Hybrid Strategy for Optimal Scheduling of Renewable Integrated Energy Hub Based on Stochastic/Robust Approach

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Energy hubs play an undeniable role in the power system as the coupling among various energy infrastructures such as electrical network, natural gas system, thermal network and renewable generation systems. This paper assesses the renewable based energy hub (REH) optimal scheduling considering combined heat and power (CHP) unit, energy storage components, auxiliary boiler and wind turbine via hybrid stochastic/robust (HSR) approach. This paper proposes a strategy to control and model the uncertainties relevant to energy prices, wind turbine generation and energy demands by using the proposed HSR method. By using the HSR method, the global optimal results of the proposed REH scheduling problem can be reached. In addition, the computation burden of the proposed problem is reduced. Furthermore, by the HSR approach, the operator of the system can follow a robust strategy to immune the system against the worst events. The proposed system can participate in the thermal energy market beside electricity market by way of self-scheduling method. Three sets of possible scenarios are used to model the forecasted errors of demands and wind generation uncertainties, while robust optimization method is implemented to manage the uncertainties relevant to electrical and thermal energy prices.

keywords: *Renewable based energy hub, uncertainty, stochastic optimization, robust optimization, hybrid approach, wind generation.*

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NOMENCLATURE

Indices:

s Index for scenarios, $[1:S]$.

t Index for scheduling time periods, $[1:T]$.

Parameters:

$E^{CHP}_{max/min}$ Maximum/minimum output of the CHP unit.

HPR CHP unit Heat to power ratio.

κ Coefficient of the maintenance cost.

HV The heat value of the gas.

$E^{Ramp-up/Ramp-down}$ CHP unit ramp up and ramp down rates.

$SDCC/SUCC$ CHP unit shut down and startup costs.

η^{CHP} The CHP unit electrical efficiency.

$H^{Boiler}_{\max/\min}$ Maximum/minimum output of the auxiliary boiler.

$P^{E}_{\max/\min}$ The EES maximum and minimum rates of stored energy.

$P^{H}_{\max/\min}$ The TES maximum/ minimum rates of stored energy.

$\lambda^{el/h/gas}$ The prices of the electrical energy, thermal energy and natural gas.

ω_s The sth scenario probability.

$VOLL$ The value of lost load.

η_{boiler} Auxiliary boiler efficiency.

$\eta^{E/H}$ The electrical and thermal energy storages' Standby efficiency.

$P^{wind}_{s,t}$ Generated power of the wind system.

$D^{E/H}_{s,t}$ The electrical/ thermal demands.

Variables:

$OCB_{s,t}, OCC_{s,t}$ Auxiliary boiler and CHP unit operation costs.

$PC_{s,t}$ Cost of the curtailed loads.

$SHCC_t, STCC_t$ CHP unit shutdown and startup costs.

$E^{CHP}_{s,t}$ Electrical output of the CHP unit.

$FCC_{s,t}, FCB_{s,t}$ Fuel costs of the CHP unit and auxiliary boiler.

$MCC_{s,t}, MCB_{s,t}$ Maintenance costs of the CHP unit and auxiliary boiler.

$H^{boiler}_{s,t}$ Thermal output of the auxiliary boiler.

$P^{E}_{s,t}$ Amount of stored energy in the EES.

$P^{H,ch/dch}_{s,t}$ Thermal input/ output of the TES.

$P^{H}_{s,t}$ Amount of stored energy in the TES.

$CE_{s,t}, CH_{s,t}$ Costs of imported electricity and thermal energy from local network.

$E^{Grid,imp/\exp}_{s,t}, H^{Grid,imp/\exp}_{s,t}$ Amount of imported/exported electrical/thermal energy.

$EL_{s,t}/HL_{s,t}$. Curtailed electrical/ thermal loads.

1. INTRODUCTION

A. Motivations

With the evolution of the energy system, multi carrier energy systems have attracted considerable attention. The energy hub is a new concept for multi carrier energy systems [1], which different energy networks such as electricity, thermal energy and natural gas integrated with together. The coordination between various energy carriers makes the operation of energy systems more optimal [2]. Furthermore, worldwide concerns about global warming and environmental emission have caused to a recent global push towards different forms of renewable resources. In addition, the impacts of the renewable generations on the power grid is developed by extensive operation from grid connected renewable systems [3]. Also, employing uncertainty modeling methods against volatility and unpredictability problem of the uncertain parameters such as renewable resources, demands and energy market tariffs is necessary for more efficient operation of the renewable integrated energy hubs (REH) in the power system [4].

B. Literature review and contributions

Different studies have been carried out in area of planning and scheduling of energy hubs in different scales. In [5] a framework for energy hub and its operation has been proposed which the proposed model incorporated different equipment such as CHP unit, photovoltaic system and energy storages. Authors of [6] attempted to extend an optimal industrial load management model which can be consolidated into energy hub management systems for any consumer. The objective is minimizing energy costs and/or demand charges for participating industrial customers. The effect of electricity price uncertainty and energy hub profit on hub operation was investigated in [7]. A model is introduced in [8] for smart energy networks considering economic and environmental objectives in a network of energy hubs. A stochastic model for planning and scheduling of the energy hub systems is presented in [9]. The Monte Carlo algorithm is used to model the uncertain parameters such as wind generation, electricity price and electrical demand of the system. The proposed hub is fed by water, electricity and gas, while, the outputs of the system are electricity, gas, water and thermal energy.

In [10], the economic dispatch problem of the integrated heat and power system is solved by using genetic algorithm. The CHP unit, as an important components of the energy hub systems, has an undeniable effect in improving the efficiency of energy systems [11]. In [12], a model is proposed for the design of energy hubs, considering reliability constraints and including the selection of components and their sizes. Some studies, e.g. [13], addressed an optimal design method for linked energy hubs containing electricity and natural gas networks and emission constraints. In [14], a method is presented for evaluating the competence of energy hubs, considering the details of supply, demand side, and limitation of the availability of primary energy resources. Authors of [15] represents the energy resource affiliation in microgrids by implementing multi-carrier energy systems. Furthermore, the authors offer suppressive reinforcement procedure to microgrid operators following the resiliency analysis. In recent studies, renewable energy resources play an important role for reducing energy costs in multi-carrier energy systems [16]. On the other hand, the energy hub provides flexibility for energy systems to integrated operation with renewable resources. In this context, a set of business concepts for renewable energy-based energy hubs is proposed in [17]. In [18] an integrated demand-side management has been introduced. The proposed model considered the interplay amongst energy hubs. A stochastic method to design an energy hub that consisting of storage components, combined heat and power (CHP) unit and wind power resource is presented in [19]. The output of the wind turbine, random outages of the devices and energy demands are considered as uncertain parameters which are modeled via scenario based stochastic method using the Monte Carlo simulation model. Previously, various methodologies are implemented to systems for modeling the uncertain parameters, such as stochastic, robust, IGDT and hybrid methods [20]. Uncertainty modeling by using probabilistic methods such as stochastic programming [21] caused to increase volume of computations, while information gap decision theory (IGDT) and robust methodologies can be implemented to model the uncertain parameters with a minimum computational burden. A risk-based management of the energy hub is presented in [22] which the objective function minimizes both the economic risks and energy costs of the energy hub. In [23], electricity, natural gas and coal infrastructures' interdependencies are analyzed by a robust optimization method considering wind power uncertainties. A robust heat and power scheduling problem is presented in [24]. An integrated heat and electrical energy microgrid is studied under uncertain environment. Optimal management of a hydrothermal system is developed in [25], which a robust methodology is applied for solving the microgrid economic dispatch.

Traditionally, in the energy systems only participation on the electrical energy market has been considered [26]. Also, in [27] the interaction energy infrastructures in the electrical energy market is studied. In addition, In [28], a model to interaction electrical energy prosumers in the electricity market is presented, that only electrical energy market is considered in the proposed energy system.

While, multi carrier energy systems can be affected on different energy markets. On the other hand, energy hubs can participate on the thermal energy market beside electrical energy market.

In the previous works in the energy hub field, the uncertainties are modeled by using stochastic, robust and IGDT methods, while there is an undeniable needed to model the uncertain parameters for addressing the unavoidable uncertain parameters and reducing the computational burden of finding the global optimal of the proposed problem. Moreover, it is necessary to make robust the energy systems against uncertainties. Also, robust optimization method is an effective strategy for modeling of two uncertain parameters simultaneously to make the proposed system robust. The main contribution of this paper is to propose a new hybrid stochastic/robust (HSR) optimization approach for the REH scheduling problem. Compared to existing methods, the proposed HSR optimization method is considered as a promising approach not only in achieving the high-quality solutions but also in reducing computational volume of optimization problems. In addition, the proposed REH can follow a robust strategy to face with electrical and thermal energy price market uncertainties. Previously, little attentions are paid to the impact of the energy hubs on the different energy markets. Furthermore, the proposed for REH system can participate on the thermal market beside electrical energy market. The contributions of the current paper can be stated as follows:

1) A new hybrid method for scheduling problem of the REH based on the HSR optimization method which can manage the risks related to uncertain parameters.

2) By applying the proposed HSR method the operator can benefit from both robust and stochastic methodologies' advantages. The REH system becomes immune against higher costs.

3) The proposed system can take robust strategy to face with energy prices uncertainty by applying the proposed HSR method.

4) The REH system can participate on the thermal energy market beside electricity market.

C. Paper organization

The remainder of the current paper is organized as follows. The mathematical model of the REH and the proposed hybrid method is introduced in Section 2. The assumptions, numerical simulation and results are discussed in Section 3. Finally, Section 4 provides the conclusion drawn from the current paper.

2. REH SCHEDULING PROBLEM BASED ON HSR METHOD

In the large scale energy systems the several uncertain parameters make a challenge for the optimization problems to schedule various components to find a solution to reach optimal results. In this paper, by taking this challenge the robust method for modeling energy price uncertainty is implemented and scenario-based stochastic programming for modeling the wind turbine generation, thermal and electrical demands is considered.

A. Scheduling problem based on pure stochastic optimization

In this subsection a pure stochastic optimization method is described for scheduling of REH. The system operator makes decisions for determine the optimal generation of equipment such as CHP unit, energy storages, auxiliary boiler and exported and imported thermal and electrical energies to/from local networks based on three sets of possible scenarios. In the current paper, different scenarios based on historical data or forecasted results are implemented to model the uncertain demands and wind turbine generation [22]. Furthermore, computational volume of the REH scheduling problem is reduced by a proper scenario reduction algorithm.

A.1. Scenario generation

Owing to the stochastic nature of the energy demands, modeling the uncertain demands in the scheduling of the REH is necessary. In this paper, normal distribution is used to model the uncertain parameters relevant to electrical and thermal demands [29]. In this paper, Monte Carlo simulation is applied to generate a set of possible scenarios by normal distribution.

$$\mathrm{PDF}\left(d\right)=\frac{1}{\sqrt{2\pi\sigma_d^2}}exp\left[-\frac{\left(d-\mu_d\right)^2}{2\sigma_d^2}\right] \tag{1}$$

In addition, the uncertainty and intermittency of wind speed is modeled by using the Rayleigh or Weibull PDF [29]. In this paper, the variation of wind speed is modeled by applying the Rayleigh PDF [30]:

$$\mathrm{PDF}\left(v\right)=\left(\frac{v}{c^2}\right)\ exp\left[-\left(\frac{v^2}{2c^2}\right)\right] \tag{2}$$

As it is noted, the wind power generation is relevant to wind speed. Also, the power generated by wind turbine can be formulated as (3):

$$P_s^w\left(v\right)=\begin{cases}0 & \text{if } v\leq v_{in}^c \text{ or } v\geq_{out}^c\\ \frac{v-v_{in}^c}{v_r-v_{in}^c}P_s^r & \text{if } v_{in}^c\leq v\leq v_r\\ P_s^r & 0\end{cases} \tag{3}$$

where P_s^r, v_{in}^c , v_{out}^c, v_r are the rated output power of wind turbine, cut-in, cut-out and rated wind speed, respectively.

A.2. Scenario reduction

Applying a proper scenario reduction model is quite necessary for large scale optimal scheduling problems. The scenario reduction algorithm is a scenario-based approximation method to keep essential features of the initial scenarios [31]. The SCENRED tool contains forward and backward algorithms to reduce the number of scenarios. These algorithms have different features, the results of forward method are more accurate, but it need to higher computing time, while, the backward method has the better performance in the lower computing time [32, 33]. Furthermore, SCENRED has two options for reduction, $red_{percentage}$ and $Red_{num\,leaves}$. The $red_{percentage}$ reduces the scenarios based on distance between reduced and initial scenarios and the Red_{num} leaves works based on desired number of preserved scenarios [34]. In this paper, initial scenarios are reduced to ten scenarios with new probabilities by using fast backward reduction algorithm while the factor of $red_{num\,leaves}$ is set to 10. In the current paper, scenario reduction method is done by implementing the SCENRED tool in the General Algebraic Modeling System (GAMS) environment [24]. In this work, two stages stochastic optimization is implemented to scheduling problem of the REH at the first.

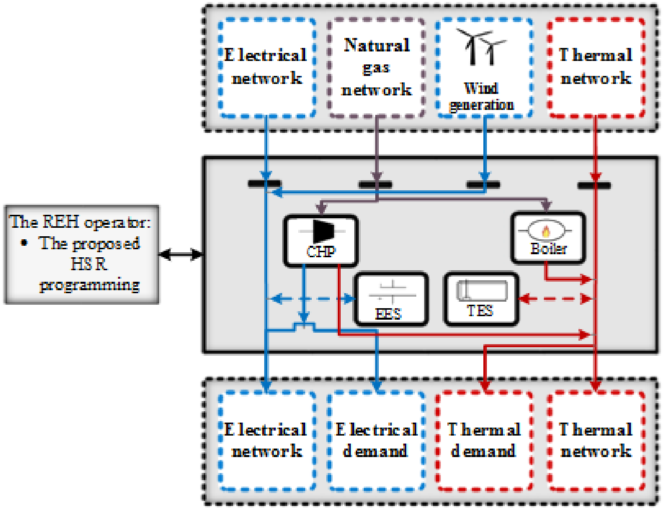

Fig. 1. The structure of the proposed REH

A.3. Mathematic model of the stochastic optimization

The generation facilities of the proposed REH system consist of wind turbine, boiler system, CHP unit, electrical energy storage (EES), thermal energy storage (TES) as well as the local electricity, thermal energy and natural gas grid connection. Wind turbine generation, natural gas, grid-received electrical energy and local grid-received thermal energy are the inputs of the REH system, while the outputs are exported electrical and thermal energies as well as electrical and thermal demands. The structure of the proposed REH is presented in Fig. 1.

The objective function of the scheduling problem minimizes the operational cost of REH system. The objective function terms are the operation costs of the auxiliary boiler and CHP unit, penalty costs of unsupplied demands, costs and revenues of the imported and exported electrical and thermal energies, shutdown and startup costs of the CHP unit.

$$\min Z = \sum_{t=1}^{T} \sum_{s=1}^{S} \left\{ \begin{array}{l} \left(\omega_s \times \left(\begin{array}{l} OCC_{s,t} + OCB_{s,t} + PC_{s,t} \\ +CE_{s,t} + CH_{s,t} - RE_{s,t} - RH_{s,t} \end{array} \right) \right) \\ +STCC_t + SHCC_t \end{array} \right. \tag{4}$$

A.4. Constraints of the CHP unit

The operation cost of the CHP unit which consists of maintenance and fuel costs are given by (5).

$$OCC_{s,t} = MCC_{s,t} + FCC_{s,t} \tag{5}$$

Equations (6) and (7) show the maintenance and Fuel cost functions of the CHP unit, respectively. In addition, costs of the CHP unit startup and shutdown states are expressed as (8) and (9), respectively. a and b are binary variables that show status of the CHP unit startup and shutdown states.

$$FCC_{s,t} = E_{s,t}^{CHP} \times \left(\frac{\lambda_t^{gas}}{HV \times \eta^{CHP}} \right) \tag{6}$$

$$MCC_{s,t} = E_{s,t}^{CHP} \times \kappa^{CHP} \tag{7}$$

$$STCC_t = SUCC \times a_t \tag{8}$$

$$SHCC_t = SDCC \times b_t \tag{9}$$

Equations (10) and (11) show the minimum and maximum ranges of the CHP unit outputs. In addition, it should be noted that the CHP unit electrical and thermal generations are dependent and could not be controlled separately. The CHP unit electrical and thermal generations cannot change too precipitately. Also, this can be formulated by (12) and (13), ramp-up and ramp-down constraints, respectively. In the following constraints is the binary variable which shows the CHP unit generation status. In other words, it equals to 1 for a CHP unit in the ON state and 0 otherwise.

$$E_{\min}^{CHP} \le E_{s,t}^{CHP} \le E_{\max}^{CHP} \tag{10}$$

$$H_{s,t}^{CHP} = E_{s,t}^{CHP} \times HPR \times \eta_{HE} \tag{11}$$

$$E_{s,t}^{CHP} - E_{s,t-1}^{CHP} \le i_{t-1} \times E^{Ramp-up} + a_t \times E_{min}^{CHP} \tag{12}$$

$$E_{s,t-1}^{CHP} - E_{s,t}^{CHP} \le i_t \times E^{Ramp-down} + b_t \times E_{min}^{CHP} \tag{13}$$

A.5. Constraints of the auxiliary boiler

The operation cost, fuel and Maintenance costs of the boiler are similar to CHP unit and are introduced by (14) - (16), respectively.

$$OCB_{s,t} = MCB_{s,t} + FCB_{s,t} \tag{14}$$

$$FCB_{s,t} = H_{s,t}^{boiler} \times \left(\frac{\lambda_t^{gas}}{HV \times \eta^{boiler}} \right) \tag{15}$$

$$MCB_{s,t} = H_{s,t}^{boiler} \times \kappa^{boiler} \tag{16}$$

Constraint (17) expresses the rate of the auxiliary boiler output.

$$H_{min}^{boiler} \le H_{s,t}^{Boiler} \le H_{max}^{boiler} \tag{17}$$

In the above equation H_{min}^{boiler} and H_{max}^{boiler} are the maximum and minimum ranges of the boiler output, respectively.

A.6. Electrical and thermal energy storage (EES and TES) systems constraints

Equations (18)-(21) indicate the constraints of the electrical and thermal storages. Storage transition function of the storages is shown in (18). Equation (19) indicates the limitation of the stored energy in the storages. Minimum and maximum charging/discharging capacity of the electrical and thermal energy storages are referred in (20) and (21), respectively. In the following constraints, $P_{Max/Min}^{E/H,ch/dch}$ and $\eta_{ch/dch}^{E/H}$ are maximum/minimum rates of the charging/discharging states and charging/discharging efficiency of the energy storages, respectively.

$$P_{s,t}^{E/H} = \left(P_{s,t-1}^{E/H} \times \eta^{E/H} \right) + \left(P_{s,t}^{E/H,ch} \times \eta_{ch}^{E/H} \right) - \left(P_{s,t}^{E/H.dch} / \eta_{dch}^{E/H} \right) \tag{18}$$

$$P_{Min}^{E/H} \le P_{s,t}^{E/H} \le P_{Max}^{E/H} \tag{19}$$

$$P_{Min}^{E/H,ch} \le P_{s,t}^{E/H.ch} \le P_{Max}^{E/H,ch} \tag{20}$$

$$P_{Min}^{E/H,dch} \le P_{s,t}^{E/H,dch} \le P_{Max}^{E/H,dch} \tag{21}$$

A.7. Local networks connection constraints

Costs of the imported electrical and thermal energies from the local networks are formulated as (22) and (23).

$$CE_{s,t} = E^{imp.}_{s,t} \times \lambda^{el,imp.}_{t} \tag{22}$$

$$RE_{s,t} = E^{Grid,\exp.}_{s,t} \times \lambda^{el,\exp.}_{t} \tag{23}$$

Equations (24) and (25) show revenues of the exported electrical and thermal energies to the local networks.

$$CH_{s,t} = H^{Grid,imp.}_{s,t} \times \lambda^{h,imp.}_{t} \tag{24}$$

$$RH_{s,t} = E^{Grid,\exp.}_{s,t} \times \lambda^{h,\exp.}_{t} \tag{25}$$

Constraints (26) - (28) define the ranges of the exported and imported electrical energy between REH and local network. Equation (28) prevents the REH from exporting and importing electricity to and from local network, simultaneously.

$$E^{Grid,imp.}_{s,t} \le m^{e}_{s,t} \times E^{Grid,imp.}_{Max} \tag{26}$$

$$E^{Grid,\exp.}_{s,t} \le n^{e}_{s,t} \times E^{Grid,\exp.}_{Max} \tag{27}$$

$$m^{e}_{s,t} + n^{e}_{s,t} \le 1 \tag{28}$$

In the above equations, E^{Grid}_{Max} shows electrical network capacity. The binary variables, $m^{e}\$and\mathrm{n}^{e}$, show imported and exported electrical and thermal energies status, respectively.

The capacity limitations of the exported and imported thermal energy between REH and local networks are formulated as (29) and (30). Similar to electricity, (31) prevents the REH from exporting and importing thermal energy to and from local network, simultaneously. The binary variables, m^h and n^h, show imported and exported thermal energy states, respectively.

$$H^{Grid,imp.}_{s,t} \le m^{h}_{s,t} \times H^{Grid,imp.}_{Max} \tag{29}$$

$$H^{Grid,exp.}_{s,t} \le n^{h}_{s,t} \times H^{Grid,exp.}_{Max} \tag{30}$$

$$m^{h}_{s,t} + n^{h}_{s,t} \le 1 \tag{31}$$

In the above equations, H^{Grid}_{Max} shows thermal network capacity.

A.8. Penalty cost

The penalty cost of curtailed loads is formulated by (32) based on value of loss loads ($VOLLs$).

$$PC_{s,t} = EL_{s,t} \times VOLL^{E} + HL_{s,t} \times VOLL^{H} \tag{32}$$

A.9. Power balancing constraints

In the REH system the generated electrical and thermal energies by the REH equipment and the energies which are supplied by the local networks must satisfy the demands in each time blocks of the REH scheduling horizon. This can be formulated by (33) and (34). It should be noted that, EL and HL are curtailed electrical and thermal demands.

$$D^{E}_{s,t} - EL_{s,t} \le E^{CHP}_{s,t} + E^{Grid,imp.}_{s,t} - E^{Grid,\exp.}_{s,t} + P^{E,ch}_{s,t} - P^{E,dch}_{s,t} + P^{wind}_{s,t} \tag{33}$$

$$D^{H}_{s,t} - HL_{s,t} \le H^{CHP}_{s,t} + H^{boiler}_{s,t} + P^{H,ch}_{s,t} - P^{H,dch}_{s,t} H^{Grid,imp.}_{s,t} - H^{Grid,\exp.}_{s,t} \tag{34}$$

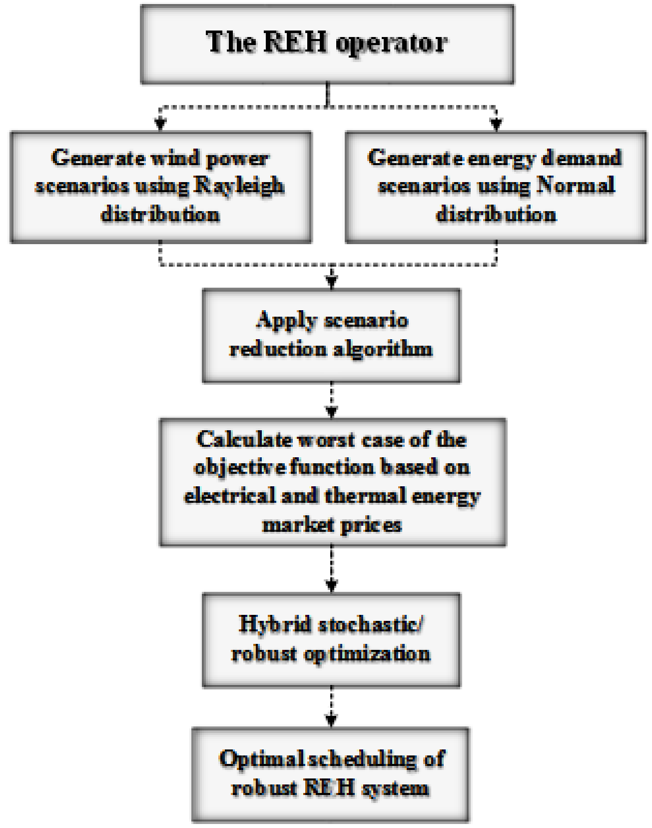

Fig. 2. Schematic flow chart of the proposed HSR optimization method.

B. Hybrid stochastic/robust (HSR) optimization

As it is mentioned, it is necessary to schedule large scale energy systems operation with minimum computational burden. In this paper a hybrid stochastic/robust (HSR) method is presented to find a minimum operation cost. The proposed HSR is different from pure stochastic optimization mode. On one hand, since the computational volume is related to number of the scenarios, the computational burden is increased by adding a more uncertainty. in the proposed HSR method, the error between the forecasted and practical amount of the uncertainties are modeled by robust optimization [35]. Moreover, by applying the HSR optimization model, the REH decision maker can take a robust strategy to face with uncertain energy price to immune the REH against high operation costs.

In proposed HSR method, electrical, thermal energies and wind power generation uncertainties are modeled by three sets of possible scenarios and the robust method is used to model the electrical and thermal energies' market prices. First of all, the REH scheduling problem is solved by pure stochastic optimization based on worst case of objective function, after that, robust methodology is applied to problem to find a robust solution for the REH system against the electricity and thermal energy prices. Finally, the result, which is taken from the proposed method, is an optimal scheduling of the robust REH system. Figure 2 shows the schematic flow chart of the proposed hybrid optimization model.

It should be noted that, the proposed robust model is related to performance the system, which it makes the REH operation cost robust against high electrical and thermal prices. The uncertainties that are modeled in the proposed system are parametric uncertainties.

In the robust optimization, the REH problem is solved by considering the worst case of electrical and thermal prices. Also, the uncertainties related to wind generation and demands are accounted by stochastic approach. Therefore, the REH objective function is rewritten according to (35).

$$\min Z = \sum_{t=1}^{T}\sum_{s=1}^{S}\left\{\left(\begin{array}{l} OCC_{s,t} + OCB_{s,t} + PC_{s,t}) + STCC_t + SHCC_t + \\ Max \sum_{t=1}^{T}\sum_{s=1}^{S} \quad (\lambda_t^{el,imp} E_{s,t}^{Grid,imp.} - \lambda_t^{el,imp} E_{s,t}^{Grid,\exp}) \\ \quad +(\lambda_t^{h,imp.} H_{s,t}^{Grid,imp.} - \lambda_t^{h,\exp} H_{s,t}^{Grid,\exp}) \end{array}\right)\right\} \tag{35}$$

The worst case condition of thermal and electrical prices can be divided into four parts. The first part is deviations in upper bounds of the interval when importing energy from the local network. In addition, the deviations in lower bounds of the interval when exporting energy to local network is modeled by second part. The deviations in lower bounds and upper bound of thermal prices are accounted the same of electrical price deviations. The worst case of objective function shown in (35) can be reformulation as (36).

$$\left(\begin{array}{l} Max \sum_{t=1}^{T}\sum_{s=1}^{S} \begin{array}{l} (\bar{\lambda}_t^{el,imp} + z_{t,s}^{el,imp}\hat{\lambda}_t^{el,imp})E_{s,t}^{Grid,imp.} \\ -(\bar{\lambda}_t^{el,\exp} + z_{t,s}^{el,\exp}\hat{\lambda}_t^{el,\exp})E_{s,t}^{Grid,\exp}) + \\ ((\bar{\lambda}_t^{h,imp} + z_{t,s}^{h,imp}\hat{\lambda}_t^{h,imp})H_{s,t}^{Grid,imp.} \\ -(\bar{\lambda}_t^{h,\exp} + z_{t,s}^{h,\exp}\hat{\lambda}_t^{h,\exp})H_{s,t}^{Grid,\exp}) \end{array}\end{array}\right) \tag{36}$$

Subject to:

$$0 \le z_{buy}^{el,t,s} \le 1 \quad \forall t,s \quad : \xi_1^{el,t,s} \tag{37}$$

$$0 \le z_{sell}^{el,t,s} \le 1 \quad \forall t,s \quad : \xi_2^{el,t,s} \tag{38}$$

$$0 \le z_{buy}^{th,t,s} \le 1 \quad \forall t,s \quad : \xi_1^{th,t,s} \tag{39}$$

$$0 \le z_{sell}^{th,t,s} \le 1 \quad \forall t,s \quad : \xi_2^{th,t,s} \tag{40}$$

$$\sum_{t=1}^{T} z_{buy}^{el,t,s} + z_{sell}^{el,t,s} \le \Gamma_{el}^{s} \quad : \beta_{el}^{s} \tag{41}$$

$$\sum_{t=1}^{T} z_{buy}^{th,t,s} + z_{sell}^{th,t,s} \le \Gamma_{th}^{s} \quad : \beta_{th}^{s} \tag{42}$$

The Karush Kuhn Tucker (KKT) condition is applied in order to reach the robust problem. The dual of optimization problem (36) is formulated as follows:

$$\left(\mathrm{Min}\Gamma_s^{el}\beta_s^{el} + \Gamma_s^{h}\beta_s^{h} + \sum_{t=1}^{T}\sum_{s=1}^{S}\left(\xi_1^{el,t,s} + \xi_2^{el,t,s} + \xi_1^{h,t,s} + \xi_2^{h,t,s}\right)\right) \tag{43}$$

Subject to:

$$\xi_1^{el,t,s} + \beta_{el}^{s} \ge \hat{\lambda}_{buy}^{el,t,s} E_{s,t}^{imp.} \tag{44}$$

$$\xi_2^{el,t,s} + \beta_{el}^{s} \ge \hat{\lambda}_{sell}^{el,t,s} E_{s,t}^{exp.} \tag{45}$$

$$\xi_1^{th,t,s} + \beta_{th}^{s} \ge \hat{\lambda}_{t,buy}^{h,imp.,s} H_{s,t}^{Grid,imp.} \tag{46}$$

$$\xi_2^{th,t,s} + \beta_{th}^{s} \ge \hat{\lambda}_{t,sell}^{h,exp,s} H_{s,t}^{Grid,\exp.} \tag{47}$$

$$\xi_1^{el,t,s}, \xi_2^{el,t,s}, \xi_1^{th,t,s}, \xi_2^{th,t,s}, \beta_{th}^{s}, \beta_{el}^{s} \ge 0 \tag{48}$$

Single level objective function can be obtained by replacing (36) with the equivalent objective function (43) in (35).

Table 1. Characteristics of the CHP unit.

Capacity (kW)	Maintenance cost ($/kWh)	Startup/ shutdown cost ($)	Elec./ther. conversion efficiency (%)	Elec./ther. ramp-up/ramp-down (kW/h)
4000	0.039	55/55	40%/45%	800/900

Table 2. Characteristics of the auxiliary boiler.

Capacity (kW)	Maintenance cost ($/kWh)	Startup/ shutdown cost ($)	Efficiency (%)
2400	0.275	18	75

Table 3. Specifications of the electrical and thermal energy storages.

Type	Maximum charging/dischargingrange (kW)	Maximum energy(kWh)	Charging/ discharging efficiency	Stand by efficiency
Electrical	500	2000	0.95	0.98
Thermal	300	1000	0.90	0.95

3. CASE STUDY, RESULTS AND DISCUSSIONS

The stochastic nature of electrical demands, thermal demands, wind generation, energy prices and computational burden related to the uncertainties modeled by stochastic method make a challenge for the optimal scheduling of the various components of the multi carrier energy. By taking this challenge, in this work the electrical demands, thermal demands and wind power generation are modeled by three sets of possible scenarios while the robust optimization method is applied for modeling exported and imported electricity and thermal energy prices' uncertainty in the optimal scheduling of the REH.

A. Assumptions

The characteristics of the CHP unit and auxiliary boiler are given in Table 1 and Table 2, respectively. Table 3 shows the electrical and thermal energy storages specifications. The $VOLLs$ for electrical and thermal demands are assumed to be 5 $/kWh and 3 $/kWh, respectively.The capacity of the wind power generation is considered 750 kW. In addition, the wind turbine parameters can be taken from [36]. The base values of the electrical and thermal demands are chosen 1800 kW and 3000 kW, respectively. Also, electrical and thermal demands variations in 24 hours of a typical day are provided in Fig. 3. The probabilities of the scenarios after implemented SCENRED algorithm are given in the Table 4. The base values of the electricity, natural gas and thermal energy are assumed 0.2 $/kWh, 0.1 $/kWh and 0.4 $/kWh, respectively and the Fig. 4 provides the variations of electricity, thermal energy and natural gas prices in 24 hours of a day. It should be mentioned that the exported prices of electrical and thermal energies to the local networks, $\lambda^{el,\exp.}$ and $\lambda^{h,\exp.}$, are considered $1.5\lambda^{el,imp.}$ and $1.2 * \lambda^{h,imp.}$, respectively. Finally, the proposed problem is handled by using the GAMS environment [37].

B. Results and discussions

Two case studies are considered to assess the effectiveness of the proposed model. The results of the case study I and II are analyzed based on amount of imported and exported electrical and thermal energies, generations of the CHP unit and total operation cost.

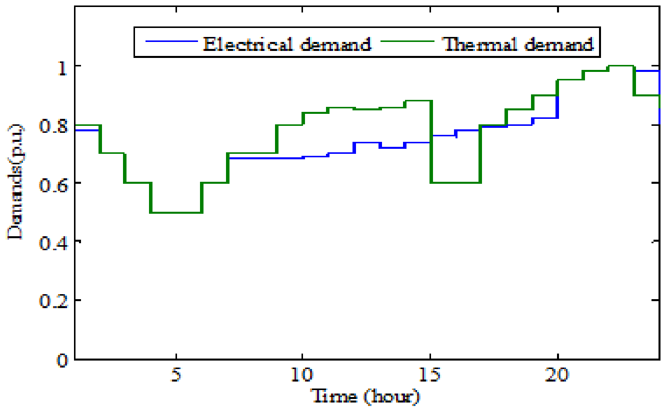

Fig. 3. The variations of the electrical and thermal demands.

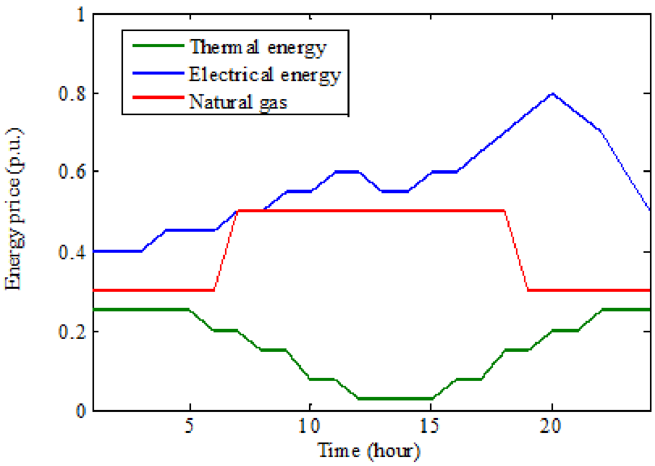

Fig. 4. The variations of the electricity, thermal energy and natural gas prices.

Table 4. Probability of each reduced scenarios.

Scenario	1	2	3	4	5
Probability	0.043	0.055	0.242	0.157	0.100
Scenario	6	7	8	9	10
Probability	0.085	0.060	0.070	0.096	0.092

Case study I: Applying the proposed HSR method on the REH scheduling with possibility of exchanging thermal energy with the local energy network.

Case study II: Applying the proposed HSR method on the REH scheduling without possibility of exchanging thermal energy.

By solving the REH scheduling problem based on the proposed HSR method, the results of the optimum robust function for $\Gamma^{E/H} = 2$ are shown in Table 5. As it is shown in Table 5, the total operation cost, exported and imported electrical/thermal energy that are achieved from implementing proposed HSR method on the REH optimal scheduling are reported and analyzed. It is obviously from Table 5, REH total operation cost of the CASE study II is reduced from 4961.58$ to 4277.92$ in comparison with case study I, a reduction by about 14%. When

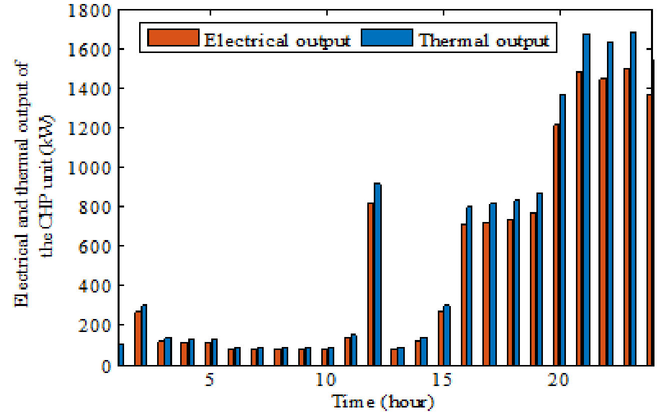

Fig. 5. Expected outputs of the CHP unit for $\Gamma^{E/H} = 5$.

the REH is isolated from thermal energy market (case study I), CHP unit is working on maximum generation capacity to supply thermal demands.

The deterministic, pure stochastic and the proposed HSR methods are implemented on the REH system for case study II to compare with previous methods and show the appropriateness and practicality of the proposed hybrid methodology. As it is clear from Table 6, the operation cost of the deterministic optimization is 3492.21$, that is lower than two other methods, but the uncertainty and unpredictability effects of the wind generation, electrical and thermal demands, electricity and thermal energy market prices are not considered, also this solution cannot model the practical systems. In addition, the pure stochastic optimization models the uncertain parameters, but cannot guarantee robustness of the proposed REH system against high operation costs which are related to energy market prices. Also, the pure stochastic method cannot provide a robust solution for the system. On the other hand, the proposed hybrid method satisfies both goals. In other words, it models the several uncertainties and guarantees the robustness of the REH system against high operation costs with a lower computational burden in comparison with pure stochastic method.

The operation of the auxiliary boiler and CHP unit in the scheduling horizon of optimization problem for $\Gamma^{E/H} = 5$ are presented in in Fig. 5 and Fig. 6, respectively. As it is clear from Fig. 5 the optimal scheduling of the CHP unit follows the energy demands and prices' deviations. For example, during hours 13-16 the electricity price and electrical demand start to decrease, so, the output of the CHP unit decreases. Furthermore, output of the boiler decreases during hours 15-17 because of decreasing the thermal demand in the mentioned hours.

Figure 7 points out the impact of robust budgets on robustness of the objective function. According to this figure can be concluded that the optimal cost is increased by increasing the robust budget and present of price deviation.

Furthermore, as it is clear from problem formulation section, the power generated by wind turbine has a positive effect on the benefits of the REH system. This fact is clear from Fig. 8. In other words, total operation cost of the REH decreases with increasing of the wind generation.

4. CONCLUSION

In this paper, a HSR strategy is proposed for optimal scheduling of the REH based on Hybrid stochastic/robust optimization

Table 5. The results of the proposed HSR method.

Case study type	Total operation cost ($)	Imported electrical energy (kW)	Exported electrical energy (kW)	Imported thermal energy (kW)	Exported thermal energy (kW)	Electrical output of the CHP (kW)	Thermal output of the CHP (kW)
Case study I	4961.58	3264.32	1864.37	-	-	13337.09	15004.23
Case study II	4277.92	6724.86	3928.68	10201.62	3968.75	12184.66	13707.74

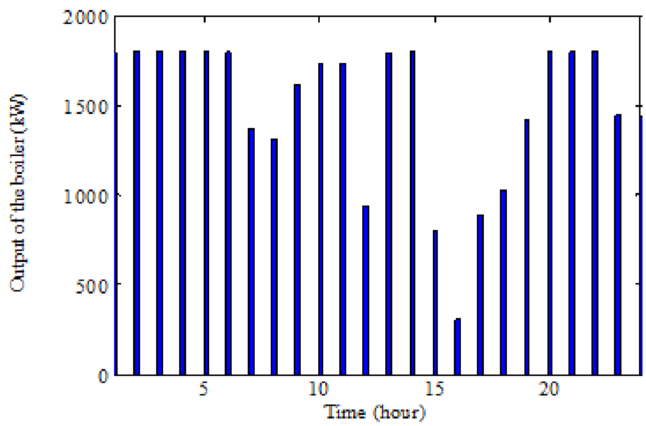

Fig. 6. Expected output of the boiler for $\Gamma^{E/H} = 5$.

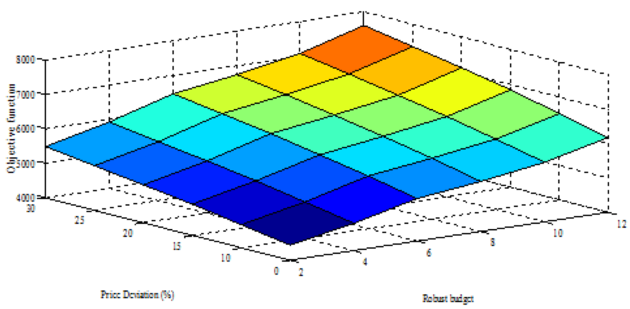

Fig. 7. Impact of robust budgets on robustness of the objective function.

Table 6. Operation costs of the different optimization methods for case study II.

Optimization method	Deterministic	Stochastic	HSR
Operation cost ($)	3492.21	3562.70	4351.43

methodology. The uncertainties related to electrical demands, thermal demands and wind power generation are modeled via scenario based stochastic method, while the robust optimization methodology is applied to gain robust solution which is feasible for all values of uncertainties. By implementing the proposed hybrid method, the proposed REH can follow a robust scheduling strategy to face with uncertain energy price while, the computational burden of the optimization problem decreased significantly in comparison with pure stochastic model.

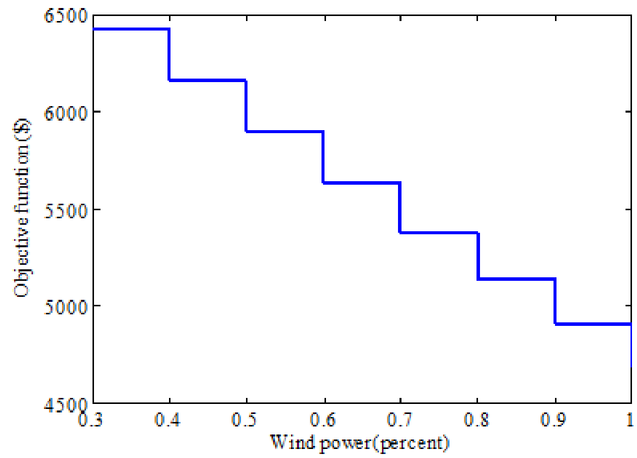

Fig. 8. Sensitivity of the objective function to wind turbine generation.

In addition, participation on the thermal energy market beside the electricity market can bring more benefits and caused a reduction in the total costs of the system and operation costs of the components. Comparisons of the results show the CHP unit work on maximum capacity in isolated mode (case study I) to supply the demands which it causes a high operation cost for CHP and REH system. In comparison with previous methods, the proposed HSR methodology models the several uncertainties and guarantees the robustness of the REH system against high operation costs. Finally, by applying the proposed method for scheduling problem of the REH system with capability of participation on various energy markets, the appropriateness and practicality of the proposed hybrid methodology is verified by the numerical results that are obtained from studied cases. As it is clear from the results, operation cost of the proposed REH with possibility of exchanging thermal energy with local network is reduced by about 14% in comparison with isolated REH from thermal energy network.

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