantorovich distance of all scenarios for selecting those ones with the minimum distance from others. Detailed analysis of the FFS method can be fully accessed in [31].

III. Simulation Results

This research aims at analyzing techno-economic-environmental aspects of optimal energy management for cooperative EHs in the gas and power coupled network. To this end, the assessment is carried out intending the modified version of the IEEE 6-bus power [32] and 6-node natural gas [26] test systems, which their integrated topology is illustrated in Fig. 2. The solar and wind power generations are intended as RESs for cost-effective energy production whereas the BSS is operated for reducing the uncontrollable features of them [33]. The required data for modeling wind turbines, solar PV systems, as well as energy price and power demand can be respectively found in [34], [23], and [35]. This work benefited from the Lead-acid battery as the BSS that its characteristics and required data can be reached in [24]. The hydrogen-based energy conversion technology is adopted by operating EL, HS, FC, and ME units to allow the system to properly utilize the excess produced power by converting it to other carriers of energy under the P2G technology process. The required data for modeling all the mentioned hydrogen-based systems can be found in [23]. Fig. 3 shows the wind speed and solar radiation during the 24 hours that are required for modeling the solar PV system and wind turbine [35]. Moreover, Table I encompasses the value of coefficients required for modeling different energy systems.

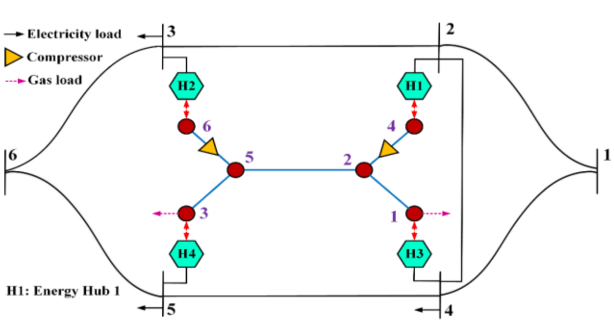

Fig. 2. Schematic of the coupled gas and power test system.

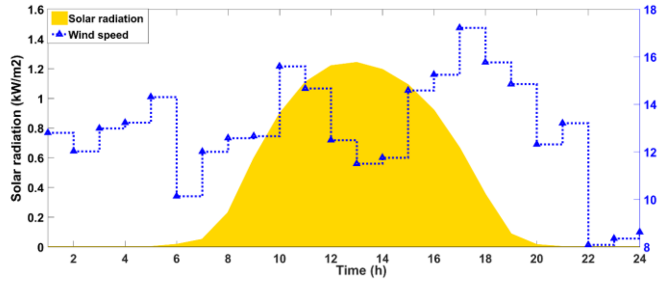

Fig. 3. Wind speed and solar radiation during the 24 hours [35].

TABLE I. THE VALUE OF COEFFICIENTS REQUIRED FOR MODELING DIFFERENT ENERGY SYSTEMS.

Parameter	LHV^{H2} (kJ/kmol)		η^{EL}	η^{FC}	η^{ME}	η^{PV}
Value	240		0.55	0.45	0.83	0.22
Parameter	LCN_h^{BSS}	IC_h^{BSS} (USD)	ξ_h^{P2G}	T^{H2} (°K)	$\Re$	V^{H2} (m³)
Value	1000	800000	25	313	8/314	4
Parameter	α_1	α_2	α_3	ϖ_h^{Cut-In} (m/s)	$\varpi_h^{Cut-Out}$ (m/s)	ϖ_h^{Rated} (m/s)
Value	0.123	-0.096	0.0184	4	22	12.5

In this study, the mixed-integer nonlinear programming (MINLP) problem is solved by deploying SBB and DICOPT solvers in the general algebraic modeling system (GAMS). The optimization problem is investigated in two Cases. Case I assesses the deterministic operation problem while the techno-economic-environmental risk-aware scheduling of EHs is scrutinized by modeling uncertainties in Case II. The total costs of \$54,018.52 and \$95,905.69 are reached for the objective function when the problem is respectively solved based on Cases I and II. Hence, the system faces more operation costs in Case II due to considering realistic conditions of EHs in terms of uncertainty quantification. In this respect, financial numerical results are tabulated in Table II. The information in this table states that EHs have achieved various costs given their scale and operating conditions. Given the results reported in Table II, the energy cost related to the operation of different systems of the electricity sector in Case II is higher than in Case I for all EHs. This analysis indicates that uncertainty quantification imposes higher costs for cooperative EHs due to considering almost all stochastic changes in the optimization process. This is while the exploitation of EHs under Case II with uncertainty modeling brings beneficial advantages, particularly in terms of gaining near-reality results. This research is conducted to coordinately operate the coupled gas and power grids aiming to improve synergies among multi-energy systems. Fig. 4 portrays optimal scheduling points for the electrical energy units.

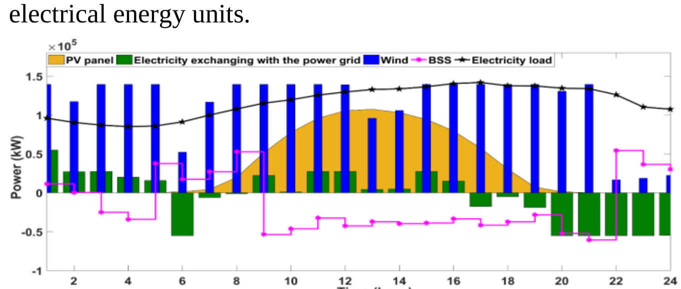

Fig. 4. Optimal scheduling points for the electrical energy units.

TABLE II. FINANCIAL RESULTS OF ENERGY HUBS

	Financial indicators	Energy hubs			
		Hub 1	**Hub 2**	**Hub 3**	**Hub 4**
Case I	**Revenue Electricity (USD)**	339.24	312.31	326	313.82
	Cost Electricity (USD)	9,679.84	13,333.78	11,558.02	12,307.33
	Revenue Gas (USD)	30,368.94	650.76	15,184.47	216.92
	Cost Gas (USD)	35,824.09	463.03	18,403.4	161.49
	Objective Function (USD)	14,795.75	12,833.74	14,450.95	11,938.08
Case II	**Financial indicators**	**Hub 1**	**Hub 2**	**Hub 3**	**Hub 4**
	Revenue Electricity (USD)	497.16	1,232.94	1,262.52	495.3
	Cost Electricity (USD)	14,434.4	28,946.21	27,556.22	19,759.4
	Revenue Gas (USD)	30,368.93	650.76	15,184.47	216.92
	Cost Gas (USD)	36,119.5	443.32	18,400.78	154.86
	Objective Function (USD)	19,687.81	27,505.83	29,510.01	19,202.04

Given Fig. 4, in addition to serving the energy demand of time period 1-5 am, the surplus of the manufactured wind power is used to charge the storage unit and maximizing the economic benefits by selling a portion of excess power to the main grid. After 6 am, the decline in the wind speed is accompanied by the increment in power consumption resulting in increasing the purchase of power from the main grid along with the discharging of the BSS for assisting EHs in balancing energy. Moreover, the surplus outputs of RESs in the mid-hours of the day are sold to the upstream grid for economic objectives. This is while another portion of the produced clean energy is taken into account for charging the BSS to make the usage of the BSS discharging option possible in the next hours with energy shortage. However, the hard condition caused by the depletion of wind turbines' outputs along with the zero solar power generation has driven EHs to use the discharging of the storage unit and receive more energy from the grid for energy balance at night. Indeed, energy storage units along with energy sharing possibilities are availed as the supportive options for EHs to enable them to successfully complete their responsibilities in continuously meeting energy demand. The information in Fig. 4 also indicates the critical role of energy storage and trading in managing excess and shortage of energy during all hours of the day, which resulted in becoming the power sector sufficiently sustainable against RESs uncertain fluctuations. The excess of produced energy can be availed by the EL for the energy conversion. In this respect, the outputs of EL and FC as well as the demand response program are demonstrated in Fig. 5.

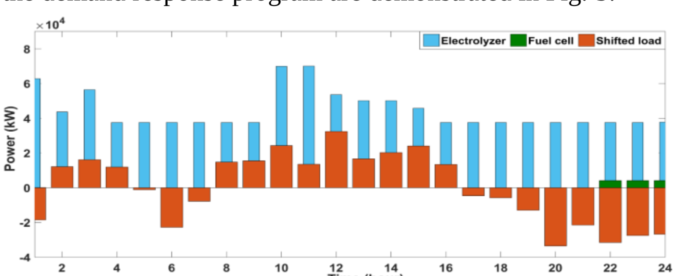

Fig. 5. Optimal scheduling for the FC and EL along with the shifted load program.

According to Fig. 5, the excess of clean produced power by wind turbines in the early morning is effectively availed by the EL to enable the system for hydrogen energy production and storing in the HS for future utilizations. The maximum generated solar power by panels in the noon hours has repeated the energy conversion process for EHs in this time period. Considering the energy conversion possibility and subsequently producing a proper level of hydrogen molar by the EL unit have enabled the system to effectively use the potential of ME and FC systems to generate multi-carrier energy when the system suffers from the lack of adequate electricity and gas production. The desirable level of produced clean power in the mid-day has resulted in moving a portion of demand to related hours. This is while EHs have used the operation of FC units to support the system in creating a dynamic energy balance at night when RESs experienced the minimum power production. As obvious from Fig. 5, the system has beneficially used the potential of EL and FC units by properly converting the surplus power to hydrogen and effectively using the stored hydrogen in the HS for generating power in the last hours of the day with the essential demand to the power. Additionally, the demand side power management was a helpful scheme for EHs in allowing them to shift a limited percentage of the power load from the hours with the lack of sufficient energy to energy-rich times. All EHs have also benefited from the P2G technology to upsurge the flexibility of the hybrid energy system with full RESs to effectively cope with intermittences of stochastic energy generators. Fig. 6 indicates optimal scheduling points for the ME and gas energy trading.

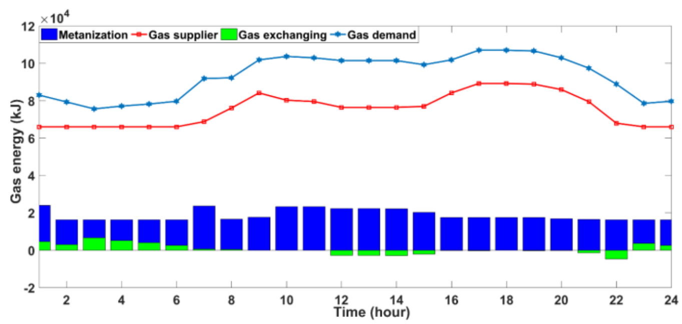

Fig. 6. Optimal scheduling for natural gas units.

In the early morning (1-7 am), Fig. 6 illustrates the closity of the supplied gas by gas suppliers to the demand. In the mentioned time period, the generated gas by the ME system is not only availed for delivering to the upstream network for maximizing economic achievements of EHs but also is considered for filling gas shortages due to differences between the supplied gas and gas load. This is while the whole output of the ME unit is considered for injecting into the gas sector to support the system to effectively respond to the increment in the natural gas demand. However, in addition to the ME support, the system has been forced to serve a small portion of gas demand by purchasing natural gas from the upstream network. Decreasing the gas energy demand at night has driven the system again to use the opportunity of selling gas to the main grid for increasing EHs revenue. Similar to the power grid, the system has benefited from energy conversion units along with gas trading opportunities to empower EHs to serve gas without energy interruption during the day. In this respect, as an energy conversion system, the ME unit has consumed hydrogen for supporting the gas structure by generating natural gas at all times of the day. In other words, the ME system and gas sharing possibility were essential ways for the sustainability of the gas sector in the presence of RESs as the main uncertain sources of the hybrid energy infrastructure.

In this work, due to the contribution of fully RESs in the power production sector, the energy network faces a high degree of uncertain volatilities in the multi-carrier energy generation process that have brought critical challenges for optimal operation of the integrated grid. In light of this penetration of renewables and the necessity of risk-aware assessment of the multi-energy system, this paper proposes innovative risk-averse and risk-seeker strategies to procure a promising decision-making paradigm for the decision-maker enabling him/her for maximizing economic benefits as well as ensure a sufficient degree of robustness. Fig. 7 presents different operation costs of EHs in robust and opportunity functions.

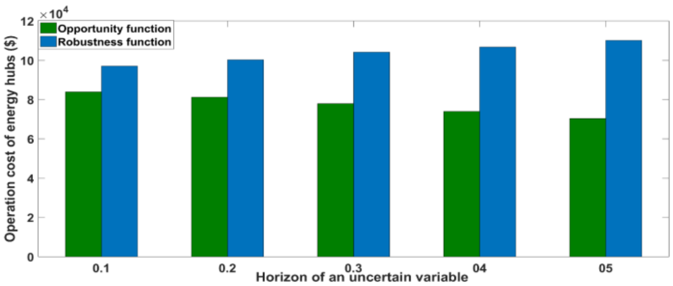

Fig. 7. The operation cost deviation of EHs in risk-averse and seeker strategies.

Given Fig. 7, EHs have experienced different trends of cost changes in robust and opportunity functions. In the risk-averse strategy (robust function), the system has witnessed the energy cost increment in line with the horizon of the uncertain variable. Indeed, being enough robust in the larger deviation period of uncertain parameters has led to imposing more energy costs for EHs. This is while the risk-seeker strategy (opportunity function) opens a new window for effectively utilizing opportunities created by desirable deviations of uncertain parameters. According to the cost changes of this strategy in Fig. 7, EHs have gained more cost-saving in response to increasing the horizon of the uncertain variable. In other words, EHs can obtain more economic benefits in the shorter stochastic deviation period that exposes them to higher risks. The presented results in Fig. 7 denote the importance of risk-aware assessment of the hybrid energy structure with multifarious uncertain sources as it provides useful information for the decision-maker to take appropriate actions in different conditions. Indeed, risk-averse and risk-seeker strategies enable the decision-maker to properly face various intermittences that come from diverse uncertain environments. Given the aforementioned strategies, the decision-maker can take an appropriate decision considering different factors such as the robustness level and economic benefits.

Given the necessity of transition towards cost-effective and eco-friendly energy production processes, the deployment of RESs on a large scale has become an undeniable step in modernizing future energy grids. However, the considerable challenge of this step is the uncertain nature of RESs in energy generation which needs innovative solutions to make the usage of RESs feasible in practice. Indeed, intermittences of RESs limit the ability of EHs in their optimal scheduling for uninterrupted power supply with high reliability. Such uncertainties expose the system to higher exploitation risks that create the challenge of adopting proper decisions for the decision-maker. Therefore, the risk-aware assessment of the system is critical for achieving near-reality outcomes. Another key challenge backs to the lack of a holistic model for the multi-energy management of cooperative EHs that hinders the optimal exploitation of the integrated system with 100% RESs. All the aforementioned challenges limit the realization of EHs with 100% RESs and the implementation of decarbonization plans in line with the grid modernization goals. This is while the deployment of full RESs, energy conversion and storage systems, as well as other energy devices provides technical and economical restrictions that can be considered as another prominent limitation for implementing such decarbonized energy structures.

This works addresses the mentioned challenge by proposing a novel techno-economic-environmental risk-aware framework in incorporated power and gas grids intending all their interactions and limitations (technical aspects) for maximizing economic benefits of EHs (economic aspects) as well as fully producing clean energy in the system (environmental aspects). In other words, EHs with 100% RESs bring tremendous environmental benefits by using only RESs for power production. Producing fully carbon-free energy enables EHs to satisfy zero-emission targets by employing a new risk-aware framework. The mentioned framework benefits power-to-gas technology along with the energy storage facilities and energy management programs to be successful in keeping the sustainability of the system with the penetration of 100% RESs. Therefore, as EHs are equipped with 100% RESs and are operated under the proposed techno-economic-environmental risk-aware framework, they can facilitate the implementation of decarbonization schemes and realize the objectives of zero-emission plans for the future energy infrastructure.

IV. CONCLUSION

A techno-economic-environmental risk-aware assessment was conducted for the optimal multi-energy management of EHs under the co-optimization of gas and power sectors. Due to this, a holistic framework was developed to enable the hybrid energy system for dynamically serving of EHs that are equipped with 100% RESs. The proposed model benefits from the robust and opportunity functions of the IGDT method for designing novel risk-averse and risk-seeker strategies that enable the decision-maker for adopting an affordable strategy in the deregulated environment. The P2G technology is adopted to allow EHs to effectively benefit from energy conversion opportunities for improving synergies among the gas and power structures and properly dealing with renewables' intermittencies. The combination of scenario generation and reduction techniques including LHS and FFS with the IGDT approach is intended to empower the hybrid system for effectively tackling uncertainties associated with RESs. The optimization problem is solved in two cases under the modified version of the IEEE 6-bus and 6-node gas systems. The obtained results presented the capability of the proposed framework in maintaining the system's sustainability as well as procuring innovative risk strategies for the decision-maker in the presence of full RESs.

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