Optimal Day-Ahead Scheduling of the Renewable Based Energy Hubs Considering Demand Side Energy Management

Daneshvar, Mohammadreza ; Mohammadi-Ivatloo, Behnam ; Asadi, Somayeh ; Zare, Kazem; Anvari-Moghaddam, Amjad

Published in:
Proceedings of 2019 International Conference on Smart Energy Systems and Technologies (SEST)

DOI (link to publication from Publisher):
10.1109/SEST.2019.8849131

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Optimal Day-Ahead Scheduling of the Renewable Based Energy Hubs Considering Demand Side Energy Management

Mohammadreza Daneshvar
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
m.r.daneshvar@ieee.org

Behnam Mohammadi-ivatloo
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
bmohammadi@tabrizu.ac.ir

Somayeh Asadi
Department of Architectural Engineering
Pennsylvania State University
Pennsylvania, USA
asadi@engr.psu.edu

Kazem Zare
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
kazem.zare@tabrizu.ac.ir

Amjad Anvari-Moghaddam
Department of Energy Technology
Aalborg University
Aalborg, Denmark
aam@et.aau.dk

***Abstract*—In recent decades, the rising penetration of various types of distributed energy resources has made interactions between all types of energy inevitable. In this respect, energy hubs are created with the aim of considering the interactions between multi-carrier energy systems throughout the smart grids. In this research, optimal scheduling of the multi-energy hubs is considered in the day-ahead market with the aim of minimizing the energy hub's cost. Because of the high usage of the clean energy production potential by employing the wind turbines and PV panels at each energy hub, the proposed model will mitigate the greenhouse gas emissions through reducing the operation of the gas-fired systems over the scheduling horizon. The combined cooling/heating and power system is also used as a backup unit for the stochastic producers to ensure energy supply with minimum load shedding. Moreover, electrical and thermal energy storage devices are also employed for storing energy during time intervals when there is a large amount of clean and free energy production. The Monte-Carlo simulation approach is used for modeling the uncertain behaviors of the stochastic producers and fast forward selection method is also used for the scenario reduction process. The flexibility of the energy demand is also investigated using demand response programs. In order to validate the effectiveness of the proposed model, IEEE 10-bus standard test system integrated with distributed energy resources is used. Simulation results demonstrate the applicability and usefulness of the proposed model in the energy management of multi energy hubs.**

Keywords*—*multi-energy hubs, renewable energy resources, flexibility assessment, demand response, day-ahead scheduling

NOMENCLATURE

Indices

t	Index of scheduling time periods.
h	Index of energy hubs.
i	Index of buses.

Parameters

$S_{h,t}^{Boiler}, S_{h,t}^{PGU}$	Size of the boiler and PGU unit.
$\vartheta^{PGU}, \psi^{PGU}$	Power generation unit (PGU) coefficients for converting the fuel to electricity.
$\eta^{Boiler}, \eta^{PGU}$	Efficiency of the boiler and PGU unit.
S_h^{BESS}	Size of battery energy storage system (BESS).
$\tau_{\min}^{BESS}$	Minimum storage limit in BESS.
Δt	Decision time interval.
$E_{Initial}^{BESS}$	Initial energy stored in BESS.
$\tau_{cha,\min}^{BESS}, \tau_{cha,\max}^{BESS}$	Minimum and maximum charging coefficients for BESS.
$\tau_{dis,\min}^{BESS}, \tau_{dis,\max}^{BESS}$	Minimum and maximum discharging coefficients for BESS.
S_h^{THS}	Size of thermal storage.
$\tau_{\min}^{THS}$	Minimum storage limit of thermal storage.
$Te_{Initial}^{THS}$	Initial thermal energy stored in thermal storage.
$\eta_{cha,h}^{THS}, \eta_{dis,h}^{THS}$	Charging and discharging efficiency of the thermal storage.
$\tau_{cha,\max}^{THS}, \tau_{cha,\min}^{THS}$	Maximum and minimum charging coefficients for the thermal storage.
$\tau_{dis,\max}^{THS}, \tau_{dis,\min}^{THS}$	Maximum and minimum discharging coefficients for the thermal storage.
S_h^{PV}, η^{PV}	Size and efficiency of the PV panel.
Sol_t^{PV}	Solar radiation at time *t.*
$\bar{P}_{h,t}^{Wind}$	Upper limit for the wind power production.
$E_{i,t}^{L}$	Electricity demand at bus *i* time *t.*
E, I	Number of energy hubs and buses in the studied system.
$P_{\min,i,t}^{LSH}, P_{\max,i,t}^{LSH}$	Maximum and minimum amount of load shedding at bus *i* time *t.*
$E_{i,t}^{L,\max}, E_{i,t}^{L,\min}$	Maximum and minimum amount of electrical load at bus *i* time *t.*
$H_{h,t}^{L}, C_{h,t}^{L}$	Heating and cooling energy demand.
η^{H}, η^{C}	Heating and cooling efficiency.
$P_{i,t}^{DAI}, P_{i,t}^{DAE}$	Inelastic and elastic portions of the electricity load purchased from the day-ahead market at bus *i* time *t.*
Υ, ψ	Elasticity limit and inelasticity control factor.
$Q_{i,t}^{L}$	Reactive power demand at bus *i* time *t.*
ζ_s	Probability of the generated scenarios.
$\lambda_{Gas,t}^{Pu}$, λ_t^{Se}	Gas purchasing and electricity selling prices at time *t.*

978-1-7281-1156-8/19/$31.00 ©2019 IEEE

λ_t^{LSH} , λ_t^{DA}	Load shedding and day-ahead market electricity prices.
Variables	
$F_{h,t}^{Boiler}, F_{h,t}^{PGU}$	Gas fuel consumed by boiler and PGU unit.
$X_{h,t}^{PGU}$	ON/OFF status of the PGU unit.
$P_{h,t}^{PGU}$	Electrical energy production of the PGU unit.
$Te_{h,t}^{CCtS}$	Thermal energy provided to the thermal storage.
$Te_{h,t}^{Hc}, Te_{h,t}^{Cc}$	Thermal energy provided to the heating and cooling components.
$Xdis_{h,t}^{BESS}$	Binary variable for battery discharging state.
$Xcha_{h,t}^{BESS}$	Binary variable for battery charging state.
$P_{h,t}^{BESS}$	Electrical energy stored in BESS.
$P_{cha,h,t}^{BESS}, P_{dis,h,t}^{BESS}$	Charging and discharging rates of BESS.
$Xdis_{h,t}^{THS}$	Discharging status of the thermal storage.
$Xcha_{h,t}^{THS}$	Charging status of the thermal storage.
$Te_{h,t}^{THS}$	Thermal energy stored in thermal storage.
$Te_{cha,h,t}^{THS}, Te_{dis,h,t}^{THS}$	Charging and discharging rates for thermal storage.
$Te_{h,t}^{CPtS}, Te_{h,t}^{HPtS}$	Thermal energy transmitted from cooling and heating components to the thermal storage.
$Te_{h,t}^{StCC}, Te_{h,t}^{StHC}$	Thermal energy transmitted to cooling and heating components from the thermal storage.
$P_{h,t}^{PV}$	Electricity production of the PV panel.
$P_{h,t}^{Wind}, Q_{h,t}^{Wind}$	Active and reactive outputs of the wind turbine.
$P_{t,h}^{DA}$	Amount of bid power of the energy hub *h*th in the day-ahead market at time *t.*
$P_{i,t}^{LSH}$	Amount of load shedding at bus *i* time *t.*
$S_{i,t}, P_t^{Loss}$	Complex power and power loss at time *t.*
$\alpha_{i,t}, \beta_{i,t}$	Energy consumption and virtual generation of the elastic load.
$P_{i,t}^{Inje}$, $Q_{i,t}^{Inje}$	Amount of active and reactive power injected at bus *i* time *t.*
$P_{i,t}^{E,Gen}$, $Q_{i,t}^{E,Gen}$	Amount of active and reactive power generation at bus *i* time *t.*
$V_{i,t}$, $\theta_{i,t}$	Voltage magnitude and phase angle at bus *i* time *t.*

I. INTRODUCTION

A. Motivation and Background

Nowadays, the increasing demand for energy has led to analyze the practical solutions for meeting the energy demand with various features and types. The newly introduced energy resources are intended for energy production due to economic issues and environmentally friendly conditions. In this regard, renewable energy resources (RERs) as the special type of distributed energy resources (DERs) have been widely exploited around the world considering economic and environmental advantages. However, the high dependency of the RERs to the climate changes caused the large uncertainties throughout the marketplace, which made the accurate scheduling of the power grid challenge. Therefore, the controllable energy production units such as combined, cooling, heating, and power system (CCHP) are used accompanying RERs to ensure the reliable energy supplying for the consumers. The use of such gas-fired energy systems along with the RERs has led to introducing the new concepts of the market players, which is called energy hubs. Indeed, energy hub integrates various energy systems such as natural gas and electricity networks [1]. At each hub, this is done with the aim of increasing energy efficiency, reducing greenhouse gas emissions and cost of energy consumption, and improving the system reliability and stability [2, 3]. On the other hand, the interactions between various types of energy are covered in the energy hub for meeting the different forms of energy such as electrical, cooling, and heating energy [4].

B. Relevant Literature

Towards an appropriate energy management scheme for energy hubs in the presence of intermittent RERs, extensive research has been carried out in recent years. In [5], the comprehensive investigations regarding the demand side energy management indicated that energy hubs can be a suitable choice for controlling the multi-energy systems in the residential sector. Optimal scheduling for energy hubs is done in [6] considering them as the price-taker with the aim of providing the appropriate conditions for their participation in the energy market. The authors in [7] presented a management model for optimal scheduling of the energy hubs with the aim of minimizing the total operation costs. In addition, a cost-effective strategy is applied for achieving the optimal set points for DERs. Short-term scheduling strategy is presented in [2] for a wind integrated energy hub to minimize the expected operation cost by employing a hybrid stochastic/ information gap decision theory (IGDT) optimization approach for uncertainty modeling. In addition to the mentioned researches, optimal scheduling of multi-energy hubs has been conducted with various goals using different approaches in recent literature. These briefly include: economical scheduling of multi carrier energy systems under energy hub method in [8], optimal scheduling of energy hubs for robust operation of DERs in [9], optimal bidding strategy for smart energy hubs with the aim of improving the energy costs in [10], and a developed generic optimal industrial load management model and IGDT method for energy hub management in [11] and [12], respectively.

As reported in the previous paragraph, the optimal scheduling of energy hubs has been done for various objectives. The main shortage of them is that the demand side energy management is not addressed effectively by them. To this end, several works have been structured to use suitable manners for managing energy consumption in the smart grids. Demand response programs as an effective tool are applied in the majority of studies for considering the energy management issue in the smart energy hubs. For example, a novel bi-level optimal scheduling model is proposed in [13] to establish the balance between exergy assessment and cost analysis for the energy hubs integrated with demand response program. In [14], mathematical optimization models integrated with demand response programs are presented for the residential energy hubs to consider the consumer preferences in controlling the residential energy demand and equipment based on the automated decision-making technologies. The authors in [15] presented a mathematical formulation for optimal scheduling of the developed energy hubs integrated with demand response programs considering the stochastic and deterministic circumstances of the energy demand, electricity price, and wind power as the two objective functions. Moreover, price-based demand response program is applied in [16] for optimal scheduling of energy hubs to manage the different types of energy demands.

C. Contributions and Organization

Although the energy management issue is considered in the mentioned references by applying the various approaches, the accurate assessment of them discovers some key research gaps that need for more evaluation for the smart energy hubs. In most of these references, the effective schemes have not been exerted for optimal energy management of the energy hubs. The flexibility of the systems incorporated with numerous RERs is the most important issue, which is not intended in the recent works. In addition, a high share of RERs not only is not considered in most of the studies for energy hubs but also the stochastic modeling of the RERs outputs is simply modeled that cannot reflect the near reality conditions of the RERs. Therefore, this paper aims to effectively address the mentioned issues. In this paper, day-ahead scheduling of the energy hubs is done with the aim of providing the opportunity of adopting the suitable bidding strategy for energy hubs in the day-ahead electricity market. Each energy hub is considered as a system with a high share of RERs for clean energy production to mitigate the harmful effects of greenhouse gas emissions. Besides the high usage of RERs potential in the system, the CCHP unit is also used as a backup system for stochastic producers. Electrical and thermal storage devices are also considered for increasing the reliability of the energy supply in the presence of RERs. The stochastic modeling of the energy hubs is carried out using the Monte-Carlo simulation (MCS) method for scenario generation and fast forward selection (FFS) approach for scenario reduction considering the wind speed and solar radiation as the uncertainty parameters. Additionally, an appropriate demand response program is employed in this research to effectively change the energy consumption behavior of the energy hubs. For this aim, essential (inelastic) and dispensable (elastic) loads are separated from the energy demand to properly use the shiftable and shavable features of the elastic loads.

The paper is organized as follows. Section II presents the mathematical models of energy hubs considering all problem constraints as well as the objective function. Simulation results along with results assessment are represented in Section III. Section IV explains the main achievements of this work as the conclusion section.

II. Methodology

In this paper, optimal day-ahead scheduling of the smart energy hubs is conducted considering the demand side energy management as well as interactions between various energy carriers includes electrical, cooling, and heating energy. Each hub is equipped with a PV panel and wind turbine for meeting the high portion of its demand through clean energy resources. In order to quantify the large uncertainties created by RERs, MCS method is used for generating several scenarios to better model the stochastic behaviors of the solar radiation and wind speed. For the systems with different complexity and size, the MCS technique is one of the appropriate methods for uncertainty modeling due to the independency of its efficiency to the size and complexity of the problems [17].

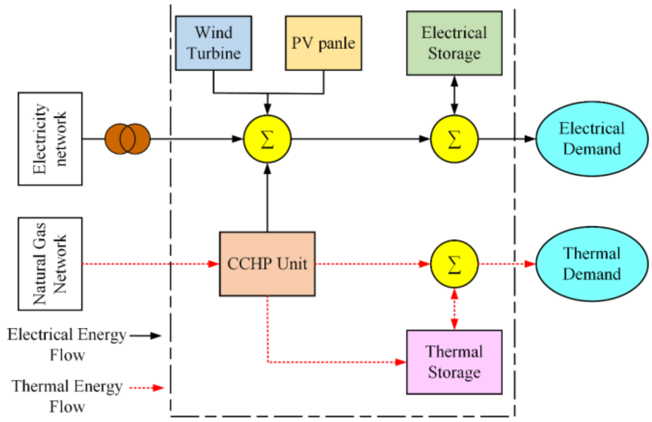

Fig. 1. The schematic of the renewable-based energy hub

In the uncertainty modeling process, scenario reduction approaches are proposed to avoid the high complexity and computational burden caused by a large number of the generated scenarios for the practical problems. In this regard, the FFS method is widely applied for scenario reduction process using the Kantorovich based algorithms [18]. In this method, the distance of each scenario is computed from the others and the scenarios with minimum distance are selected as the candidate scenarios [19]. Therefore, the FFS method is applied for reducing the number of scenarios to the logical amount in this research.

Besides the RERs, each energy hub is equipped with a CCHP unit as the backup system for supplying both the electrical and thermal demands, and electrical and thermal storages to provide the suitable condition for the high presence of the stochastic producers. The architecture of the renewable based energy hub is illustrated in Fig .1.

In this paper, a mathematical model consists of four parts is used. In the first part, energy hub modeling is presented by a complete description of the constraints of the energy hub devices namely CCHP unit, electrical and thermal storages, wind turbine, and PV panel. In the second part, demand-side modeling is introduced by applying electrical, heating, and cooling energy balance constraints. Then the demand response program formulations based on elastic and inelastic load characteristics are presented for considering the flexibility aspects in the optimal day-ahead scheduling of the energy hubs.

Finally, the third and the fourth parts present the electricity network modeling and objective function of the energy hubs. Additionally, the complete constraints of all parts are listed in the related sub-section with removing the subscript *s* (scenario index) from the related variables below with the aim of avoiding the repeated information.

A. Energy Hub Modeling

In order to model the energy hub structure, RERs and gas fired systems such as CCHP units as well as electrical and thermal storages are used for providing the suitable interactions between various types of the energy carriers. All of these devices are operated subject to some operational constraints, which are completely considered here.

1) CCHP Unit

This unit consists of the power generation unit (PGU), boiler, and chiller for meeting the electrical, heating, and cooling energy, respectively. Moreover, cooling and heating components are the other devices of the CCHP unit, which thermal energy generated from the boiler and PGU can be provided for them instantly or can be used for charging the thermal storage for later use. The CCHP limitations are given as:

$$F_{h,t}^{Boiler} \le S_{h,t}^{Boiler} \quad \forall t,\ \forall h \tag{1}$$

$$F_{h,t}^{PGU} \le X_{h,t}^{PGU}.S_{h,t}^{PGU} \quad \forall t,\ \forall h \tag{2}$$

$$P_{h,t}^{PGU} \le (F_{h,t}^{PGU} - X_{h,t}^{PGU}.\vartheta^{PGU})/\psi^{PGU} \quad \forall t,\ \forall h \tag{3}$$

$$Te_{h,t}^{Hc} + Te_{h,t}^{Cc} + Te_{h,t}^{CCtS} \le F_{h,t}^{Boiler}.\eta^{Boiler} + F_{h,t}^{PGU}.\eta^{PGU} \quad \forall t,\ \forall h \tag{4}$$

2) Electrical Storage

$$Xdis_{h,t}^{BESS} + Xcha_{h,t}^{BESS} \le 1 \quad \forall t,\ \forall h \tag{5}$$

$$S_{h}^{BESS}.\tau_{\min}^{BESS} \le P_{h,t}^{BESS} \le S_{h}^{BESS} \quad \forall t,\ \forall h \tag{6}$$

$$P_{h,t}^{BESS} = (P_{cha,h,t}^{BESS} - P_{dis,h,t}^{BESS}).\Delta t + E_{Initial}^{BESS} \quad \forall t = 1,\ \forall h \tag{7}$$

$$P_{h,t}^{BESS} - P_{h,t-1}^{BESS} = (P_{cha,h,t}^{BESS} - P_{dis,h,t}^{BESS}).\Delta t \quad \forall t \ge 2,\ \forall h \tag{8}$$

$$Xcha_{h,t}^{BESS}.S_{h}^{BESS}.\tau_{cha,\min}^{BESS} \le P_{cha,h,t}^{BESS} \le Xcha_{h,t}^{BESS}.S_{h}^{BESS}.\tau_{cha,\max}^{BESS} \tag{9}$$

$$Xdis_{h,t}^{BESS}.S_{h}^{BESS}.\tau_{dis,\min}^{BESS} \le P_{dis,h,t}^{BESS} \le Xdis_{h,t}^{BESS}.S_{h}^{BESS}.\tau_{dis,\max}^{BESS} \tag{10}$$

3) Thermal Storage

$$Xdis_{h,t}^{THS} + Xcha_{h,t}^{THS} \le 1 \quad \forall t,\ \forall h \tag{11}$$

$$S_{h}^{THS}.\tau_{\min}^{THS} \le Te_{h,t}^{THS} \le S_{h}^{THS} \quad \forall t,\ \forall h \tag{12}$$

$$Te_{h,t}^{THS} = (Te_{cha,h,t}^{THS} - Te_{dis,h,t}^{THS}).\Delta t + Te_{Initial}^{THS} \quad \forall t = 1,\ \forall h \tag{13}$$

$$Te_{h,t}^{THS} - Te_{h,t-1}^{THS} = (Te_{cha,h,t}^{THS} - Te_{dis,h,t}^{THS}).\Delta t \quad \forall t \ge 2,\ \forall h \tag{14}$$

$$Te_{h,t}^{CCtS} + Te_{h,t}^{CPtS} + Te_{h,t}^{HPtS} \le S_{h}^{THS} \quad \forall t,\ \forall h \tag{15}$$

$$Te_{h,t}^{StCC} + Te_{h,t}^{StHC} \le Te_{dis,h,t}^{THS}.\eta_{dis,h}^{THS} \quad \forall t,\ \forall h \tag{16}$$

$$Te_{cha,h,t}^{THS} \le (Te_{h,t}^{CCtS} + Te_{h,t}^{CPtS} + Te_{h,t}^{HPtS}).\eta_{cha,h}^{THS} \quad \forall t,\ \forall h \tag{17}$$

$$Xcha_{h,t}^{THS}.S_{h}^{THS}.\tau_{cha,\min}^{THS} \le Te_{cha,h,t}^{THS} \le Xcha_{h,t}^{THS}.S_{h}^{THS}.\tau_{cha,\max}^{THS} \tag{18}$$

$$Xdis_{h,t}^{THS}.S_{h}^{THS}.\tau_{dis,\min}^{THS} \le Te_{dis,h,t}^{THS} \le Xdis_{h,t}^{THS}.S_{h}^{THS}.\tau_{dis,\max}^{THS} \tag{19}$$

4) PV Panels

$$P_{h,t}^{PV} \le S_{h}^{PV}.\eta^{PV}.Sol_{t}^{PV} \quad \forall t,\ \forall h \tag{20}$$

5) Wind Turbines

$$0 \le P_{h,t}^{Wind} \le \bar{P}_{h,t}^{Wind} \tag{21}$$

$$P_{h,t}^{Wind} / \sqrt{(P_{h,t}^{Wind})^2 + (Q_{h,t}^{Wind})^2} = \text{Constant} \tag{22}$$

B. Demand Side Model

1) Electrical Energy Load

$$\begin{aligned}&\sum_{h=1}^{E}(P_{t,h}^{DA} + P_{h,t}^{PGU} + P_{h,t}^{PV} + \eta_{dis,h}^{BESS}.P_{dis,h,t}^{BESS} + P_{h,t}^{Wind}) = \\ &\sum_{i=1}^{I}(E_{i,t}^{L} - P_{i,t}^{LSH}) + P_{cha,h,t}^{BESS}/\eta_{cha,h}^{BESS} + P_{t}^{Loss} \quad \forall t\end{aligned} \tag{23}$$

$$P_{\min,i,t}^{LSH} \le P_{i,t}^{LSH} \le P_{\max,i,t}^{LSH} \quad \forall t,\ \forall i \tag{24}$$

$$E_{i,t}^{L,\min} \le E_{i,t}^{L} - P_{i,t}^{LSH} \le E_{i,t}^{L,\max} \tag{25}$$

2) Thermal Energy Load

$$(Te_{h,t}^{Hc} + Te_{h,t}^{StHC}).\eta^{H} = H_{h,t}^{L} + Te_{h,t}^{HPtS} \quad \forall t,\ \forall h \tag{26}$$

$$(Te_{h,t}^{Cc} + Te_{h,t}^{StCC}).\eta^{C} = C_{h,t}^{L} + Te_{h,t}^{CPtS} \quad \forall t,\ \forall h \tag{27}$$

3) Demand Response Modeling

$$0 \le \alpha_{i,t} + \beta_{i,t} \le \Upsilon \tag{28}$$

$$E_{i,t}^{L} = P_{i,t}^{DAI} + \alpha_{i,t}P_{i,t}^{DAE} \tag{29}$$

$$P_{i,t}^{DAI} = \psi P_{t,h}^{DA} \tag{30}$$

$$P_{i,t}^{DAE} = (1-\psi)P_{t,h}^{DA} \tag{31}$$

C. Electricity Network Modeling

$$P_{i,t}^{Inje} = P_{i,t}^{E,Gen} + \beta_{i,t}P_{i,t}^{DAE} + P_{i,t}^{LSH} - E_{i,t}^{L} \quad \forall t,\ \forall i \tag{32}$$

$$Q_{i,t}^{Inje} = Q_{i,t}^{E,Gen} - Q_{i,t}^{L} \quad \forall t,\ \forall i \tag{33}$$

$$S_{i,t} \le S_{i,t}^{Max} \quad \forall t,\ \forall i \tag{34}$$

$$V_{i}^{Min} \le V_{i,t} \le V_{i}^{Max} \quad \forall t,\ \forall i \tag{35}$$

$$\theta_{i}^{Min} \le \theta_{i,t} \le \theta_{i}^{Max} \quad \forall t,\ \forall i \tag{36}$$

Equations (34) to (36) present the allowable range of the complex power, voltage magnitude, and phase angle, respectively.

D. Objective Function

In this research, the main objective of optimal day-ahead scheduling of energy hubs is to minimize their energy costs over the scheduling horizon. This objective function consists of four terms, which the CCHP fuel consumption cost is presented in the first term, the second term represents the load shedding cost, the revenue of selling energy to the consumers is taken into account in the third term, and the fourth term denotes the revenue (cost) of selling (purchasing) energy to (from) the power grid from (by) energy hub *h*th in the day-ahead market.

$$\begin{aligned}OF_{h} = &\sum_{s=1}^{S}\zeta_{s}.[\sum_{t=1}^{T}\lambda_{Gas,t}^{Pu}.(F_{h,t,s}^{PGU} + F_{h,t}^{Boiler}) + \sum_{i=1}^{I}\sum_{t=1}^{T}\lambda_{t}^{LSH}.P_{i,t,s}^{LSH} \\ &+ \sum_{t=1}^{T}\sum_{i=1}^{I}\lambda_{t}^{Se}.(P_{i,t,s}^{LSH} - E_{i,t}^{L}).\Delta t - \sum_{t=1}^{T}\lambda_{t}^{DA}.P_{t,h}^{DA}\,\Delta t] \quad \forall h\end{aligned} \tag{37}$$

III. Simulation Results

In this study, a proposed day-ahead scheduling model for renewable-based energy hubs is tested on the modified IEEE 10-bus distribution system. The complete information of this test system can be accessed in [20] and the schematic of it is demonstrated in Fig. 2. In this study, we have intended the five energy hubs with different structures, which their structures are the combination of the RERs, electrical and thermal storages, and CCHP unit. The high potential of the wind turbines and PV panels are used for clean energy production that their required parameters can be found in [18]. The CCHP unit is used for supporting the stochastic producers in reliable meeting the energy demand of each energy hub and complete information of this unit is available in [21]. Electrical and thermal storages are also employed to store the energy in off-peak times for later use when the energy consumption is at a high level. The required data of storage systems along with energy demand of each hub can be reached from [22]. In addition, the time-of-use pricing scheme is applied for this study, which all information about the various prices can be obtained from [23]. Because of using the nonlinear equations in electricity network modeling along with binary variables related to the storage systems and CCHP unit, the optimal scheduling problem of energy hubs is the mix integer nonlinear problem (MINLP).

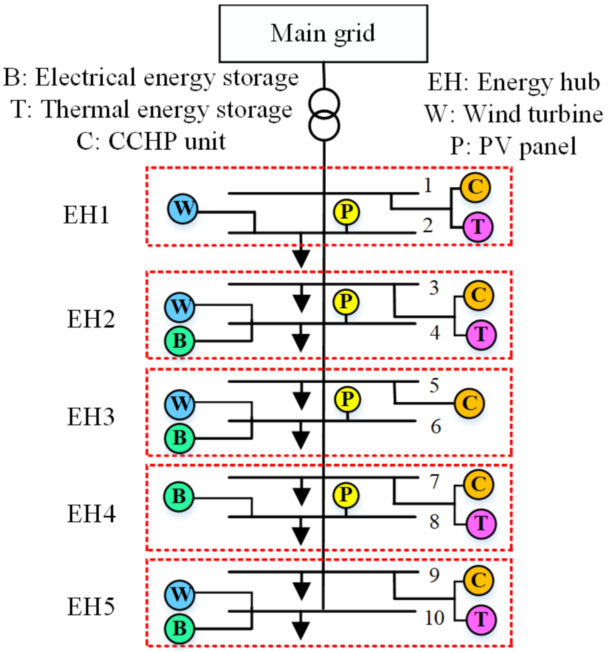

Fig. 2. Schematic of the modified IEEE 10-bus test system

For solving this problem, the General Algebraic Modeling System (GAMS) by DICOPT and SBB solvers is used. After solving the problem, the same results are obtained for the mentioned solvers that indicate the optimality rate of the extracted results. In addition, the amount of total cost is equal to \$38564,8. The amount of total revenue and cost of each energy hub is also illustrated in Fig. 3.

As seen in this figure, the energy cost of each energy hub is greater than its revenue due to the various conditions of each hub for meeting the energy demand during the time intervals. Since the revenue and energy cost of each energy hub directly depends on its energy demand and size of other components such as RERs and CCHP unit, thereby energy hub 3 with largest energy demand, size of energy production units, and storage systems has the maximum energy cost and revenue among all energy hubs. On the other hand, minimum revenue and energy cost is realized for energy hub 4 due to the lower energy demand and lack of wind turbine as the fuel and carbon-free energy resources. Because of the large capacity of the wind turbines considered in this study without any fuel cost, the existence of these units in the energy production process can provide the suitable conditions for the energy hubs not only to meet their energy demand through clean energy resources but also to minimize their energy costs. The optimal scheduling for the wind turbine, BESS, and PGU unit is demonstrated in Fig. 4.

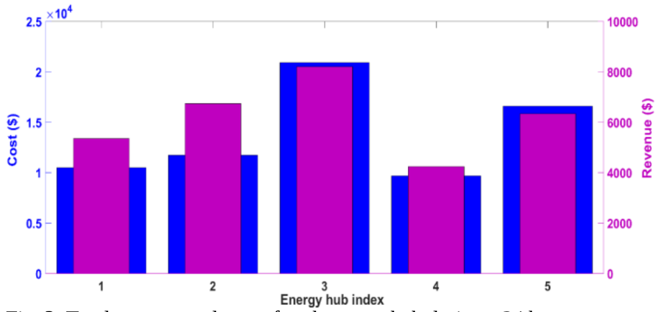

Fig. 3. Total revenue and cost of each energy hub during a 24 hours

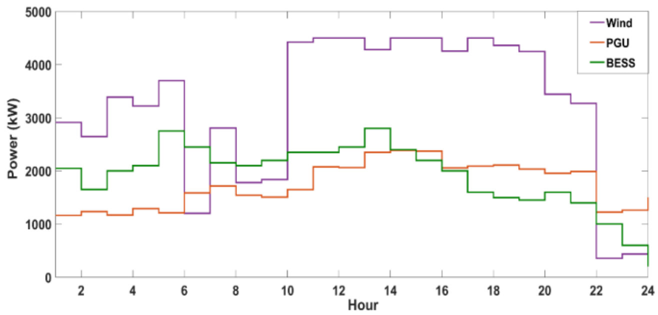

Fig. 4. Optimal scheduling of the wind turbine, CCHP unit, and BESS

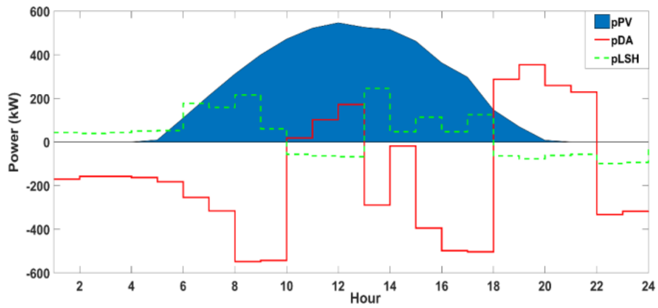

Fig. 5. Optimal scheduling of the PV panel, energy traded in the DA market, and the amount of load shedding during a day

As obvious from this figure, higher wind speed in the early morning results in more energy production by the wind turbines and accordingly higher charging rates of the BESS in these time intervals. However, in the morning (6-10 am), decreasing the outputs of wind turbines has led to discharge the BESS and increasing the outputs of PGU unit for meeting the energy demand of these hours. In the time interval 10-12 am and 12-20 pm, the maximum production of wind turbines along with the appropriate setting of the PGU and BESS are used for supplying the energy demand of peak times. Moreover, because of reducing the wind power at night (22-24 pm), the effective potential of the PGU unit along with BESS are used for meeting the energy load of the off-peak hours.

In this study, the energy trading possibility is provided for the energy hubs to minimize their energy costs by adopting the appropriate bidding strategy over the scheduling horizon. In addition, the PV panels are also intended in each hub to the effective usage of their outputs in the peak times when the energy demand and solar radiation are at the maximum level. According to Fig. 5, energy hubs could purchase energy in the early morning to charge the BESS when the price of energy is low in comparison with other times with the aim of using the stored energy in the hours with high energy price and demand (peak times). On the other side, energy hubs sell a portion of their generated energy to the main grid in the peak times (10-12 am and 18-21 pm) with a high energy price for maximizing their revenue.

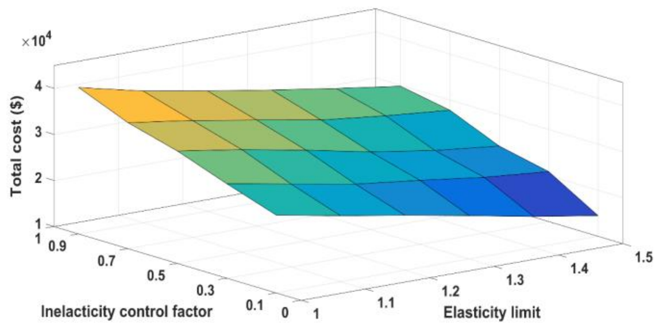

Fig. 6. The relationship between demand response factors with a total cost

Moreover, the maximum energy production of the PV panels is used in the peak times to help meeting of the energy load in the mentioned hours. Because of lower energy production in the morning (6-9 am), the load shedding possibility is also considered for the energy hubs to establish a dynamic balance between energy supply and demand. Additionally, this possibility is also used in the part of peak time (13- 18 pm) for balancing energy in the system. In order to better manage the energy consumption to avoid the more amount of load shedding in the system, demand-side energy management is intended in this paper by applying for the demand response program. For this aim, the energy demand is divided into the elastic and inelastic loads and shifting capability of the elastic loads is used for creating the dynamic energy balance during a day. The relationship between the elasticity limit as well as inelasticity control factor and total cost of energy hubs is shown in Fig. 6.

As seen in this figure, increasing the elasticity limit creates a higher load shifting possibility which in turn decreases the operation of CCHP unit and reduces the total energy costs. Moreover, increasing the inelasticity control factor increases a portion of the inelastic loads in the system which results in reduced load shifting capability. This condition imposes costly mechanisms for the energy hubs to meet their energy demands.

IV. Conclusion

In this study, optimal day-ahead scheduling was conducted for various types of energy hubs with the aim of minimizing the energy cost of each hub over the scheduling horizon. The different combinations of RERs, electrical and thermal storages and CCHP unit were used for constructing the energy hubs in the modified IEEE 10-bus test system. For uncertainty modeling, wind speed and solar radiation were treated as uncertainty parameters and MCS and FFS methods were employed for scenario generation and reduction, respectively. The flexibility of the studied system was investigated using the new model of the demand response program by considering the shiftable and curtailable features of the elastic loads. After solving the problem, the assessment of the results indicated that using the effective potential of elastic loads can increase the system’s flexibility and reduce the operation cost of energy hubs in the deregulated environment. Moreover, based on the extracted results, an operation of the fuel and carbon-free energy resources not only can reduce the energy cost of energy hubs significantly but also can mitigate the greenhouse gas emissions in the system.

References

[1] X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Optimal expansion planning of energy hub with multiple energy infrastructures," *IEEE Transactions on Smart Grid,* vol. 6, no. 5, pp. 2302-2311, 2015.

[2] A. Dolatabadi, M. Jadidbonab, and B. Mohammadi-ivatloo, "Short-term scheduling strategy for wind-based energy hub: a hybrid stochastic/IGDT approach," *IEEE Transactions on Sustainable Energy,* vol. 10, no. 1, pp. 438-448, 2019.

[3] K. Orehounig, R. Evins, and V. Dorer, "Integration of decentralized energy systems in neighbourhoods using the energy hub approach," *Applied Energy,* vol. 154, pp. 277-289, 2015.

[4] F. Brahman, M. Honarmand, and S. Jadid, "Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system," *Energy and Buildings,* vol. 90, pp. 65-75, 2015.

[5] M. Mohammadi, Y. Noorollahi, B. Mohammadi-ivatloo, M. Hosseinzadeh, H. Yousefi, and S. T. Khorasani, "Optimal management of energy hubs and smart energy hubs–a review," *Renewable and Sustainable Energy Reviews,* vol. 89, pp. 33-50, 2018.

[6] H. Fan, Q. Chen, W. Liu, J. Li, and Y. Chen, "Optimal scheduling for energy hub in power markets," in *2016 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*, 2016, pp. 127-131: IEEE.

[7] M. S. Javadi, A. Anvari-Moghaddam, and J. M. Guerrero, "Optimal scheduling of a multi-carrier energy hub supplemented by battery energy storage systems," in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, 2017, pp. 1-6: IEEE.

[8] S. Pazouki, M.-R. Haghifam, and J. Olamaei, "Economical scheduling of multi carrier energy systems integrating renewable, energy storage and demand response under energy hub approach," in *2013 Smart Grid Conference (SGC)*, 2013, pp. 80-84: IEEE.

[9] A. Zidan and H. A. Gabbar, "Optimal scheduling of energy hubs in interconnected multi energy systems," in *2016 IEEE Smart Energy Grid Engineering (SEGE)*, 2016, pp. 164-169: IEEE.

[10] V. Davatgaran, M. Saniei, and S. S. Mortazavi, "Optimal bidding strategy for an energy hub in energy market," *Energy,* vol. 148, pp. 482-493, 2018.

[11] S. Paudyal, C. A. Cañizares, and K. Bhattacharya, "Optimal operation of industrial energy hubs in smart grids," *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 684-694, 2015.

[12] M. S. Javadi, A. Anvari-Moghaddam, and J. M. Guerrero, "Robust energy hub management using information gap decision theory," in *IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 410-415: IEEE.

[13] Z. Guo, S. Yao, J. Gu, C. Xu, G. Li, and M. Zhou, "Bi-level Optimal Scheduling of Demand Response Integrated Energy Hub Through Cost and Exergy Assessments," in *2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 2018, pp. 1-6: IEEE.

[14] M. C. Bozchalui, S. A. Hashmi, H. Hassen, C. A. Cañizares, and K. Bhattacharya, "Optimal operation of residential energy hubs in smart grids," *IEEE Transactions on Smart Grid,* vol. 3, no. 4, pp. 1755-1766, 2012.

[15] S. Pazouki and M.-R. Haghifam, "Optimal planning and scheduling of energy hub in presence of wind, storage and demand response under uncertainty," *International Journal of Electrical Power & Energy Systems,* vol. 80, pp. 219-239, 2016.

[16] A. Pasban-Gajan, M. Moeini-Aghtaie, Z. Parvini, and M. Fotuhi-Firuzabad, "Optimal scheduling of renewable-based energy hubs considering time-of-use pricing scheme," in *2017 Smart Grid Conference (SGC)*, 2017, pp. 1-6: IEEE.

[17] Z. Shu and P. Jirutitijaroen, "Latin hypercube sampling techniques for power systems reliability analysis with renewable energy sources," *IEEE Transactions on Power Systems,* vol. 26, no. 4, pp. 2066-2073, 2011.

[18] M. Daneshvar, M. Pesaran, and B. Mohammadi-ivatloo, "Transactive energy integration in future smart rural network electrification," *Journal of Cleaner Production,* vol. 190, pp. 645-654, 2018.

[19] K. Bruninx, E. Delarue, and W. D’haeseleer, "A practical approach on scenario generation & reduction algorithms based on probability distance measures–the case of wind power forecast errors," *WP EN2014-15,* 2014.

[20] H. Karimi and R. Dashti, "Comprehensive framework for capacitor placement in distribution networks from the perspective of distribution system management in a restructured environment," *International Journal of Electrical Power & Energy Systems,* vol. 82, pp. 11-18, 2016.

[21] M. Daneshvar, B. Mohammadi-ivatloo, and K. Zare, "Integration of Distributed Energy Resources Under the Transactive Energy Structure in the Future Smart Distribution Networks," *Operation of Distributed Energy Resources in Smart Distribution Networks,* p. 349, 2018.

[22] Y. Chen and M. Hu, "Balancing collective and individual interests in transactive energy management of interconnected micro-grid clusters," *Energy,* vol. 109, pp. 1075-1085, 2016.

[23] C. Zhang, Q. Wang, J. Wang, P. Pinson, and J. Østergaard, "Real-time trading strategies of proactive DISCO with heterogeneous DG owners," *IEEE Transactions on Smart Grid,* vol. 9, no. 3, pp. 1688-1697, 2018.