Energy 106 (2016) 343–355

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Efficient operation of energy hubs in time-of-use and dynamic pricing electricity markets

Farhad Kamyab [a], Shahab Bahrami [b, *]

[a] Department of Electrical Engineering, Tarbiat Modares University, 14115-111, Tehran, Iran
[b] Department of Electrical and Computer Engineering, The University of British Columbia, V6T 1Z4, Vancouver, Canada

A R T I C L E I N F O

Article history:
Received 30 October 2015
Received in revised form
30 January 2016
Accepted 16 March 2016
Available online 6 April 2016

Keywords:
Energy hub
Energy management system
Competitive market
Time-of-use pricing
Dynamic pricing

A B S T R A C T

Natural gas can support the electricity grid through integration of the existing natural gas and electric networks into *energy hubs*. This paper elaborates on the design of an efficient algorithm for the EMS (energy management system) inside a residential energy hub. We study the strategic operation of the energy hubs in a competitive electricity market. Each energy hub aims to jointly minimize the operating cost and the discomfort cost caused by modifying the electrical and thermal load profiles. We show that there exists a competitive equilibrium for the energy hubs. A linear time EMS scheduling algorithm is proposed to determine that equilibrium. The optimal strategy of the energy hubs are compared for two widely used electricity pricing mechanisms, namely the TOU (time-of-use) and the dynamic pricing schemes. Furthermore, we study the effects of the electrical storage system and renewable resources on the hubs' optimal strategies. Simulations are performed for a group of ten residential energy hubs in a competitive electricity market. It is shown that the energy hubs' daily cost will be reduced by using the proposed scheduling algorithm. It is also shown that the dynamic pricing scheme can better motivate the energy hubs toward modifying their daily operation.

1. Introduction

Growing global energy consumption and the environmental impacts of fossil fuels in conventional power plants have increased the tendency towards using renewable resources of energy. Additionally, natural gas can play an imperative role in the global energy market through generating electricity in large-scaled gas plants and small-scaled CHP (combined heat and power) systems [1]. Combining different sources of energies from renewable (such as wind and solar energies) to natural gas into one multi-energy system can facilitate achieving a more sustainable energy network. Integrating energy infrastructures means to couple them at certain network nodes or branches; thereby, enabling exchange of power between the previously separated energy systems [2]. These couplings can be described by the concept of *energy hub* [3]. An energy hub is a multi-generation system, where multiple energy carriers are converted, stored and distributed to meet the energy demand. The converter devices can be micro-turbines [4] and gas boilers implemented in the CHP system [5]. Microturbine is used to convert electricity to natural gas. Other technologies are also suggested to convert natural gas to electricity such as ICEs (internal combustion engines) [6–8]. such The energy hub can be viewed as an extension of a network node in an electric power system which exchanges power via multiple energy input and output ports [9]. It is inevitable to operate the energy hub in an efficient way by designing an effective EMS (energy management system) to control the flow of energy in the converter devices [10]. In the literature, there are a number of studies addressing the energy management problem in the energy hubs. Brahman et al. [11] have proposed an optimal energy management strategy for one isolated residential energy hub to coordinate the CHP system, PV (photo voltaic) panels, EV (electric vehicle) [12] and energy storage, while satisfying the electrical and thermal demands. Moreover, they have considered a demand response program including electrical load shifting, load curtailing and flexible thermal loads in a TOU (time-of-use) pricing scheme. Rastegar et al. [13] have modeled a residential household as an energy hub, considering different electrical and heating appliances, residential CHP, and EV. The operation of the energy hub is optimized and the electrical load demand is optimally managed to minimize the customer's

* Corresponding author. Tel.: +1 7788883301.
E-mail addresses: farhad.kamyab@modares.ac.ir (F. Kamyab), bahramis@ece.ubc.ca (S. Bahrami).

http://dx.doi.org/10.1016/j.energy.2016.03.074
0360-5442/

List of symbols

$\mathscr{H} \triangleq \{1,\ldots,H\}$	The set of time slots
$\mathscr{N} \triangleq \{1,\ldots,N\}$	The set of energy hubs
$\eta^{e}_{i,MT}$	The micro-turbine's electrical efficiency
$\eta^{g}_{i,MT}$	The micro-turbine's thermal efficiency
$\eta_{i,B}$	The gas boiler's efficiency
$\eta^{grid}_{i,T}$	The grid transformer's efficiency
$\eta^{PV}_{i,T}$	The PV system transformer's efficiency
$\eta^{\{ch,dch\}}_{i,st}$	The storage's charging/discharging efficiency
$\alpha_i(h)$	The dispatch factor in energy hub i in time h
η^{PV}_{a}	The PV array efficiency
S^{PV}	The PV array area
ϕ	The irradiance
$L^{st}_i(h)$	The storage's energy level in hub i in time h
$T_{i,c}$	The cold water temperature in energy hub i
$T_{i,in}(h)$	The indoor temperature in hub i in time h
$T_{i,out}(h)$	The outdoor temperature in energy hub i in time h
$T_{i,s}(h)$	The hot water temperature in energy hub i in time h
$T^{des}_{i,s}(h)$	The desired hot water temperature in hub i in time h
$V_{i,c}$	The cold water volume in energy hub i
$V_{i,t}$	The total water storage volume in hub i
$p^{m}_{e,h}$	The wholesale electricity price in time h
$p_e(h)$	The retail electricity price in time h
$p_g(h)$	The retail natural gas price in time h
$E^{in}_i(h)$	The input electricity in energy hub i and time h
$E^{out}_i(h)$	The output electricity in energy hub i and time h
$H^{in}_i(h)$	The input natural gas in energy hub i and time h
$H^{out}_i(h)$	The output natural gas in energy hub i and time h
$E^{PV}_i(h)$	The PV's output power in energy hub i and time h
$E^{st}_i(h)$	The storage' output power in energy hub i and time h
$H^{air}_i(h)$	The power to the heat the air in energy hub i in time h
$H^{load}_i(h)$	The other thermal loads in energy hub i in time h
$H^{loss}_i(h)$	The thermal power loss in energy hub i in time h
$H^{st}_i(h)$	The heating power to the storage in hub i in time h
$\overline{E}^{out}_i(h)$	The desired load demand in energy hub i and time h

payment in response to a three-level TOU pricing scheme and fixed prices of the natural gas. Pazouki et al. [14] have studied the optimal operation of an energy hub that includes several distribution generations by considering the daily cost, reliability and emission in both deterministic and uncertain environment of the wind, prices and demand. Parisio et al. [15] have proposed a control-oriented approach using robust optimization technique to model and optimize an energy hub operation. They provided a general modeling framework for energy hub which leads to a mixed integer dynamic model. A short-term operation scheduling problem is proposed considering both deterministic environment and uncertain converter devices' efficiency. Bozchalui et al. [16] have proposed an optimization model for a residential energy hub that can be incorporated into the EMS. The proposed model can be used to optimally control all major residential energy loads, storage and production components. They have considered different objective functions such as minimization of the demand, total cost of electricity and gas, emission, and peak load, while considering the customer's preferences. Orehounig et al. [17] deployed the energy hub concept at the urban level, considering the integration of renewable sources at residential and commercial buildings and neighborhood scale. They have considered multiple energy resources, which allows for a higher flexibility of the system. They developed an optimization process to determine the optimal combination of renewable energy resources to reduce emission. They also determined the optimal configuration of local storage units to increase the energy autonomy of the neighborhood, as well as to curtail peaks in the energy demand in a low-voltage grid.

Although the operation of *single* isolated energy hub is well-studied in the literature [11]–[17], the operation of a *group* of energy hubs in a competitive electricity market is not studied well. In this paper, the interaction among energy hubs is modeled in a competitive electricity market. The behavioral model of each energy hub can empower it to effectively manage its electrical and thermal load demand, energy production, and energy storage in real-time. The major contributions of this paper are as follows:

- The interaction among energy hubs is modeled in a competitive electricity market to determine their optimal operation. The strategic behavior of the energy hubs is studied in the TOU and dynamic electricity pricing schemes with fixed pricing scheme for the natural gas. It is shown that the dynamic pricing scheme is more efficient than the TOU pricing scheme in reducing the generation of electricity utility company in peak-time periods due to higher price elasticity of the energy hubs.
- The competitive market equilibrium is studied. It is shown that there exists atleast one equilibrium for the proposed market. A distributed scheduling algorithm is developed to determine the market equilibrium. The running time of the proposed algorithm is shown to be linear by considering different number of energy hubs in the system.
- The proposed distributed algorithm is simulated on an energy system with ten energy hubs. Simulation results show that the operation cost of the energy hubs will be reduced by using the proposed scheduling algorithm. Besides, the peak load in the electricity network is decreased by about 30% in dynamic pricing scheme and by about 20% in TOU pricing.

Our approach can be partly compared with the one proposed in Ref. [18]. Our approach is different from Ref. [18] in two respects. First, in Ref. [18], the energy hub is modeled by the input and output electrical and thermal powers. Whereas, we give a detailed model for the thermal load by considering the hot water storage and air conditioning system. Besides, we study the effects of renewable resources and electrical storage system in the optimal strategy of each energy hub. Second, in Ref. [18], the behavior of energy hubs is studied in a strategic market, in which the energy hubs are *price making*. The interaction among energy hubs is modeled as an ordinal potential game. Whereas, we study the interaction among *price taking* energy hubs in a competitive market since this model is more common in the existing electricity and natural gas markets. We also compare the TOU pricing and dynamic pricing schemes in motivating the energy hubs to modify their operation.

The rest of this paper is organized as follows. Some important parameters used in this paper are given in Nomenclature. In Section 2, the system model is given. The detailed specification of an energy hub model is described as well. In Section 3, the objective function and the operating constraints for an energy are explained. In Section 4, the interaction among energy hubs in a competitive electricity market is modeled and a distributed