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Published in:
2021 IEEE International Conference on Environment and Electrical Engineering

DOI (link to publication from Publisher):
10.1109/EEEIC/ICPSEurope51590.2021.9584800

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Daneshvar, M., Mohammadi-Ivatloo, B., Zare, K., & Anvari-Moghaddam, A. (2021). Techno-Economic Analysis of Hybrid Energy Systems with 100% Renewables in the Grid Modernization Process. In *2021 IEEE International Conference on Environment and Electrical Engineering: EEEIC 2021* (pp. 1-6). IEEE Press. https://doi.org/10.1109/EEEIC/ICPSEurope51590.2021.9584800

Techno-Economic Analysis of Hybrid Energy Systems with 100% Renewables in the Grid Modernization Process

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***Abstract*—Recently, grid modernization efforts are developed to ease the realization of the transition from conventional energy systems to modern integrated energy grids. In this regard, energy hubs have been emerged as an interconnection point among different energy grids and components to enable the collection, conversion, and storage of multi-carrier energies in a deregulated environment. This paper concentrates on the techno-economic examination of hybrid energy systems in the grid modernization process. In this regard, optimal scheduling of energy hubs (EHs) is investigated in a hybrid network with a full share of renewable energies. Each EH is equipped with the wind and solar systems, battery energy storage, power-to-gas system, fuel cell, and hydrogen storage in the interconnected electricity and gas grids. Due to a very large share of renewables, the system is highly exposed to the intermittences of stochastic producers. Hence, uncertainty quantification is carried out using the stochastic programming technique, in which the Latin Hyperbolic Sampling method is selected for scenario production while the fast forward selection appraoch is considered for scenario diminution. The effectiveness of the proposed model is examined in a coupled structure of the IEEE 6-bus electric power system and a 6-node natural gas grid. The results highlight the applicability of the suggested model in providing the sustainable condition for the system in time to time balancing energy in the integrated energy network with 100% renewables.**

Keywords—grid modernization, energy hub, 100% renewable energy resources, power-to-gas technology, hybrid energy network, multi-carrier energy systems

I. Introduction

A. Motivation and Background

Over recent years, cutting-edge technologies are developing to be fully considered in the co-generation and tri-generation process for a rapid transition toward multi-carrier energy systems [1]. This progress is targeted to be developed in response to the call for efficient energy processes and effective energy management schemes by mushrooming the renewable-based energy production units in integrated energy systems [2]. As the usage of the stochastic producers is increased in the energy generation sector, sustainability comes to a challenge in the complex structure of the multi-vector energy grid [3]. In this regard, energy hubs (EHs) are recognized as interconnection point among various energy grids and components, which enable the collection, conversion, and storage of various energies in a sustainable way by considering the restrictions of multi-vector energy networks [4]. Indeed, EHs make grids susceptible to properly utilize the environment's potential to fully supply clean energy carriers that is one of the prominent goals of the future modern multi-energy grids [5]. In this respect, energy conversion systems play a crucial role in the realization of exploiting 100% renewable-based EHs for a fully pollutant-free energy supply act in the system [6]. On the other hand, the hybrid model of gas and electricity networks has been known as one of the suitable structures for operating carbon-free EHs to reliably serve both the electrical and thermal energy loads. Therefore, co-optimization of the aforementioned networks is essential for achieving confident results. Thereby, this article is motivated to analyze the optimal stochastic scheduling of the interconnected EHs equipped with 100% renewables by co-optimizing both the natural gas and electrical networks.

B. Relevant Literature

Over the past decades, multi-vector energy is recognized as one of the undeniable requirements for modernizing the customer side [7]. Herein, developing hybrid energy systems as well as increasing the penetration of carbon-free energy resources have made energy management in the EHs challengeable. This issue has driven energy management focuses from fossil-fuel based uni-dimension energy systems to multi-vector clean energy grids. For this aim, optimal scheduling of EHs is examined from different perspectives in recent years. For instance, the authors in [8] presented a robust framework based on the chance-constrained optimization for optimal energy management of the EH in the presence of multi-carrier energy demand considering the unpredictability of uncertain parameters. In [9], the authors offered a novel model for energy management of the EH to increase the interconnections of various systems in a smart platform. The stochastic dynamic optimization formulation was presented in [10] to manage energy interactions by modeling variabilities of the electricity price and demand. In the same work, an approximate dynamic programming framework was developed to support the achievement of dynamic dispatch policies. This is while a cost-based mathematical optimization model was used not only in [11] to optimally manage EHs but also the model was developed to capture the intermittences in the studied system using the information gap decision theory (IGDT) technique.

In multi-vector energy systems, decarbonization of the integrated energy grids is intended as pioneering efforts due to the indispensability of switching from uni-dimension energy networks to multi-dimension grids for increasing synergies among different carriers [12]. The feasibility of these efforts is significantly enhanced by the operation of 100% renewables as attractive decarbonization schemes that enable clean society to come to view in the modern infrastructure of hybrid energy grids [13]. In this regard, fully equipped renewable systems with different types of clean energy generation units have taken substantial attention in recent literature. For instance, the authors in [14] offered a novel decomposition-based strategy to model multiple uncertainties in the coordinated planning of the power system with 100% renewable energy resources (RERs). In [15], the possibility of transiting toward the sustainable energy grid with 100% renewables was investigated considering the multi-vector energy systems. The results indicated that integration of the energy grids could allow effective electrification by enhancing the flexibility of the whole grid. Moreover, a fundamental linear optimization model was presented in [16] to analyze the applicability of the distributed battery storage systems for raising the flexibility of the hybrid system with 100% renewables in balancing energy.

C. *Contributions and Organization*

Given the assessed researches in the previous section, substantial research gaps are identified to be addressed in detail. In recent studies, although energy management of EHs is assessed using different techniques, a holistic model is not suggested for the hybrid system. In other words, developing a sustainable model that can simultaneously support clean natural gas and electricity generation is ignored in the integrated structure of the energy grid with the full contribution of RERs. Therefore, this article is aimed to offer a new model for coordinated scheduling of the electricity and gas networks considering their restrictions. To this end, four EHs with 100% RERs are equipped with hybrid energy devices to keep the sustainability of the energy grid in a highly deregulated environment. The power-to-gas (P2G) unit is used for developing the proposed model aiming to effectively improve the synergies among the multi-carrier energies. Because the system is fully empowered with clean energy production systems, the impact of different intermittences is inevitable in the accuracy of the results. Hence, the stochastic programming appraoch is exerted for uncertainty quantification, in which Latin hyperbolic sampling (LHS) and fast forward selection (FFS) approaches are respectively intended for scenario production and reduction.

The paper is organized as follows. Section II characterizes the problem formulation as well as stochastic modeling of the system. Section III provides a discussion regarding the simulation results. Finally, Section IV is the conclusion of this paper.

II. Optimal Scheduling for Energy Hubs

A. *Energy Hub Architecture*

In this study, the optimal scheduling of EHs with 100% RERs is aimed at the coordinated operation of the interconnected structure of the gas and electricity grids for fully clean energy generation that is known as one of the main goals in the grid modernization process. The structure of each EH is clarified in Fig. 1.

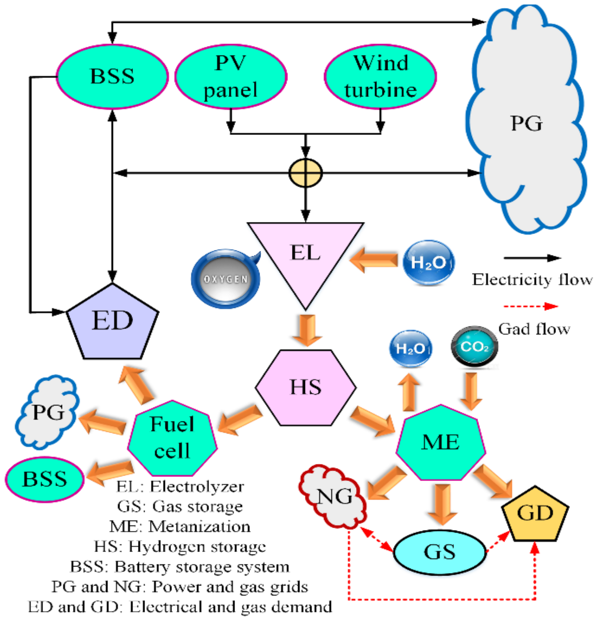

Fig. 1. Schematic of the EH with 100% RERs

According to Fig. 1, wind systems and solar panels are used for pollutant-free energy generation, and BSS is used for assurance of the nonstop energy supply in the system. The electrolyzer (EL) system is operated for effective usage of RERs outputs by converting a surplus of electricity to the hydrogen molar that can be stored in the hydrogen storage (HS). The fuel cell (FC) unit is considered for supporting the EH by producing electricity when its generation is lower than its consumption. The metanization (ME) system is used for completing the P2G cycle by generating natural gas that can be injected into the gas grid or can be stored in the gas storage system. Each EH can share electricity and gas with the energy network to enhance the hybrid energy structure's flexibility in meeting electricity and natural gas demand.

B. *Objective Function*

The main goal of this research is to minimize the EHs' operation cost in the coordinated optimal scheduling of the electricity-gas coupled grid. For this aim, the objective function can be written as:

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

where, OF_h is the objective function for the energy hubs. ψ_s states the probability of scenario *s*th. The amount of CO_2 consumption per unit of natural gas generation is presented by the coefficient ξ_h^{P2G} . $\rho_{CO_2}^{P2G}$ is the price of CO_2. The efficiency and electricity used by the P2G system are respectively presented by η^{P2G} and $E_{h,t,s}^{ME}$. $\rho_t^{S,G}$ and $E_{h,t,s}^{S,G}$ are the price and the amount of gas supply for the EH *h* at time *t* and scenario *s*. Φ_h^{BSS} models the lifetime degradation cost of the battery storage system (BSS). $E_{h,t,s}^{BSS}$ and $\Theta_{h,t,s}^{BSS}$ indicate the power and energy of BSS. The leakage loss factor is presented by η^{Lc}. $\rho_t^{T,E}$ and $\rho_t^{T,G}$ are the electricity and gas exchanging price with the main grid. $E_{h,t,s}^{T,E}$ and $E_{h,t,s}^{T,G}$ are the amounts of electrical and gas energy trading with the upstream grid. The negative/positive amount of these variables present energy purchasing/selling from/to the upstream grid. $\rho_t^{S,E}$ and $\rho_t^{S,G}$ are the gas and electricity selling prices to the consumers. $D_{i,t}^{E}$ and $D_{g,t}^{G}$ are the gas and electricity demand. In (1), the first term models the operation cost of the P2G system. The second term presents the cost of purchased gas from gas suppliers. The third term formulates the operation cost of BSS. The fourth and the fifth terms model the cost/revenue of electrical and gas energy sharing with the upstream grid, respectively. The sixth and the seventh terms indicate the revenue from selling electricity and gas to the consumers, respectively. The two last terms model the cost of load response (LR) and price response (PR) schemes. The index *s* is removed from the variables below to avoid repetitive information.

C. Constraints

1) Electricity balance

In the power grid, the electrical energy balance constraint should be established at each time period for assurance of uninterrupted energy supply. This constraint is given as:

$$E_{h,t}^{Wind} + E_{h,t}^{PV} + E_{h,t}^{BSS} + E_{h,t}^{FC} = E_{h,t}^{T,E} + E_{h,t}^{EL} + D_{i,t}^{E} - \sum_{i=1}^{N_b} E_{i,t}^{LR} \quad (2)$$

where, $E_{h,t}^{Wind}$ and $E_{h,t}^{PV}$ are the electricity production by the wind and solar systems in hub *h* at time *t*. $E_{h,t}^{FC}$ and $E_{h,t}^{EL}$ are the electricity generation by FC and electricity consumption by EL. $E_{i,t}^{LR}$ states the interrupted load (IL).

2) PV panel

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

where, η^{PV} states the efficiency of the PV panel. κ_t^{PV}, A_h^{PV}, and T^a are the solar radiation, area of PV, and ambient temperature, respectively.

3) Battery storage system (BSS)

In energy grids with 100% renewables, the exploitation of an adequate capacity of the storage system is inevitable to reliably cope with the intermittencies of the stochastic producers. Herein, BSS is used in EHs to add the capability of storing surplus clean energy produced in the system for them with the aim of using it at required times. The mathematical formulations for BSS are as follows.

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

$$SOC_{h,t} = \frac{\Theta_{h,t}^{BSS}}{\Theta_{RC}^{BSS}} \quad (5)$$

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

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

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

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

where, η^{Cc} is the loss factor for discharging and charging of BSS. $SOC_{h,t}$ is the BSS state of charge, limited by upper and lower bounds as indicated by $SOC_{h,t}^{\max}$ and $SOC_{h,t}^{\min}$, respectively. Θ_{RC}^{BSS} represents the rated energy capacity for BSS. The maximum amounts of electricity discharging and charging are represented by $\bar{E}_{h,t}^{Dis,BSS}$ and $\bar{E}_{h,t}^{Ch,BSS}$. The amounts of life cycle number and investment cost for BSS are respectively denoted by LCN_h^{BSS} and IC_h^{BSS} in the EH *h*th. Equation (4) formulates the electricity balance in BSS. Equations (5) and (6) model the BSS's state of charge and its permissible range. Equation (9) computes the degradation cost of BSS.

4) Wind turbine

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

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

where, $Q_{h,t}^{Wind}$ is the wind turbine's reactive produced power in EH *h*. $E_h^{W,R}$ is the rated wind power. The cut in and cut out wind velocities are denoted by ϖ_h^{Cut-In} and $\varpi_h^{Cut-Out}$. ϖ_h^{Rated} denotes the rated wind speed and ϖ_t indicates the wind speed at time *t*. α_1, α_2, and α_3 are coefficients used for modeling wind power output.

5) Demand-side energy management (DSEM)

Demand-side energy management schemes are typically undertaken for increasing the systems' flexibility in establishing energy balance during 24-hours [17]. In this regard, as load and price response schemes can be properly supportive for the network with 100% RERs, these programs are employed for supporting the system in time to time energy balancing.

a) Load response scheme

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

$$0 \le E_{i,t}^{LR} \le E_{\max,t}^{LR} \quad (13)$$

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

where, γ_1^{LR} and γ_2^{LR} are the coefficients for IL cost.

b) Price response scheme

$$\text{Cost}_t^{PR} = \sum_{i=1}^{N_b} \rho_t^{PR}.(\left|E_{i,t}^{PR}\right|/2) \quad (15)$$

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

$$\underline{\varphi}.D_{i,t}^{E,F} \le E_{i,t}^{PR} \le \bar{\varphi}.D_{i,t}^{E,F} \quad (17)$$

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

where, ρ_t^{PR} is the incentive price for the consumers who participated in the PR scheme. $E_{i,t}^{PR}$ is the amount of shifted load. $D_{i,t}^{E,F}$ is the forecasted amount of electrical energy load.

6) Electricity network

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

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

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

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

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

where, the active and reactive power generation (flow) are denoted by $E_{i,t}^{E,Gen}$ and $Q_{i,t}^{E,Gen}$ ($E_{i,t}^{flow}$ and $Q_{i,t}^{flow}$). The complex power along with its upper and lower limits are respectively indicated by $C_{i,j,t}, C_{i,j}^{\max}$, and $C_{i,j}^{\min}$. The amounts of voltage at bus *i* and its phase angle are presented by $V_{i,t}$ and $\delta_{i,t}$.

7) Electrolyzer system (EL)

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

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

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

where, $N_{h,t}^{EL,H2}$ is the hydrogen molar produced by EL. η^{EL} is the efficiency of EL. LHV^{H2} is the lower heating value of hydrogen.

8) Fuel cell system (FC)

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

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

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

where, $N_{h,t}^{FC,H2}$ is the hydrogen molar consumed by FC. η^{FC} is the efficiency of FC.

9) Metanization system (ME)

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

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

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

where, $N_{h,t}^{ME,H2}$ is the hydrogen molar consumed by ME. η^{ME} is the efficiency of ME. $G_{h,t}^{ME}$ is the amount of produced gas by ME.

10) Hydrogen storage system (HS)

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

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

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

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

where, $E_{h,t}^{HS}$ is the hydrogen stored in HS, which its hydrogen charging and discharging amounts are indicated by $N_{h,t}^{HS,C}$ and $N_{h,t}^{HS,D}$. $\Re$ is the gas constant. T^{H2} and V^{H2} are the mean temperature and overall tank volume.

11) Natural gas network

In this work, the coordinated scheduling of the natural gas system is conducted in the integrated energy network subject to the following constraints [18].

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

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

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

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

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

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

where, $E_{g,t}^{GS}$ and $f_{g,l,t}^{Gas}$ are the gas storage energy and gas flow in line *g-l* at time *t*. A^{SG}, A^{ME}, A^{GS} are the incidence matrix for the gas supplier, ME, and gas storage. $\Upsilon_{g,t}$ and $\Upsilon_{l,t}$ are the gas pressure in nodes *g* and *l*. $\Gamma_{g,l}$ is the coefficient related to the Weymouth Equation. Equation (37) models the gas nodal balance. Equations (38) and (39) formulate the gas flow and its direction in the pipeline *g-l*.

D. Uncertainty Modeling

In the fully equipped renewable grids, uncertainties, especially in the energy generation section, are inevitable parts of the system modeling. In this work, solar irradiation and wind speed are intended as uncertain parameters, and stochastic programming is used to model their volatilities. Due to this, the LHS approach is considered to produce scenarios from different states of the uncertain parameters' occurrence. Since numerous scenarios can be concluded in complexity and high computational burden that are improper for the practical problems, the FFS technique is exerted to diminish the number of scenarios to the expedient level. Detailed information about the LHS and FFS methods can be fully found in [19].

III. Simulation Results

In this study, a techno-economic analysis of EHs is targeted to be examined in the electricity-gas coupled grid. For this aim, the modified IEEE 6-bus electricity [20] and 6-node gas [18] test systems are considered that their coupled topology is depicted in Fig. 2. The solar panel and wind turbine are used for cost-effective energy generation that their parameters can be accessed in [21]. The BSS is used for alleviating the uncontrollable features of RERs [22]. The EL, HS, FC, and ME systems are used for appropriately converting the excess electricity in the system using the potential of the P2G technology. The required parameters for modeling the aforementioned systems can be fully found in [23]. Also, electricity and gas prices can be reached in [24].

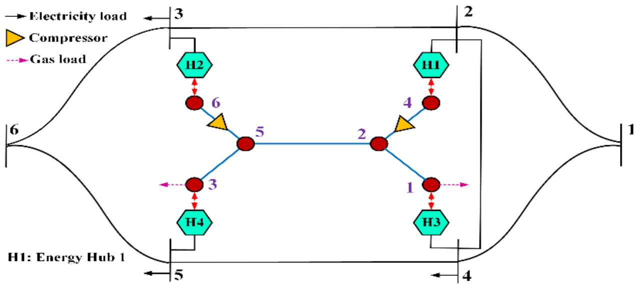

Fig. 2. Schematic of the studied test system

The SBB and DICOPT solvers are deployed using the general algebraic modeling system (GAMS) to solve the mixed-integer nonlinear programming (MINLP) problem with nonlinear equations and binary variables. The same consequences are obtained from the aforementioned solvers that specify the suitable degree of the optimality of the results. The problem is solved in two cases: Case I models the deterministic version of the problem without uncertainty modeling, and Case II scrutinizes the problem by quantifying the uncertainties. After solving the problem, the objective function $5902017.170 and $5902476.449 are respectively gained for Cases I and II. Indeed, realistic modeling of the problem in Case II has exposed the EHs to more energy cost than Case I. The financial indicators for EHs are listed in Table I.

TABLE I. FINANCIAL INDICATORS FOR ENERGY HUBS

	Financial indicators	Energy hubs			
		Hub 1	***Hub 2***	***Hub 3***	***Hub 4***
Case I	***Revenue Electricity***	332.157	344.940	327.514	325.848
	Cost Electricity	6360.334	12272.296	10785.238	8531.017
	Revenue Gas	30368.935	650.763	15184.474	216.923
	Cost Gas	3633093.452	485983.4247	1642005	150737.962
	Total cost	3608752.694	497260.017	1637278.251	158726.209
Case II	**Financial indicators**	***Hub 1***	***Hub 2***	***Hub 3***	***Hub 4***
	Revenue Electricity	346.060	340.794	330.282	323.435
	Cost Electricity	6901.632	10036.514	11245.4	10234.658
	Revenue Gas	30368.935	650.763	15184.474	216.923
	Cost Gas	3633093.452	485983.425	1642005	150738.075
	Total cost	3609280.089	495028.381	1637735.603	160432.376

Given Table I, EHs have obtained different economic benefits based on their scale and operated systems. In this regard, coordinated operation of gas and electricity grids is done to improve the synergies between the hybrid energy devices. The optimal scheduling of the electricity units is portrayed in Fig. 3.

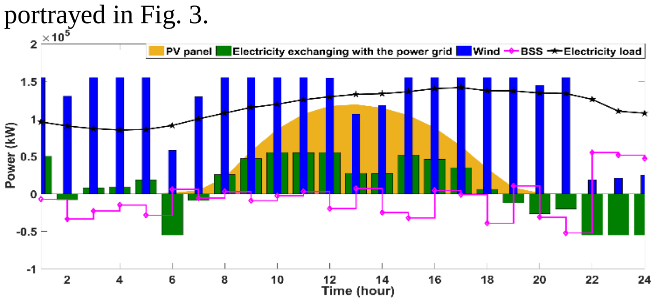

Fig. 3. Optimal scheduling of the electrical energy systems in the EH

According to Fig. 3, in the time period 1-5 am, the wind turbine output not only is used for serving energy load but also the surplus of the produced electricity is dedicated for charging BSS and selling to the power grid to maximize EH's economic benefit. From 6 am, by simultaneously increasing the energy consumption and dropping wind speed, the system has purchased energy from the main grid and has used discharging possibility of BSS for supporting wind turbines in dynamic energy supply. In the mid-hours of the day, in addition to cover the electricity load, the excess outputs of RERs are sold to the power network. However, due to zero output of PV panels and substantially decreasing wind power production at night (10-12 pm), the BSS along with purchasing electricity from the upstream network is used for meeting electricity load. In this regard, the surplus of generated clean electricity is used by the EL system for energy conversion. The optimal scheduling of EL and FC, along with the price response scheme, is shown in Fig. 4.

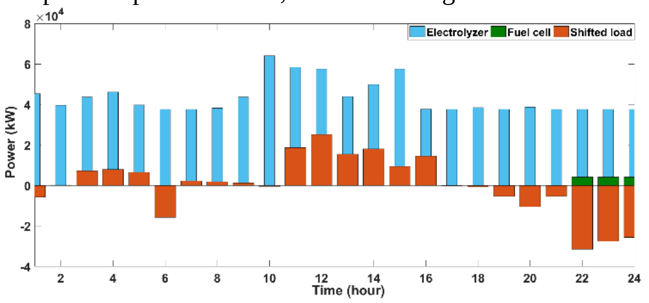

Fig. 4. Optimal scheduling of the shifted load, EL, and FC systems

As obvious from Fig. 4, given the desired output of the wind turbine in the early morning, the excess clean electricity is used by EL for generating hydrogen molar and storing it in the HS for later use. The same process is repeated in the noon times as the solar power generation is at the maximum amount in these hours. The more pollutant-free electricity production in the mid-day by RERs has been led to the shifting of a portion of electricity load to these times. This is while the effective potential of the FC system is used at the end of the day for supporting the system in establishing a time-to-time electricity balance when RERs outputs are at the minimum amount. In this work, the P2G system is also operated to upsurge the integrated energy network's flexibility with 100% RERs in properly coping with the uncontrollable features of stochastic producers. The optimal scheduling of ME and gas trading are portrayed in Fig. 5.

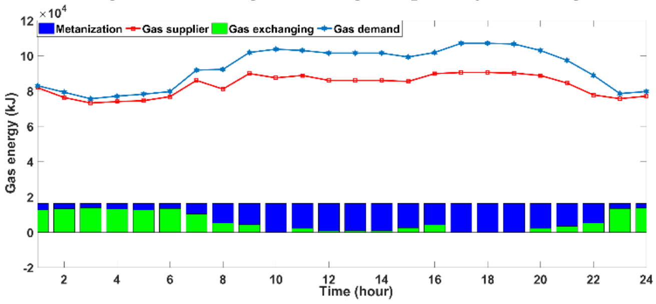

Fig. 5. Optimal scheduling of the gas systems

In Fig. 5, the supplied gas energy by gas supplier systems is close to the gas load in the early morning (1-7 am). In these hours, the natural gas produced by ME is used for selling to the gas grid to maximize the economic benefit of the EH. However, in the mid hours of the day, increasing the gas energy load has been led to the use of the ME's output for supporting the gas supply system for dynamically balancing gas demand. This is while by decreasing gas consumption at the end of the day, the surplus gas production by ME is sold to the gas grid for increasing energy revenue.

IV. Conclusion

In this study, a techno-economic analysis of the optimal scheduling of EHs was carried out considering the coordinated operation of the electricity-gas coupled grid. For this aim, a new model for the hybrid energy system was proposed to meet the network's energy load with 100% RERs in a sustainable manner. The potential of the P2G system was used for developing the hybrid energy system to effectively support the electricity and natural gas grids in properly dealing with fluctuations of RERs. The LHS and FFS approaches were exerted to produce and reduce scenarios in the uncertainty quantification process under the stochastic programming technique. To validate the effectiveness of the offered model, the modified IEEE 6-bus and 6-node gas test system was selected and examined in two cases (Case I without uncertainty modeling and Case II with uncertainty quantification). The results proved the applicability of the offered model in keeping the sustainability of the hybrid energy structure in the presence of 100% RERs.

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