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***Abstract*—This paper presents an operation strategy of energy hubs in the presence of electrical, heating, and cooling demand as well as renewable power generation uncertainties. The proposed strategy can be used for optimal decision making of energy providers companies, as well as, other private participants of hub operators. The presence of electrical energy storage devise in the assumed energy hub can handle the fluctuations in the operating points raised by such uncertainties. In order to modeling of hourly demands and renewable power generation uncertainties a scenario generation model is adopted in this paper. The considered energy hub in this study follows a centralized framework and the energy hub operator is responsible for optimal operation of the hub assets based on the day-ahead scheduling. The simulation result illustrates that in the presence of electrical energy storage devices the optimal operation of hub assets can be attained.**

Keywords—electrical energy storage, energy hub, stochastic programming, optimal operation.

I. INTRODUCTION

By increasing the role of the demand side in energy supply chain, the concept of the energy hub has emerged. In fact, the energy hub has various energy carriers in the input to supply the load demand. The input of the energy hub can be electricity, Natural Gas (NG), and also water. The type of consumption can be electrical energy, heat, cooling, cold water and warm water.

The components making up energy hubs can be categorized into three groups: generation technologies, energy conversion devices, and energy storage systems. Renewable energy technologies such as wind turbines and solar panels are generation technologies; boilers, Combined Heat and Power (CHP) units, micro-turbines and Electrical Heat Pumps (EHP) ae of energy conversion devices, and electrical and heat storage systems are of storage systems.

The optimal energy hub management is impacted by the uncertainties which can be either in the input or the output of the energy hub. The uncertain hourly electricity and NG price are of uncertainties in the input while the renewable power output is of the uncertainties in the output. Besides, the electrical, heat and cooling load demand forecast is of the system uncertainties.

However, the impact of each uncertain parameter is not the same as others. It is noted that the output of the energy hub can also affect the input like the hourly energy price.

The energy hub is modeled in this paper in a centralized manner, the amount of the load demand of the energy hub is negligible compared to the total load demand of the system; thus the variations of the load demand of the energy hub cannot impact the load profile of the system.

Many research works have been carried out thus far regarding the optimal operation and planning of energy hubs and their assets. The energy hub was first introduced in 2007 [1] and the research works have started to be completed over these years [2-5]. Ref. [6] proposes an economic dispatch model for the energy hub, while Ref. [7] investigated the demand response programs in the energy hub using a Mixed-Integer Non-Linear programming model. Different approaches have been presented so far to characterize the operation uncertainties. In this respect, Ref. [8] used a robust optimization technique and Ref. [9] utilized the stochastic programming. Furthermore, Ref. [10] proposed a stochastic planning method to optimally determine the size of the hub assets. A hybrid optimization technique has been employed in Ref. [11] to solve the problem of optimal determination of the energy hub assets by assessing the generation strategies over the operation horizon. This paper determined the optimal operating points of the pre-installed assets using a probabilistic viewpoint. The main contributions of the paper can be briefly stated as follows:

- Proposing an energy flow based for the energy hub.
- Utilizing an efficient stochastic operation model.
- Using renewable energies as distributed generation next to the load demand.

This paper is organized as follows. Section II presents the conceptual model of the energy hub and the relation of different parts from the input to the output. The mathematical formulation of the energy hub operation is proposed in section III. Section IV includes the simulation results and some relevant conclusions have been drawn in section V.

II. CONCEPTUAL MODEL OF THE ENERGY HUB

The energy hub proposed in this paper includes various generation technologies, storage systems as well as different energy conversion systems. The energy hub is connected to the electrical grid and the NG system through its input. Besides, a solar panel has been installed to use the renewable energies. The auxiliary boiler and the CHP unit together with the EHP are supposed to supply the heat load demand. The cooling load demand is also supplied using the EHP and the absorption chiller. It is worth noting that the EHP can operate in either cooling or heating modes.

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Furthermore, Electrical Energy Storage (EES) system has been installed to mitigate the load demand and generation fluctuations and operating costs. The EES system can be managed in a way to store energy over off-peak hours and also over the hours with excess solar power and inject energy to the system over peak hours. The EES system can also be utilized to supply the required energy for the assets to meet the cooling and the heat load demand. The energy hubs may include renewable energies in limited size, generally a few kilowatts. Although the operating costs of such units are low, they may bring severe challenges into the energy hub optimal operation due to their uncertain power output.

III. Mathematical Modeling

The mathematical representation of the proposed model in a stochastic framework using a scenario-based optimization technique is included in this section in which the objective function is composed of the operating costs of the hub and intended to be minimized. Note that the energy hub is connected to the electrical grid and transacts energy resulting in costs/revenues. This mode of operation has been also taken into consideration in the objective function.

$$Min \sum_{s=1}^{N_s} \omega_s \left[\sum_{t=1}^{N_T} \left[\begin{array}{l} \left(PG_{s,t}^{G2H}.\lambda_t^{Buy} - PG_{s,t}^{H2G}.\lambda_t^{Sell} \right) + \\ F_{s,t}^{CHP} + F_{s,t}^{Boiler} + F_{s,t}^{Chiller} + F_{s,t}^{EHP} + F_{s,t}^{Heater} + \\ \sigma_t^{Elec.} W_{s,t}^{Elec.} + \sigma_t^{Heating} W_{s,t}^{Heating} + \sigma_t^{Cooling} W_{s,t}^{Cooling} \end{array} \right] \right] \quad (1)$$

The number of seasons and days, is indicated by s and t, respectively. The objective function comprises three parts in which the first part shows the cost of energy transaction with the electrical grid. The second part shows the cost of energy generation cost from the energy hub. Finally, the last part represents the electrical, heat and cooling energy losses. The scenarios have been denoted by s and ω is the occurrence probability of each scenario. Moreover, f, $PG_{s,t}^{G2H}$ and $PG_{s,t}^{H2G}$ are the operating cost, energy transmitted to the energy hub from the electrical grid and the energy transmitted to the electrical grid from the energy hub, respectively. λ_t^{Sell} and λ_t^{Buy} indicate the energy selling and purchasing prices, respectively. This optimization problem is subject to several constraints as:

$$F_{s,t}^{CHP} = a_{NG}^{CHP}\left(PG_{s,t}^{CHP}\right)^2 + b_{NG}^{CHP}\left(PG_{s,t}^{CHP}\right) + c_{NG}^{CHP}\left(PH_{s,t}^{CHP}\right)^2 + d_{NG}^{CHP}\left(PH_{s,t}^{CHP}\right) + e_{NG}^{CHP}\left(PG_{s,t}^{CHP}\right)\left(PH_{s,t}^{CHP}\right) + f_{NG}^{CHP} \quad (2)$$

$$F_{s,t}^{Boiler} = a_{NG}^{CHP}\left(PH_{s,t}^{Boiler}\right) + b_{NG}^{Boiler} \quad (3)$$

$$F_{s,t}^{Chiller} = a_{NG}^{Chiller}\left(PC_{s,t}^{Chiller}\right) + b_{NG}^{Chiller} \quad (4)$$

$$F_{s,t}^{EHP} = a^{EHP}(PH_{s,t}^{EHP} + PC_{s,t}^{EHP})^2 + b^{EHP}(PH_{s,t}^{EHP} + PC_{s,t}^{EHP}) + c^{EHP} \quad (5)$$

$$F_{s,t}^{Heater} = a^{Heater}\left(PH_{s,t}^{Heater}\right) + b^{Heater} \quad (6)$$

The operating cost of the CHP unit has been shown in Eq. (2). The different cost coefficients of the units with respect to different days and seasons of the year are represented as *a, b, c, d, e* and *f* . Furthermore, $PG_{s,t}^{CHP}$ and $PH_{s,t}^{CHP}$ indicate the electrical power and the heat generated by the CHP unit. The generation cost of the auxiliary boiler is represented in (3) while the operating cost of the chiller is shown in (4). Both equations are linear and are expressed in terms of NG consumption. Eq. (5). Shows the EHP's cost of operation. It should be considered that the EHP operates in one of the modes, i.e. producing heat $PH_{s,t}^{EHP}$ or producing $PC_{s,t}^{EHP}$. Besides the cost imposed to the energy hub by the electrical heater is represented in (6) using a linear expression. The EES system is present in the energy hub beside other assets while its operating cost is assumed negligible. The following constraints indicate the technical limitations of the system.

$$PG_{s,t}^{CHP} - PG_A^{CHP} - \frac{PG_A^{CHP} - PG_B^{CHP}}{PH_A^{CHP} - PH_B^{CHP}}\left(PH_{s,t}^{CHP} - PH_A^{CHP}\right) \le 0 \quad (7)$$

$$PG_{s,t}^{CHP} - PG_B^{CHP} - \frac{PG_B^{CHP} - PG_C^{CHP}}{PH_B^{CHP} - PH_C^{CHP}}\left(PH_{s,t}^{CHP} - PH_B^{CHP}\right) \ge -\left(1 - I_{s,t}^{CHP}\right).M \quad (8)$$

$$PG_{s,t}^{CHP} - PG_C^{CHP} - \frac{PG_C^{CHP} - PG_D^{CHP}}{PH_C^{CHP} - PH_D^{CHP}}\left(PH_{s,t}^{CHP} - PH_C^{CHP}\right) \ge -\left(1 - I_{s,t}^{CHP}\right).M \quad (9)$$

$$0 \le PH_{s,t}^{CHP} \le PH_{s,B}^{CHP}.I_{s,t}^{CHP} \quad (10)$$

$$PG_C^{CHP}.I_{s,t}^{CHP} \le PG_{s,t}^{CHP} \le PG_A^{CHP}.I_{s,t}^{CHP} \quad (11)$$

$$PH_{s,t}^{Boiler,Min}.I_{s,t}^{Boiler} \le PH_{s,t}^{Boiler} \le PH_{s,t}^{Boiler,Max}.I_{s,t}^{Boiler} \quad (12)$$

$$PC^{Chiller,Min}.I_{s,t}^{Chiller} \le PC_{s,t}^{Chiller} \le PC^{Chiller,Max}.I_{s,t}^{Chiller} \quad (13)$$

$$PC_{s,t}^{Chiller} = PH_{s,t}.COP^{Chiller} \quad (14)$$

$$PC^{EHP,Min}.I_{s,t}^{EHP,Cooling} \le PC_{s,t}^{EHP} \le PC^{EHP,Max}.I_{s,t}^{EHP,Cooling} \quad (15)$$

$$PH^{EHP,Min}.I_{s,t}^{EHP,Heatling} \le PH_{s,t}^{EHP} \le PH^{EHP,Max}.I_{s,t}^{EHP,Heatling} \quad (16)$$

$$0 \le I_{i,t}^{EHP,Heating} + I_{i,t}^{EHP,Cooling} \le 1 \quad (17)$$

$$PC_{s,t}^{EHP} = PG_{s,t}.COP^{EHP,Cooling} \quad (18)$$

$$PH_{s,t}^{EHP,Heating} = PG_{s,t}.COP^{EHP,Heating} \quad (19)$$

$$0 \le PH_{s,t}^{Heater} \le PH_{s,t}^{Heater,Max}.I_{s,t}^{Heater} \quad (20)$$

$$PH_{s,t}^{Heater} = PG_{s,t}.COP^{Heater} \quad (21)$$

$$Eng_{s,t}^{EES} = Eng_{s,t-1}^{EES} + PG_{s,t}^{EES,Ch.}.\eta^{EES,Ch.} - PG_{s,t}^{EES,Dis.} / \eta^{EES,Dis.} \quad (22)$$

$$Eng^{EES,Min} \le Eng_{s,t}^{EES} \le Eng^{EES,Max} \quad (23)$$

$$Eng_{t=0}^{EES} = Eng_{t=24}^{EES} \quad (24)$$

$$0 \le PG_{s,t}^{EES,Ch.} \le PG_{s,t}^{EES,Ch.,Max}.I_{s,t}^{EES,Ch.} \quad (25)$$

$$0 \le PG_{s,t}^{EES,Dis.} \le PG_{s,t}^{EES,Dis.,Max}.I_{s,t}^{EES,Dis.} \quad (26)$$

$$0 \le I_{s,t}^{EES,Ch.} + I_{s,t}^{EES,Dis.} \le 1 \quad (27)$$

$$0 \le PG_{s,t}^{G2H} \le PL^{Max}.I_{s,t}^{G2H} \quad (28)$$

$$0 \le PG_{s,t}^{H2G} \le PL^{Max}.I_{s,t}^{H2G} \quad (29)$$

$$0 \le I_{s,t}^{G2H} + I_{s,t}^{H2G} \le 1 \quad (30)$$

where the binary variable I is assigned to the model to determine the status of an asset. Constraints (7) to (11) present the mathematical modeling of the CHP unit as in Ref. [1]. It is noted that the Big-M method has been used in this paper. A convex quadrilateral is used to identify the CHP unit's feasible operating region. $I_{s,t}^{CHP}$ forces the CHP unit to operate in the related FOR when it is on. The heat generated by the boiler and the chiller has been modeled in (12) and (13), respectively. As a heat pump, in order to generate cooling power, the chiller absorbs heat. In this regard, its coefficient of performance is denoted by $COP^{Chiller}$. As it has been previously mentioned, the EHP should operate in one the mentioned modes as stated in (15)-(17). Moreover, Eqs. (18) and (19) represent the coefficient of production for cooling and heating as. $COP^{EHP,Heating}$ and $COP^{EHP,Cooling}$, respectively, which reflect the efficiency of energy conversion for a heat pump. The constraint relating to the heat generated by the electric heater is stated in (20) while the electricity to heat energy conversion is represented by (21). The constraints of the EES unit are presented in (22)-(27) [12], while (28)-(30) model the energy which is being transacted between the electrical grid and energy hub. The feeder connecting both has a maximum capacity denoted by PL^{Max}. Equations ((31)-(33)) represent the critical power balance for the electricity, heat and cooling power, considering the fact that no curtailment is allowed. In this respect, the CHP unit, EES unit, solar panel as well as the electrical grid are able to supply the required electric energy, while the EHP, electric heater, boiler, and CHP unit, are supposed to generate heat. Meanwhile, the cooling power procurement is assumed by the EHP and absorption chiller

$$P_{s,t}^{Load} + W_{s,t}^{Elec.} = PG_{s,t}^{G2H} + PG_{s,t}^{CHP} + PG_{s,t}^{EES} + PG_{s,t}^{PV} \quad (31)$$

$$PH_{s,t}^{Load} + W_{s,t}^{Heating} = PH_{s,t}^{Boiler} + PH_{s,t}^{Heater} + PH_{s,t}^{CHP} + PH_{s,t}^{EHP,Heating} \quad (32)$$

$$PC_{s,t}^{Load} + W_{s,t}^{Cooling} = PC_{s,t}^{Chiller} + PC_{s,t}^{EHP,Cooling} \quad (33)$$

IV. Simulation Results

The presented model has been simulated using the data of the energy hub in [8]. In this respect, the warm and the cold seasons, i.e. summer and winter have been considered where the data of electrical, heat and cooling load demand as well as the data of the installed solar panels are depicted in Figs. 1-4.

It is noteworthy that the data related to the work days have been utilized to generate the scenarios [11]. The maximum number of scenarios for each uncertain parameter is considered 1000 and then reduced to 10.

The simulation results show that the CHP unit operates with the maximum capacity to generate electricity without any heat power due to the relatively high electricity tariff and low NG price. Moreover, the cooling load demand is supplied through the absorption chiller beside the EHP. As the electricity price is high, the heater is not used to supply the heat load demand and the boiler is supposed to generate the required heat.

It is worth noting that the EHP is used only over few hours and due to the operation limitation of such unit, it operates only in the cooling mode. In winter, the electrical and cooling load demands reduce which in turn lead to mitigating the electricity price compared to summer.

On the other hand, the heat load demand would be reflected by the NG price. Table I represents the optimal schedule of the energy hub in the presence of the EES system. The CHP unit is used in winter in a way to simultaneously generate electricity and heat.

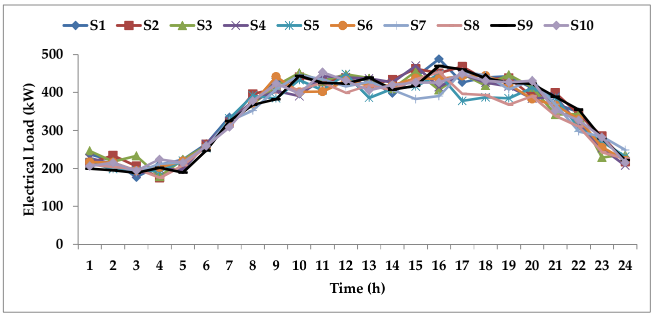

Fig. 1. The electrical load demand in summer.

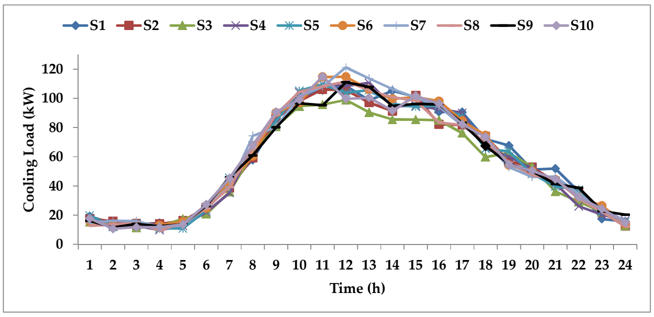

Fig. 2. The cooling load demand in summer.

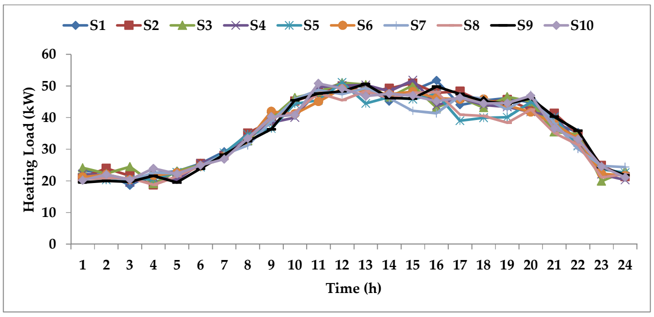

Fig. 3. The heat load demand in summer.

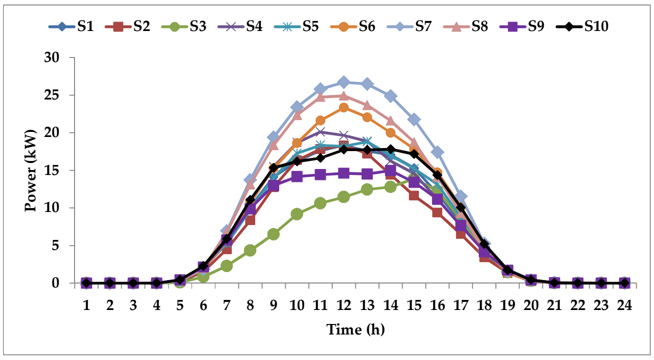

Fig. 4. The scenarios of the solar power in summer.

TABLE I. OPTIMAL OPERATION STRATEGY FOR HUB ASSETS

Unit	Asset Operation Strategy	
	Summer	***Winter***
CHP_Heat	Not Used	Fully Used
CHP_Elec.	Fully Used	Fully Used
EHP_Heat	Not Used	Not Used
EHP_Cool	Partially Used	Not Used
Boiler	Fully Used	Fully Used
Chiller	Fully Used	Partially Used
EES	Fully Used	Fully Used
Heater	Not Used	Partially Used

The generation of this asset is almost constant at each hour in all scenarios. This means that the energy hub operator can fix the hourly operating point of the CHP unit for each scenario. The boiler permanently operates together with the CHP unit to supply the heat load demand while as it has been previously mentioned, the heater is used only over some hours. The EHP is quite deactivated in winter and it can be considered for the annual maintenance, as the cooling load demand is at its minimum amount and the absorption chiller is used to supply the demand. Furthermore, an analysis has been carried out to specify the role of the EES system in mitigating the energy hub's operating cost.

The obtained results are represented in Table II showing that the EES system would be able to store energy over the off-peak hours when the electricity price is low and contributes to supplying the electrical load demand when the energy price is high. Fig. 5 depicts the stored energy in the battery for the energy hub operation in summer.

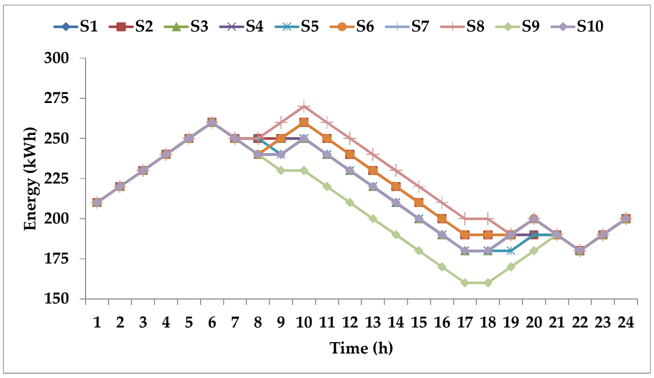

Fig. 5. The energy stored in the EES system in summer.

TABLE II. OPTIMAL OPERATION STRATEGY FOR HUB ASSETS

Season	Daily Expected Operational Cost	
	With ESS	***Without ESS***
Summer	1243268.322	1271908.190
Winter	1445444.302	1453791.569

V. CONCLUSION

This paper investigated the optimal energy hub management in summer and winter. According to the energy flow model, the output of each asset is modeled as the input of each asset, while an asset may have more than one input or output. Thus, the modeling using the energy flow is more flexible compared to the matrix-based modeling. In addition, some assets can operate in more than one mode while only operating in one mode is allowable at a time. For instance, the EES system and the EHP follow the same operation pattern. Some assets such as the CHP unit have two outputs while the operating point depends upon the possible obtainable electricity and heat. This paper also took into account the uncertainties related to the load demand and renewable power generation forecasts. The simulation results show that the uncertainties can be effectively managed using the EES system.

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