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Opportunistic Info-Gap Approach for Optimization of Electrical and Heating Loads in Multi-Energy Systems in the Presence of a Demand Response Program

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***Abstract*—There are significant changes occurring both in the electricity system and the natural gas system. These two energy carries can be combined to form what is known as an energy hub. These energy hubs can play a significant role in the energy system and thus understanding of their optimization, especially their costs, is important. This paper proposes a risk management framework for an energy-hub through the utilization of the information-gap decision theory (IGDT). The uncertainties introduced from the various load profiles, such as the electric and heating loads, are considered in this risk management framework. The modeled energy-hub consists of several distributed generation systems such as a micro-combined heat and power (μCHP), electric heat pump (EHP), electric heater (EH), absorption chiller (AC) and an energy storage system (ESS). A demand response (DR) program is also considered to shift a percentage of electric load away from the peak period to minimize the operational cost of the hub. A feasible test system is also applied to demonstrate the proposed model's effectiveness.**

***Keywords*—Demand response, energy-hub, Info-gap Theory, distributed generation system, risk management, uncertainty.**

NOMENCLATURE

Superscripts

EHP	Electric heat pump
μCHP	Micro combined heat and power
AC	Absorption chiller
EH	Electric heater
BO	Boiler
ESS	Energy storage system
Ch./Dis.	Charging/Discharging mode of ESS
NG	Natural gas from the grid
PG	Electricity power from the grid

Subscripts and indices

s	Season
t	Time horizon
c/h	Cooling/heating

Parameters and variables

OC_0	The deterministic minimum cost of energy-hub
OC	The operation cost of each entity
$\lambda^{NG} / \lambda^{PG}_t$	The natural gas/ electricity price
$G^{NG}_{s,t}$	The bought natural gas from the gas grid
$P^{PG}_{s,t}$	The amount of electricity bought or sold from or to the grid
$C^{EHP}_{s,t} / H^{EHP}_{s,t}$	The cooling/heating generation of EHP
$P^{\mu CHP}_{s,t} / H^{\mu CHP}_{s,t}$	The electricity/ heating generation of μCHP
$C^{AC}_{s,t}$	The cooling generation of AC
η^{AC}	The cooling conversion ratio of AC
$E^{ESS}_{s,t}$	The energy level of ESS
$P^{ESS,ch.}_{s,t} / P^{ESS,dis.}_{s,t}$	The charge/discharge amount of ESS
$\eta^{ESS}_{ch.} / \eta^{ESS}_{dis.}$	The charge/discharge ratio of ESS
$b^{ESS,ch.}_{s,t} / b^{ESS,dis.}_{s,t}$	Binary variables for charge/discharge mode of ESS
$P^{DR}_{s,t}$	The load after implementation of DR program
$idr_{s,t}$	The shifted amount of demand
$TOU_{s,t}$	The movable amount of load in TOU program
$P^{load}_{s,t} / H^{load}_{s,t} / C^{load}_{s,t}$	The initial electric, heating and cooling loads

I. INTRODUCTION

The transition to sustainable energy to meet the needs of the human race is one of the most important challenges facing the world. As fossil fueled power plants generally have large drawbacks related to efficiency, costs and pollution, it is not reasonable to rely on them as the main source of energy.

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In addition, the management and operation of energy systems dependent on a single energy carrier are more costly relative to multi-energy systems. The growth and development of distributed energy systems such as combined heat and power (CHP), electric heat pump (EHP) also makes transferring from the single energy systems to multi-energy systems much easier. Multi-energy systems rely on various energy carriers such as electricity, natural gas, heating and cooling vectors. The operator of this system is responsible for managing these various energy carriers to optimize their performance to minimize operational costs [1].

There are several papers which have analyzed recent developments in multi-energy systems and energy-hubs. For instance, a comprehensive review on the various models and the concept of the energy-hub has been done in [2] in order to introduce different inputs, outputs and internal units and entities in the energy-hub. Additionally, several papers have also focused on the performance and management of the energy-hub. The authors in [3] proposed an optimal bidding strategy for the energy-hub which is participating in the energy markets. The uncertainty of the market price is also managed without consideration of the uncertainty of the load. Energy Storage Systems (ESS) can also form part of an energy-hub and can provide a percentage of the electrical energy of required by the hub [4], [5]. Thus, consideration of an ESS provides the capability to reduce the operational cost of the energy hub. Another key factor is the utilization of demand response (DR) programs in multi-energy systems [6]. Integration of various forms of energy in the energy-hub can provide increase consumer's participation in DR programs and improve the performance of the energy-hub [7].

The management and optimization of energy-hubs is an emerging and interesting topic of research. A stochastic optimization approach has been proposed in [8]. The uncertainty of the wind generation and energy demand are be managed through the conditional value-at-risk method. A hybrid stochastic-information-gap decision theory (IGDT) method has been employed to evaluate the scheduling and management of the energy- hub with the aim of minimizing the expected operation cost of energy hub in [9]. However, the IGDT function only handles the market price uncertainty market prices and not those from the load.

The main contribution of this paper is to propose an opportunistic risk management procedure applied to an energy hub that consists a micro-CHP, EHP, electrical heater (EH), boiler (BO), absorption chiller (AC) and an ESS. For this purpose, two uncertain parameters relating to the consumers are taken into account, which are the electrical and heating loads. A time-of-use (TOU) DR program is also included to shift a percentage of the electrical load from the peak period to off-peak period to minimize the operation costs of both the assets and the energy hub. The opportunistic approach is better suited to risk-seeking decision makers who want to explore the benefits of favorable deviations in the forecasted uncertain parameter such that costs are further reduced.

The paper organization as follows, Section II introduces and explains the proposed model. Then, the simulation results and discussion are provided in Section III. Finally, the most important findings are presented in the Section IV.

II. THE PROPOSED MODEL

The proposed energy hub is supplied by the power grid and the natural gas network. Therefore, there are two inputs for the multi-energy system. The energy-hub has the capability to buy natural gas from the gas network and buy or sell electricity from or to the power grid.

Therefore, the electricity flow is bidirectional in the grid side of the energy-hub. There are three outputs are included for consumers to meet their electrical, heating and cooling demands. Inside the multi-energy system, several entities have been considered with the aim to optimize their operation to minimize the operation cost of the energy-hub.

The units considered in the energy-hub are as follow: an EHP, a micro-CHP (μCHP) system, an AC, a BO, an EH and an ESS. Some of these units consume natural gas only such as μCHP, AC and boiler. The EHP, EH and ESS units use electricity. To meet the demands, the AC unit can meet the cooling demand of the consumers, the BO and EH are responsible for meeting the heating demand and the μCHP system can supply both electrical and heating demands for the consumers. The EHP unit is also addressing the heating and cooling loads. Finally, the energy hub can charge or discharge the ESS.

This model of the multi-energy system is presented in two parts. Firstly, a deterministic model is presented which assumes no uncertainty in the system and the optimization problem is to find the minimum cost of the multi-energy system. Then, the uncertainty will be taken into account in the second part. In this stage, the IGDT opportunity approach is implemented to the model.

A. Deterministic stage

As mentioned above, in this stage it is assumed that there is no uncertainty and all data are forecasted accurately. The problem formulation of this stage is written as follows:

$$min$$

$$OC_0 = \sum_{s=1}^{S}\sum_{t=0}^{T}\begin{pmatrix} OC_{s,t}^{EHP} + OC_{s,t}^{\mu CHP} + OC_{s,t}^{AC} + \\ OC_{s,t}^{BO} + OC_{s,t}^{EH} + \\ \lambda^{NG} G_{s,t}^{NG} + \lambda_t^{PG} P_{s,t}^{PG} \end{pmatrix} \quad (1)$$

$$s.t:$$

$$OC_{s,t}^{EHP} = x^{EHP}(H_{s,t}^{EHP} + C_{s,t}^{EHP})^2 + \\ y^{EHP}(H_{s,t}^{EHP} + C_{s,t}^{EHP}) + z^{EHP} \quad (2)$$

$$C_{s,t}^{EHP} = \eta^{EHP,c} P_{s,t} \quad (3)$$

$$H_{s,t}^{EHP} = \eta^{EHP,h} P_{s,t} \quad (4)$$

$$C^{EHP,\min} b_{s,t}^{EHP,c} \le C_{s,t}^{EHP} \le C^{EHP,Max} b_{s,t}^{EHP,c} \quad (5)$$

$$H^{EHP,\min} b_{s,t}^{EHP,h} \le H_{s,t}^{EHP} \le H^{EHP,Max} b_{s,t}^{EHP,h} \quad (6)$$

$$b_{s,t}^{EHP,c} + b_{s,t}^{EHP,h} \le 1 \quad (7)$$

$$OC_{s,t}^{\mu CHP} = u^{\mu CHP}(P_{s,t}^{\mu CHP})^2 + v^{\mu CHP}(P_{s,t}^{\mu CHP}) \\ w^{\mu CHP}(H_{s,t}^{\mu CHP})^2 + x^{\mu CHP}(H_{s,t}^{\mu CHP}) \\ y^{\mu CHP}(P_{s,t}^{\mu CHP})(H_{s,t}^{\mu CHP}) + z^{\mu CHP} \quad (8)$$

$$P_{s,t}^{\mu CHP} - P_{x}^{\mu CHP} - \left(\frac{P_{x}^{\mu CHP} - P_{y}^{\mu CHP}}{H_{x}^{\mu CHP} - H_{y}^{\mu CHP}} \right) \left(H_{s,t}^{\mu CHP} - H_{x}^{\mu CHP} \right) \leq 0 \tag{9}$$

$$P_{s,t}^{\mu CHP} - P_{y}^{\mu CHP} - \left(\frac{P_{y}^{\mu CHP} - P_{z}^{\mu CHP}}{H_{y}^{\mu CHP} - H_{z}^{\mu CHP}} \right) \left(H_{s,t}^{\mu CHP} - H_{y}^{\mu CHP} \right) \geq -M(1 - b_{s,t}^{\mu CHP}) \tag{10}$$

$$P_{s,t}^{\mu CHP} - P_{z}^{\mu CHP} - \left(\frac{P_{z}^{\mu CHP} - P_{u}^{\mu CHP}}{H_{z}^{\mu CHP} - H_{u}^{\mu CHP}} \right) \left(H_{s,t}^{\mu CHP} - H_{z}^{\mu CHP} \right) \geq -M(1 - b_{s,t}^{\mu CHP}) \tag{11}$$

$$P_{z}^{\mu CHP} b_{s,t}^{\mu CHP} \leq P_{s,t}^{\mu CHP} \leq P_{x}^{\mu CHP} b_{s,t}^{\mu CHP} \tag{12}$$

$$0 \leq H_{s,t}^{\mu CHP} \leq H_{y}^{\mu CHP} b_{s,t}^{\mu CHP} \tag{13}$$

$$OC_{s,t}^{AC} = y^{AC}(C_{s,t}^{AC}) + z^{AC} \tag{14}$$

$$C^{AC,\min} b_{s,t}^{AC} \leq C_{s,t}^{AC} \leq C^{AC,Max} b_{s,t}^{AC} \tag{15}$$

$$C_{s,t}^{AC} = \eta^{AC} P_{s,t} \tag{16}$$

$$OC_{s,t}^{BO} = y^{BO}(H_{s,t}^{BO}) + z^{BO} \tag{17}$$

$$H^{BO,\min} b_{s,t}^{BO} \leq H_{s,t}^{BO} \leq H^{BO,Max} b_{s,t}^{BO} \tag{18}$$

$$OC_{s,t}^{EH} = y^{EH}(H_{s,t}^{EH}) + z^{EH} \tag{19}$$

$$0 \leq H_{s,t}^{EH} \leq H^{EH,Max} b_{s,t}^{EH} \tag{20}$$

$$H_{s,t}^{EH} = \eta^{EH} P_{s,t} \tag{21}$$

$$E_{s,t}^{ESS} = E_{s,(t-1)}^{ESS} + \left(P_{s,t}^{ESS,ch.} \eta_{ch.}^{ESS} \right) - \left(\frac{P_{s,t}^{ESS,dis.}}{\eta_{dis.}^{ESS}} \right) \tag{22}$$

$$E^{ESS,\min} \leq E_{s,t}^{ESS} \leq E^{ESS,Max} \tag{23}$$

$$0 \leq P_{s,t}^{ESS,ch.} \leq P_{ch.}^{ESS,Max} b_{s,t}^{ESS,ch.} \tag{24}$$

$$0 \leq P_{s,t}^{ESS,dis.} \leq P_{dis.}^{ESS,Max} b_{s,t}^{ESS,dis.} \tag{25}$$

$$b_{s,t}^{ESS,ch.} + b_{s,t}^{ESS,dis.} \leq 1 \tag{26}$$

$$E_{s,t=T}^{ESS} = E_{s,t=1}^{ESS} \tag{27}$$

$$E_{s,t=1}^{ESS} = \alpha^{ESS} E^{ESS,Max} \tag{28}$$

$$P_{s,t}^{DR} = P_{s,t}^{Load} + idr_{s,t} \tag{29}$$

$$idr_{s,t} = TOU_{s,t} P_{s,t}^{Load} \tag{30}$$

$$\sum_{t=0}^{T} idr_{s,t} = 0 \tag{31}$$

$$TOU^{\min} \leq TOU_{s,t} \leq TOU^{Max} \tag{32}$$

$$0 \leq P_{s,t}^{G2H} \leq P^{PG} b_{s,t}^{G2H} \tag{33}$$

$$0 \leq P_{s,t}^{H2G} \leq P^{PG} b_{s,t}^{H2G} \tag{34}$$

$$b_{s,t}^{G2H} + b_{s,t}^{H2G} \leq 1 \tag{35}$$

$$P_{s,t}^{DR} = P_{s,t}^{G2H} + P_{s,t}^{\mu CHP} + P_{s,t}^{ESS,ch.} - P_{s,t}^{ESS,dis.} \tag{36}$$

$$H_{s,t}^{load} = H_{s,t}^{EHP,h} + H_{s,t}^{\mu CHP} + H_{s,t}^{BO} + H_{s,t}^{EH} \tag{37}$$

$$C_{s,t}^{load} = C_{s,t}^{EHP,c} + C_{s,t}^{AC} \tag{38}$$

The objective function is formulated in equation (1). As stated before, the objective of the deterministic problem is to minimize the cost of the energy-hub through optimizing its performance. The objective function includes the cost of each unit operating in the multi-energy system such as the µCHP, EHP, AC, EH, BO, and ESS. The last two terms of (1) are the cost for the amount of natural gas that is being purchased from the gas network and the amount of power that is bought from the power grid. The last term of (1), $P_{s,t}^{PG}$ is a variable which can be positive or negative. If the energy-hub buys from the grid it will be a positive value. In the other hand, if the energy-hub sells to the grid it will be a negative value which means revenue for the energy-hub.

The constraints of this deterministic stage are given in (2) – (38). The constraints of the EHP unit are presented in (2) – (7). Constraint (2) is a quadratic function for the calculation of the operations cost of EHP which *x, y*, and *z* are the EHP operation coefficients. The heating and cooling conversion constraints of the EHP are stated in (3) and (4), respectively. Then, the cooling and heating generation limits of the EHP are considered through (5) and (6). However, the EHP unit cannot generate heating and cooling at the same time which is expressed in (7). The constraints for the µCHP unit are presented in (8) – (13). The operation cost of µCHP can be calculated through (8) [10]. The feasible region of the MCHP operation is governed by (9) – (11). The limit of generated power of the MCHP is expressed in (12). Similarly, the heating generated by should be within the µCHP's capacity, as stated in (13).

The AC unit's operation cost is given in (14). The cooling from the chiller is bounded by equation (15). Moreover, the cooling conversion constraint of AC unit is evaluated by (16). The operations cost of the boiler unit for supplying the heating demand is considered in (17). The BO's heating generation is bounded by its minimum capacity, i.e., $H^{BO,min}$ and its maximum generation capacity, i.e., $H^{BO,Max}$. Equations (19) – (21) are related to the EH unit. The operation costs are shown in (19), its generation limits are shown in (20) and the amount of heating generation is related to η^{EH}, which is the heating conversion ratio of the EH unit.

The ESS's constraints are shown in (22) – (28) as developed in [11]. The amount of energy in the ESS in season *s* and time *t* is calculated by (22). The energy level of ESS has to be within its capacity limits which are shown in (23). The amount of charging power of the ESS is denoted by $P_{s,t}^{ESS,ch.}$ which is limited by (24). Similarly, the amount of discharging power of ESS unit is denoted by $P_{s,t}^{ESS,dis.}$ and limited by (25). Equation (26) shows that the ESS cannot charge or discharge at the same time. The energy level of the ESS is assumed to be same at the first hour of time horizon and at the last hour shown in (27). The initial amount of energy of the ESS has a direct relation with the maximum capacity of the ESS that is indicated by (28).

A time-of-use (TOU) program is applied in this paper to shift the electrical demand from peak period to off-peak period. The constraints of this DR program is defined by (29) – (32) [12]. In (29), $P_{s,t}^{DR}$ denotes the amount of electrical load after the DR program employment which is calculated from the amount of initial load and the amount of shifted load due to the TOU program. The amount of the shifted load is calculated by (30) which is a percentage of the movable amount of the initial load on that time horizon, i.e., $TOU_{s,t}$ multiplied by $P^{load}_{s,t}$. It should be noted that it is assumed that the total amount of the shifted electrical load over the considered period is equal to zero. Moreover, the movable amount of the initial load by the implementation of TOU program is limited by the maximum and minimum of the load that can be shifted during the studied period.

The energy transactions between the power grid and the energy-hub are given in (33) – (35). The amount of power which is bought from the grid by the energy-hub is denoted by $P^{G2H}_{s,t}$. On the other hand, the amount of energy which is sold by the energy-hub to the grid is denoted by $P^{H2G}_{s,t}$. According to the assumptions in this model, i.e., (35), the energy-hub cannot import or export energy simultaneously. Finally, the energy balance constraints are indicated by (36) – (38). Electric load can be supplied through the power grid, or the μCHP and the ESS units. The heating load also can be supplied by the EHP, μCHP, BO, and EH units. The cooling load also has to be supplied by the EHP and AC units.

B. IGDT-based opportunity stage

The uncertainty is considered in this stage as the forecasts of loads do not always match the actual loads and this may increase costs of the energy hub. This behavior can be studied through the opportunity IGDT approach [13]. The IGDT approach for uncertainty management is applied and its problem formulation is written as follows:

$$min\ \beta \tag{39}$$

s.t.

$$OC^* \le OC_\omega = (1-\sigma)OC_0 \tag{40}$$

$$OC^* = \min\left\{\sum_{s=1}^{S}\sum_{t=0}^{T}\begin{pmatrix} OC^{EHP}_{s,t}+OC^{\mu CHP}_{s,t}+OC^{AC}_{s,t}+ \\ OC^{BO}_{s,t}+OC^{EH}_{s,t}+ \\ \lambda^{NG}G^{NG}_{s,t}+\lambda^{PG}_{t}P^{PG}_{s,t} \end{pmatrix}\right\} \tag{41}$$

$$(1-\beta)\tilde{P}^{load}_{s,t} \le P^{load}_{s,t} \le (1+\beta)\tilde{P}^{load}_{s,t} \tag{42}$$

$$(1-\beta)\tilde{H}^{load}_{s,t} \le H^{load}_{s,t} \le (1+\beta)\tilde{H}^{load}_{s,t} \tag{43}$$

$$(2)-(38) \tag{44}$$

where OC_ω is the target cost of the energy-hub if the electrical and heating loads deviate favorably. The target cost is usually lower than the deterministic minimum cost of the energy-hub, i.e., OC_0. According to the problem formulation in (39) – (44), the minimum uncertainty, i.e., β, will occur if $P^{load}_{s,t} = (1-\beta)\tilde{P}^{load}_{s,t}$ and $H^{load}_{s,t} = (1-\beta)\tilde{H}^{load}_{s,t}$. Thus, in the above problem formulation, equations (42) and (44) could be replaced by a single level problem formulation as follows:

$$min\ \beta \tag{45}$$

s.t.

$$OC^* = \sum_{s=1}^{S}\sum_{t=0}^{T}\begin{pmatrix} OC^{EHP}_{s,t}+OC^{\mu CHP}_{s,t}+OC^{AC}_{s,t}+ \\ OC^{BO}_{s,t}+OC^{EH}_{s,t}+ \\ \lambda^{NG}G^{NG}_{s,t}+\lambda^{PG}_{t}P^{PG}_{s,t} \end{pmatrix} \tag{46}$$

$$OC^* \le OC_\omega = (1-\sigma)OC_0 \tag{47}$$

$$P^{load}_{s,t} = (1-\beta)\tilde{P}^{load}_{s,t} \tag{48}$$

$$H^{load}_{s,t} = (1-\beta)\tilde{H}^{load}_{s,t} \tag{49}$$

$$(2)-(38) \tag{50}$$

It should be noted that β is the minimum favorable amount of uncertainty deviation which can make OC_ω achievable.

III. SIMULATION RESULTS AND DISCUSSION

The energy-hub consists of EHP, AC, μCHP, EH, BO, and ESS units. The considered test data for each of these entities are as follows:

The maximum/minimum capacity of the EHP unit is 200/10 kW, respectively. As stated before, the EHP unit can operate in both heating and cooling modes. The AC capacity is 75 kW and can cover a portion of the cooling load and this entity can only supplement the cooling load in hot weather. Otherwise, the cooling load will only be supplied by the EHP unit and this this unit uses natural gas. Moreover, it is assumed that the only input of the AC unit is natural gas and the generated heat from the MCHP cannot be utilized by the absorption chiller. An μCHP with 375 kW nominal capacity is considered in this test system. While the maximum heat/electric generation of this unit is 125/150 kW, respectively. The coefficients of the μCHP unit are as follows: $u^{\mu CHP}$=2.87-E4, $v^{\mu CHP}$=2.083, $w^{\mu CHP}$=1.66-E4, $x^{\mu CHP}$=0.183, $y^{\mu CHP}$=0.00125, $z^{\mu CHP}$= 13.75. The electrical heater has a capacity of 300 kW for heating. The energy price in winter is set so that the gas price is higher than the grid electricity price, therefore, the EH unit can supply a significant amount of heating load during winter as it uses electricity to generate heat. For the BO unit, the maximum capacity is 400 kW. The ESS has a capacity of 300 kWh. The maximum charging ratio of the ESS is 10 kW while the maximum discharging level is 20 kW. The ESS cannot charge or discharge at the same time. The minimum level of energy of the ESS is considered to be 50 kWh and it is assumed that the initial and the final level of the ESS is set to 200 kWh.

The electrical load is depicted in Fig. 1. In this figure, four forecasted load profiles are considered for each season. S1 represents the spring, S2 is for summer, S3 is for fall and S4 is for winter. One day is studied from each season with a time resolution of one hour. According to the figure, the peak electric demand starts at 9:00 and ends at 22:00. The forecasted heating and cooling loads are also illustrated in Fig. 2 and Fig. 3.

The deterministic results show that the minimum cost of the energy-hub required to meet the demand is 56 100 000 €.

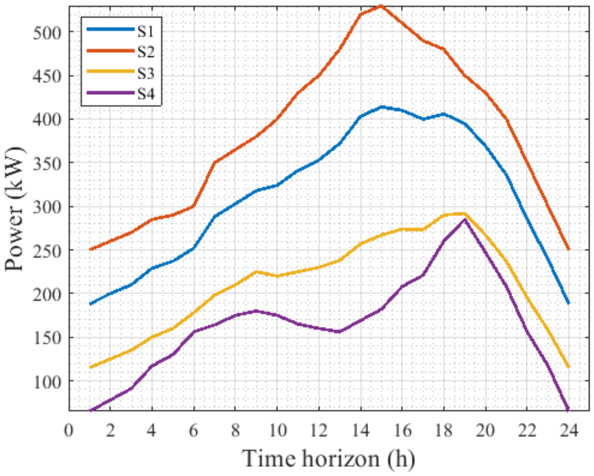

Fig. 1. The electricity demand of the consumers for each season

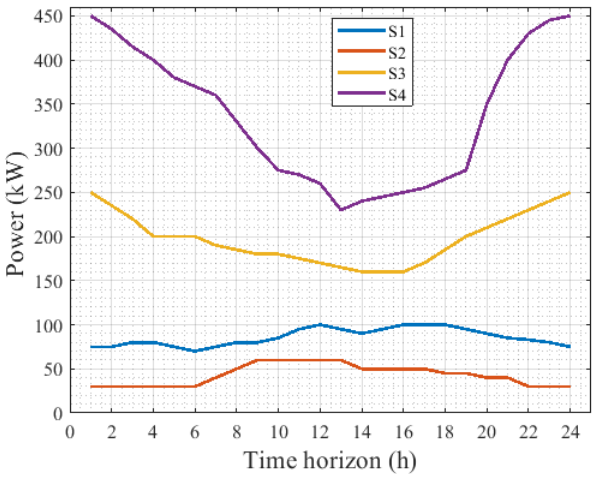

Fig. 2. The heating demand of the consumers for each

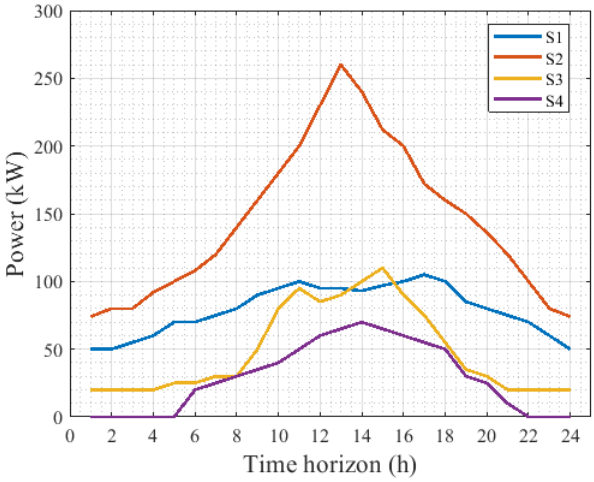

Fig. 3. The cooling demand of the consumers for each season

By implementing the IGDT opportunity function, the uncertainty of the heating and electric loads is considered. Different deviation factors of the operational cost of the energy-hub are considered and the problem is solved for each single deviation factor. The minimum amount of uncertainty of the electric and heating loads in the favorable case are depicted in Fig. 4. In this figure, by increasing the cost deviation factor, the opportunity function value also increases. To explain this in more detail, let us consider a specific amount for the cost deviation factor, i.e., 0.20. By choosing this value, the correlated target cost will be $OC_{\omega} = (1-0.20)OC_0 = 42{,}075{,}000$€. In order to be able to achieve this target cost, the observed electric and heating loads have to be at least 17.7% lower than the forecasted values.

The load profile after implementation of the TOU DR program is illustrated in Fig. 5. The results show that the load profiles during peak period after the employment of TOU program has decreased and shifted to the off-peak period. For instance, the load profile of S1 has increased during the off-peak period due to low prices relative to the high peak hours. The usual load demand at 15:00 is equal to 530 kW and after implementation of TOU program it decreases to 470 kW. It should be noted that the application of a risk management method imposes some cost to the decision-maker [13].

Hence, the opportunity cost of the studied system is also depicted in Fig. 6. It can be observed that for higher values of the opportunity function, the opportunity cost increases significantly. This cost can be higher than the profit (reducing operational cost) that the decision-maker receives by the applying of IGDT method.

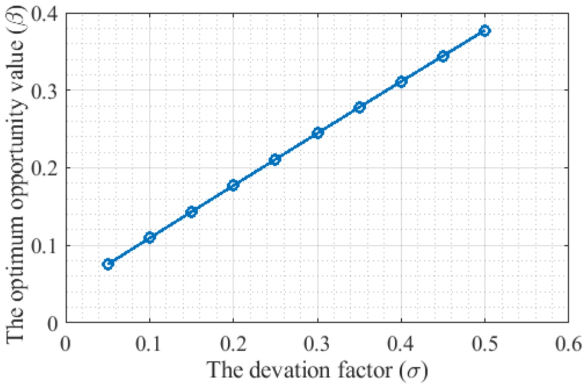

Fig. 4. The opportunity function value in different cost deviation factors

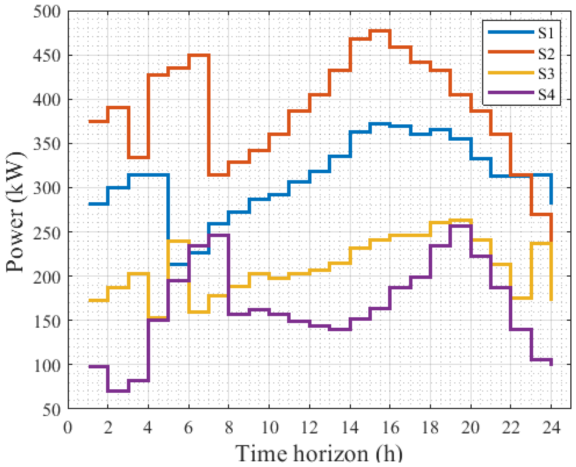

Fig. 5. The electricity profile after employment of TOU program

The operation of the ESS during the studied period for each season is shown in Fig. 7. The results show that during the off-peak period, the ESS is in the charging mode and at 10:00 in S1, it reaches to its maximum capacity and then starts discharging to cover the electric consumption of the entities that are operating in the energy-hub or supplying the electric load. The ESS discharges until its minimum capacity is reached when the demand for electric load is high.

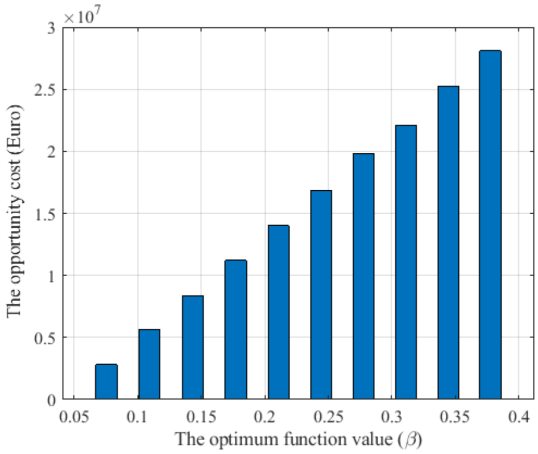

Fig. 6. The opportunity cost of the multi-energy hub for various opportunity function values

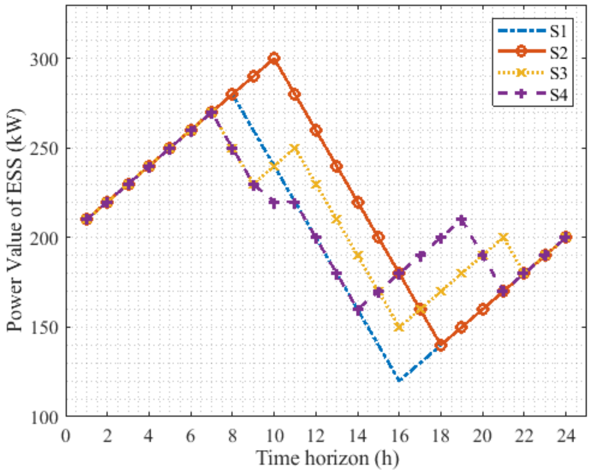

Fig. 7. The operation of ESS in the IGDT opportunistic approach for each season

IV. CONCLUSION

An energy-hub with several entities is considered in this paper. The energy-hub is responsible for supplying electric, heating and cooling loads. It also can receive electricity and natural gas from the upstream network. A TOU DR program is also employed to shift a percentage of electric demand during the peak period. A storage system is also used in this hub to assist the entities that are in the energy-hub or even by directly The ESS can contribute to minimizing the operational cost of the hub. As the risk measure, an IGDT opportunity approach is employed to enable the decision maker to meet its target cost by the occurrence of the favorable electric and heating load deviations from the forecasted values. The electric and heating loads are considered as uncertain parameters. The numerical results indicate that the employment of the IGDT method for the decision-maker imposes costs that in some cases are higher than the benefit that the decision-maker gains. Thus, employment of this method is dependent to the cost that is imposed on the system Another important result is related to the implementation of the DR program. The applied TOU program shifts a percentage of the demand to the off-peak period which can have a positive effect on the minimization of the operational costs of the hub. For future work, a multi-objective optimization problem can be applied to observe the impacts of each uncertain factor independently.

REFERENCES

[1] I. Gerami Moghaddam, M. Saniei, and E. Mashhour, “Improvement of energy performance employing electrical heat pump in scheduling a residential energy hub,” *Int. Trans. Electr. Energy Syst.*, vol. 26, no. 12, pp. 2618–2642.

[2] M. Mohammadi, Y. Noorollahi, B. Mohammadi-ivatloo, and H. Yousefi, “Energy hub: From a model to a concept – A review,” *Renewable and Sustainable Energy Reviews*, vol. 80. Elsevier Ltd, pp. 1512–1527, Dec. 01, 2017.

[3] V. Davatgaran, M. Saniei, and S. S. Mortazavi, “Optimal bidding strategy for an energy hub in energy market,” *Energy*, vol. 148, pp. 482–493, Apr. 2018.

[4] S. Mazzoni, S. Ooi, B. Nastasi, and A. Romagnoli, “Energy storage technologies as techno-economic parameters for master-planning and optimal dispatch in smart multi energy systems,” *Appl. Energy*, vol. 254, p. 113682, Nov. 2019.

[5] P. Gabrielli, F. Fürer, G. Mavromatidis, and M. Mazzotti, “Robust and optimal design of multi-energy systems with seasonal storage through uncertainty analysis,” *Appl. Energy*, vol. 238, pp. 1192–1210, Mar. 2019.

[6] J. Wang, H. Zhong, Z. Ma, Q. Xia, and C. Kang, “Review and prospect of integrated demand response in the multi-energy system,” *Applied Energy*. 2017.

[7] A. Mansour-Saatloo, M. Agabalaye-Rahvar, M. A. Mirzaei, B. Mohammadi-Ivatloo, M. Abapour, and K. Zare, “Robust scheduling of hydrogen based smart micro energy hub with integrated demand response,” *J. Clean. Prod.*, vol. 267, p. 122041, Sep. 2020.

[8] A. Dolatabadi and B. Mohammadi-Ivatloo, “Stochastic risk-constrained scheduling of smart energy hub in the presence of wind power and demand response,” *Appl. Therm. Eng.*, vol. 123, pp. 40–49, Aug. 2017.

[9] A. Dolatabadi, M. Jadidbonab, and B. Mohammadi-Ivatloo, “Short-Term Scheduling Strategy for Wind-Based Energy Hub: A Hybrid Stochastic/IGDT Approach,” *IEEE Trans. Sustain. Energy*, 2019.

[10] S.-E. Razavi, M. S. Javadi, and A. Esmaeel Nezhad, “Mixed-integer nonlinear programming framework for combined heat and power units with nonconvex feasible operating region: Feasibility, optimality, and flexibility evaluation,” *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 3, p. e2767, Mar. 2019.

[11] M. S. Javadi, M. Lotfi, A. Esmaeelnezhad, A. Anvari-Moghaddam, J. M. Guerrero, and J. Catalao, “Optimal Operation of Energy Hubs Considering Uncertainties and Different Time Resolutions,” *IEEE Trans. Ind. Appl.*, pp. 1–1, Jun. 2020.

[12] M. Nazari-Heris, S. Abapour, and B. Mohammadi-Ivatloo, “Optimal economic dispatch of FC-CHP based heat and power micro-grids,” *Appl. Therm. Eng.*, vol. 114, pp. 756–769, Mar. 2017.

[13] M. Vahid-Ghavidel, J. P. S. Catalão, M. Shafie-Khah, S. S. Barhagh, and B. Mohammadi-Ivatloo, “IGDT opportunity method in the trading framework of risk-seeker demand response aggregators,” Jun. 2019.