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Optimal electrical and thermal energy management of a residential energy hub in the presence of PV systems

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Abstract*— In order to reduce greenhouse gas emissions, transmission and distribution losses and the consumption of primary energy specific strategies are needed in all energy services. The energy hub is a new concept for future multi-carrier energy systems. An energy hub acts as an interface between different energy carriers such as electricity and natural gas distribution systems. In addition, worldwide concerns over global warming and climate change have caused to a recent global push towards many forms of renewable generation technologies. The energy hub offers an opportunity to system operators by providing the flexibility to manipulate the effects of volatility and intermittency of renewable, in particular wind and solar, energy resources. Since, energy hub can connect to the upstream network or distribution network, and import /export electricity from/to the local grid, proper operation of the energy hub is crucial from the local grid point of view. In this paper, a stochastic model of energy hubs for solving the optimal scheduling problem is presented. Also, a linear two-stage model is presented for optimal scheduling of energy hub consisting of solar panels, boiler, combined heat and power (CHP) system and energy storage devices. The objective is to supply daily electrical and thermal demands of a residential energy hub for tackling penetration of renewable energies and reducing operation cost. Stochastic programming method is adopted to handle the uncertainties of solar power generation. The Monte Carlo simulation approach is used to generate several scenarios. At last, the results obtained from the studied cases indicate the appropriateness and usefulness of the proposed model.

Keywords*— Energy hub; photovoltaic generation; energy storage system; stochastic programming.

I. INTRODUCTION

The conventional energy services, i.e., electrical and natural gas infrastructures have often operated separately. However in recent years, synergies among different energy infrastructures has been increased. The idea of energy hub is introduced in [1] to link various types of energy systems. From a local grid point of view, an energy hub is a functional unit capable of receiving, converting and storing of various forms of energy [2]. In fact, an energy hub plays an important role in connecting and interdependent operations of current various energy infrastructures. The energy hub can include different types of components such as combined heat and power systems (CHPs), boilers, electrical energy storages (EES), heat energy storages (HES), etc.

Recently, a lot of researchers have concentrated on the scheduling and planning of energy hub systems. In [3] a hybrid stochastic/information gap decision theory (IGDT) approach is implemented to optimize the operation of energy hub system. The uncertainties pertaining to the wind power generation and energy demands in the scheduling problem are modeled via scenarios, while an IGDT method is applied to find an interval for energy prices to study the opportunity and robustness functions. A long-term scenario based two-stage stochastic model for optimal planning and operation of energy hub is presented in [4], which determines the optimum number and size of components. Moreover, reliability indices such as expected energy not supplied (EENS) and loss of load probability (LOLP) have been considered to cover energy demands with desirable reliability level.

In this paper, a stochastic model of energy hubs for solving the 24-h optimal scheduling problem is conducted. A stochastic mixed-integer linear programming (MILP) model is presented for optimal scheduling of energy hub consisting of CHP system, boiler unit, solar panels, and energy storage devices.

II. SOLAR RADIATION MODEL

The Stochastic nature and uncertainty of the solar radiation make a challenge for the energy hub operator to schedule the CHP system, boiler unit, solar panels, and energy storage devices in an optimal way. Hourly global solar radiation estimation has been modeled in many recent works [5, 6]. The effect of hourly solar radiation is modeled by normal distribution in this paper. Table I shows the modeling of hourly solar radiation uncertainty, which are taken normal distribution according to [7].

TABLE I
Pdf of Hourly Solar Radiation

Month	Hour	Distribution	Standard deviation (σ)
November, April	9:00 am to 3:00 pm	$N(\mu,\sigma^2)$	12% μ
November, April	The remainder of the day	$N(\mu,\sigma^2)$	25% μ
May, October	9:00 am to 3:00 pm	$N(\mu,\sigma^2)$	3% μ
May, October	The remainder of the day	$N(\mu,\sigma^2)$	8% μ

III. Mathematical Stochastic Model for Scheduling of Energy Hub

A. solar panels system modelling

Power of the energy hub system, which is produced by solar panels, depends on various parameters such as environmental temperature, date and time, longitude and latitude of the PV arrays. For instance, hourly sampled global horizontal irradiation and ambient temperature data are provided by different meteorological sites of the GeoModel Solar Company [8]. In order to study the power generation of PV panels system, a mathematical formulation for time t and scenario ω can be proposed as follows [9]:

$$PPV_{(t,\omega)} = \eta_{PV} \times SPV \times G_{(t,\omega)} \quad (1)$$

Where η_{PV}, SPV and $G_{(t,\omega)}$ are the efficiency, area and solar radiation of PV panels, respectively.

The PV panels efficiency can be obtained as follows [10]:

$$\eta_{PV} = \eta^{PVr} \times \eta^{MPPT} \{1 - \vartheta(TC - TC_r)\} \quad (2)$$

Where η^{PVr}, η^{MPPT} and TC_r are the reference efficiency, tracker efficiency and reference temperature, respectively.

The temperature of the PV arrays is formulated by the following equation proposed by [11]:

$$TC = T_{ambient} + ((NOCT - 20)/800)G_{(t,\omega)} \quad (3)$$

Where $T_{ambient}$ and $NOCT$ are the ambient and normal operating cell temperature, respectively.

The hourly solar radiance on the PV arrays can be defined as (4):

$$G_{(t,\omega)} = G^b_{(t,\omega)} + G^d_{(t,\omega)} + G^r_{(t,\omega)} = G^{bn}_{(t,\omega)} \left[\rho(\cos(\chi) + C)\sin^2(\frac{\phi}{2}) + \cos^2(\frac{\phi}{2})\sin(\chi) + \cos(\theta) \right] \quad (4)$$

Where G^b, G^d, G^r and G^{bn} are the direct, sky diffuse, ground reflected and direct normal radiation, respectively.

Angle between the PV arrays and the solar rays, sun zenith and plate azimuth angles and also solar declination angle are defined as (5)-(7):

$$\cos\theta = \left[\sin\phi \sin\chi \cos(\psi - \upsilon) + \cos\phi\cos\chi\right] \quad (5)$$

$$\cos\theta = \cos\chi = \cos\delta\cos\lambda\cos\varphi + \sin\delta\sin\lambda \quad (6)$$

$$\delta = 23.44\sin\left[360\left(\frac{d-80}{365.25}\right)\right] \quad (7)$$

Where $\chi, \psi, \upsilon, \delta, \lambda$, φ and d are the zenith, sun azimuth, plate azimuth, solar declination angle, latitude, solar angle and number of the days, respectively.

Solar angle can be expressed by (8)–(13):

$$\varphi = 15 \times (T_{ls} - 12) \quad (8)$$

$$T_{ls} = T_l + TC/60 \quad (9)$$

$$TC = 4(L_{loc} - L_{STM}) + E_{OT} \quad (10)$$

$$L_{STM} = 15° \times t_z \quad (11)$$

$$E_{OT} = 9.87\sin(2Q) - 1.5\sin(Q) - 7.53\cos(Q) \quad (12)$$

$$Q = \frac{360(N_{day} - 81)}{364} \quad (13)$$

Where T_{ls}, T and N_{day} are the local standard, local time and number of the day, respectively.

B. Scheduling problem objective function

The objective of the proposed scheduling problem is to minimize the total operating costs of the energy hub system in which technical concerns are satisfied. The objective function can be defined as (14):

$$Min\ \ Cost = Min \sum_{t=1}^{T}\sum_{\omega=1}^{\omega} \pi_\omega \left\{ CF^{CHP}_{t,\omega} + CM^{CHP}_{t,\omega} + CF^{Boiler}_{t,\omega} + CM^{Boiler}_{t,\omega} + CG^{Buy}_{t,\omega} - CG^{Sell}_{t,\omega} \right\} \quad (14)$$

Where *CF, CM* and *CG* are the fuel, maintenance and grid exchange costs, respectively and can be expressed as follows:

$$CF^{CHP}_{t,\omega} = \left[PE^{CHP}_{t,\omega} * \left(\frac{\lambda^{Gas}_t}{\eta^{CHP} * HV} \right) \right] \quad (15)$$

$$CM^{CHP}_{t,\omega} = PE^{CHP}_{t,\omega} * \varpi^{CHP} \quad (16)$$

$$CF^{Boiler}_{t,\omega} = \left[PH^{Boiler}_{t,\omega} * \left(\frac{\lambda^{Gas}_t}{\eta^{Boiler} * HV} \right) \right] \quad (17)$$

$$CM_{t,\omega}^{Boiler} = PH_{t,\omega}^{Boiler} * \varpi^{Boiler} \quad (18)$$

$$CG_{t,\omega}^{Buy} - CG_{t,\omega}^{Sell} = \left(PE_{s,t}^{buy} * \lambda_t^{e,buy}\right) - \left(PE_{s,t}^{Sell} * \lambda_t^{e,Sell}\right) \quad (19)$$

C. *Scheduling problem constraints*

The power and thermal generations of the CHP are limited by (20) and (21).

$$PTH_{t,\omega}^{CHP} = PE_{t,\omega}^{CHP} \times \eta_{HE} \times HPR^{CHP} \quad (20)$$

$$PE_{Min}^{CHP} \le PE_{t,s}^{CHP} \le PE_{Max}^{CHP} \quad (21)$$

Where η_{HE} and HPR are the efficiency of the heat exchanger and heat-to-power ratio, respectively.

Equations (22) and (23) express the storage transition function and maximum energy capacities.

$$S_{t+1,\omega} = \left(S_{t,\omega} * \eta_{ST}\right) + \left(S_{t,\omega}^{in} * \eta_{storage}\right) - \left(\frac{S_{t,\omega}^{out}}{\eta_{storage}}\right) \quad (22)$$

$$S_{t,\omega} \le S_{Max} \quad (23)$$

IV. Simulation Results

In this section, the proposed scheduling model is applied to a comprehensive example. The energy hub components consist of a CHP unit, a boiler, storage devices and the solar system as well as the local electricity and natural gas grid connections, which is depicted, in Fig. 1. The facilities characteristics such as CHP, boiler and storage devices can be taken from [2]. The specifications of the solar system can be taken from [7]. Variation of energy hub different demands and the electricity and natural gas prices during different hours are shown in Fig.2 and Fig.3, respectively. In addition, 0.4 \$/kWh and 0.1 \$/m^3 are chosen for base values of electricity and natural gas prices, respectively. In order to model inaccuracies related to solar radiation, at first, Monte Carlo simulation approach is used to generate 1000 scenarios with equal probabilities (1/1000) and then these 1000 scenarios are reduced to 10 scenarios with an effective scenario reduction method to reduce volume of computations. Finally, with respect to all above assumptions, the proposed stochastic scheduling problem is implemented in General Algebraic Modeling System (GAMS) 23.6 software and is solved using the linear programming solver CPLEX [12] on a PC with an Intel Core Duo 2.8 GHz processor and 4 GB of RAM.

Table 2 illustrates simulation results of scheduling problem for proposed energy hub. As presented in Table 2, when the energy hub is connected to local electrical grid, total operation cost of energy hub and operation cost of CHP and boiler units are 11432.67, 10393.25, 1728, respectively. This lies in the fact that, CHP unit produce less electricity due to possibility of importing electricity from local grid.

V. Conclusion

This paper presents a scenario based two-stage stochastic model to optimal scheduling of energy hub in the presence of solar energy system. The proposed model covers the electrical and thermal demands with minimum operation cost. In the optimal scheduling problem of the energy hub, the objective is to serve different energy loads by using the CHP unit, boiler, PV system and local grids with the minimum cost. The Monte Carlo simulation approach is used to model solar radiation inaccuracies. Finally, an illustrative example is provided to demonstrate that solar integrated energy hub in presence of energy storages offers an optimal operation by providing more degree of flexibility for hub operators.

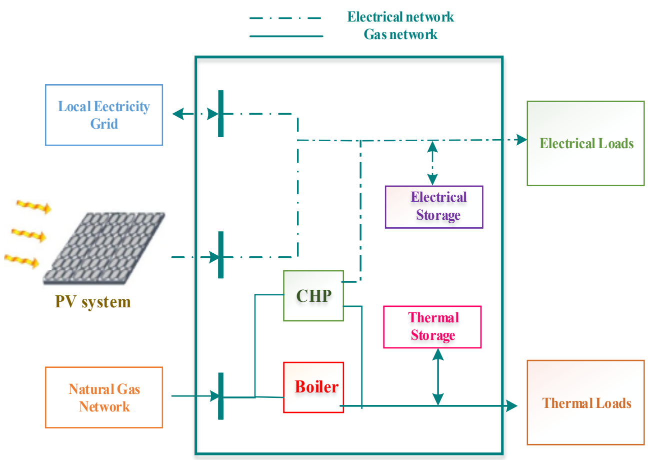

Fig. 1. Schematic of the proposed energy hub.

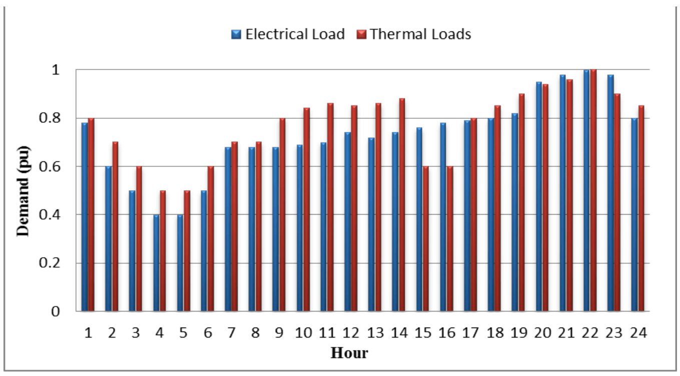

Fig. 2. Electrical and thermal energy demands.

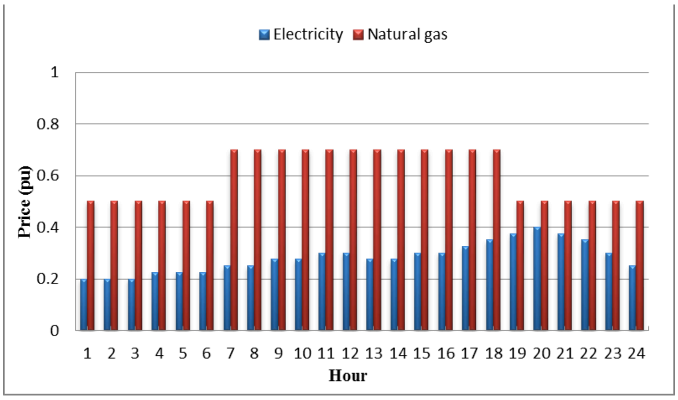

Fig. 3. Electricity and natural gas prices.

TABLE II
Simulation results of scheduling problem.

Total operation cost ($)	11432.67
Cost of imported electricity ($)	172.84
Income of exported electricity ($)	1778.99
Operation cost of CHP ($)	10393.25
Operation cost of boiler ($)	1728

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