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Risk-Averse Decentralized Optimal Scheduling of a Virtual Energy Hub Plant Equipped with Multi Energy Conversion Facilities in Energy Markets

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Abstract—Distributed multi-energy systems, in addition to their advantages, pose significant challenges to future energy networks. One of these challenges is how these systems participate in energy markets. To overcome this issue, this paper introduces a virtual energy hub plant (VEHP) comprised of multiple energy hubs (EHs) to participate in the energy market in a cost-effective manner. Each EH is equipped with multiple distributed energy resources (DERs) in order to supply electrical, heating and cooling loads. Moreover, an integrated demand response (IDR) program and vehicle-to-grid (V2G) capable electric vehicles (EVs) are taken into consideration to enhance the flexibility to EHs. The manager of the VEHP participates in the existing day-ahead markets on behalf of EHs after collecting their bids. Since EHs are independent entities, a hybrid model of mobile edge computing system and analytical target cascading theory (MEC-ATC) is proposed to preserve data privacy of EHs. Further, to tackle the uncertainty of renewables, a robust optimization method is applied. Obtained results corroborated the proposed scheduling is efficient and could increase the VEHP's profit about 21.4% in light of using flexible technologies.

Index Terms—Virtual energy hub plant, mobile edge computing (MEC), analytical target cascading theory (ATC), combined heat and power (CHP) unit, uncertainty

I. INTRODUCTION

The considerable depletion of fossil fuel supply and the environmental damage caused by greenhouse gases have resulted in a rise in the development of renewable energy sources (RESs) over the last decades. However, the inherent characteristics of RES, such as their intermittent nature and randomness, restrict the rate of development of these resources [1]. Virtual power plants (VPPs), which integrate advanced information technologies, distributed energy resources, and energy storage systems, have recently been proposed to mitigate these concerns [2]. Furthermore, including multi-energy

resources in VPPs can be a practical approach to enhance the overall efficiency of energy systems, improve the capacity to balance energy supply and demand, and allow the high-efficiency use of RESs [3]. As a result of combining multiple energy resources with VPP, a unique idea known as a virtual energy hub (VEH) has emerged. Hence, the main objective of this paper is to propose a decentralized optimization model to maximize the profit of a VEH made up of multiple EH systems in energy markets while keeping each EH system's data private.

A. Related works

In recent years, numerous studies have focused on the optimal scheduling of VPPs in electricity markets by considering RESs. In [1], a chance constraint model taking into the renewables uncertainty has been introduced to formulate the power flexibility problem. Further, a robust scheduling optimization model has been proposed for VPPs in [4], which the optimization aims to maximize the revenue considering energy and reserve market as well as power network constraints. In [5], an optimal self-scheduling problem for a VPP integrated with RESs and hydro power units is presented to optimize energy utilization, power production and financial benefits while analyzing the risk of uncertainties in RESs. In [6], a model predictive control for real-time operation of VPPs in order to handle the intermittency of RESs has been proposed, which the model is able to adjust VPPs operation based on the prediction of RESs output power.

In recent years, a few pieces of literature have investigated the optimal performance of VEHs in energy market. For instance, a self-scheduling risk-constrained method based on information gap decision theory (IGDT) is introduced in [7] to maximize the profit of a VEH in local heat and power markets. Study [8] has proposed a robust scheduling for a

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multi-energy VPP equipped with storage systems as well as demand response program to optimally participate in power and heat markets. A two-stage robust-stochastic optimization method is also presented in [9] for optimal participation of a VEH in energy markets with multiple industrial EHs to minimize the operational costs and risk associated with existing uncertainties. Moreover, a VEH integrated with electrical transport system, photovoltaic (PV) generation and battery storage system is studied in [10], under the cooperative decision-making method.

The above-reviewed studies have adopted a centralized solution approach which the centralized solver has access to the whole system. However, preserving data privacy is essential in an energy system with multiple independent entities. In this regard, decentralized approaches have been introduced in previous works. In [11], a decentralized bi-level methodology using analytical target cascading theory (ATC) has been proposed to coordinate microgrids with active distribution system, where the upper level seeks the distribution network and the lower level aims to maximize profit of the microgrids. A blockchain-based lightweight decentralized approach has been presented in [12] for VPPs comprised small-scale prosumers, which the main aim is to minimize the energy cost considering participant's flexibility and operation constraints.

B. Contributions

The reviewed literature revealed some research gaps. Firstly, some of the previous works such as [1], [4]–[6], [11], [12] have mainly focused on power and ignored heating and cooling energies. Some other works [3], [7]–[10] which have taken multi-energy systems into consideration while focusing on a single energy system with a centralized approach. However, operating multiple EHs under the concept of VEHP could facilitate economic benefits. Moreover, several existing works have ignored uncertainty management [10]–[12] and some other studies have proposed a probabilistic approach [1] that depends on probability distribution functions (PDFs). Eventually, papers [1]–[3], [12] have neglected flexible technologies including demand response program, multi-energy conversion facilities and vehicle-to-grid (V2G) ability of electric vehicles (EVs). To bridge the knowledge gap, the main contributions of this paper could be highlighted as below:

- Introducing a VEHP comprised multiple EHs to work together in order to get a role in energy market. The manager of the VEHP collects bids of EHs and participates in energy market on behalf of them.
- Proposing a decentralized algorithm based on mobile edge computing (MEC) and ATC (MEC-ATC). In doing so, the centralized problem is broken into multiple sub-problems such that each EH can solve its own problem locally on an assigned edge server rather than a cloud-based system, hence the data privacy of EHs is preserved.
- Proposing a robust optimization to tackle the intermittent nature of RESs. As oppose to scenario-based approaches, the accuracy of this method is not dependent on scenarios

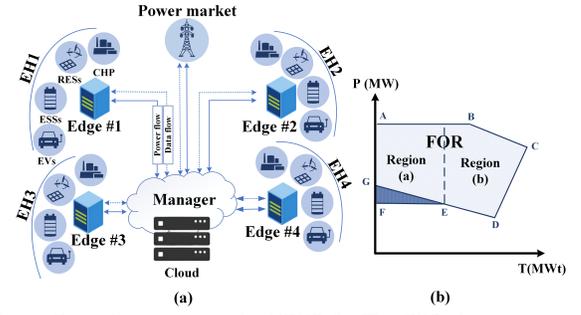


Fig. 1: (a) General overview of the VEHP (b) The FOR characteristic of the CHP units

and PDFs.

- Finally, this study considers numerous flexible energy technologies including an integrated demand response program (IDRP), CHP unit, storage systems, electrical boiler and chiller, and V2G capable EVs.

II. PROBLEM FORMULATION

A. Objective function

The centralized objective function (f_c) seeks maximizing the profit of the VEHP which has been stated in (1). In this relation, the first term is the income of the EHs by supplying consumers. The next two terms are the CHP units' fuel cost and maintenance cost, respectively. The last two terms are the income and the cost of selling and purchasing power to/from the power market, respectively. In this relation, $\mathcal{T} = \{1, 2, \dots, 24\}$ is the set of time horizon for the scheduling indexed by t ; $\mathcal{I} = \{1, 2, 3, 4\}$ is the set of EHs indexed by i ; $C_t^p/C_t^h/C_t^c$ are the price of selling power/heat/cool to the end-users; $p_{i,t}^{E,dr}/p_{i,t}^{T,dr}$ are power/heat demand after demand response; $p_{i,t}^C$ is cool demand; $\lambda_t^{gas}/\lambda_t^p$ are gas/power markets prices; $p_{i,t}^{CHP}/\eta^{CHP}/C^{CHP}$ are CHP units' output power/efficiency/maintenance cost, and p_t^{sell}/p_t^{buy} are selling/purchasing power to/from the power market.

$$\text{Max } f_c = \sum_{t \in \mathcal{T}} \left[\sum_{i \in \mathcal{I}} [C_t^p \cdot EL_{i,t}^{dr} + C_t^h \cdot HL_{i,t}^{dr} + C_t^c \cdot CL_{i,t} - \lambda_t^{gas} \cdot \frac{p_{i,t}^{CHP}}{\eta^{CHP}} - C^{CHP} \cdot p_{i,t}^{CHP}] + \lambda_t^p (p_t^{sell} - p_t^{buy}) \right] \quad (1)$$

B. CHP unit

The proposed study has applied CHP unit with non-convex feasible operation region (FOR). To tackle this issue, as depict in Fig. 1(b), FOR is divided into two convex sub-regions, such as "a" and "b". The mathematical model is given through (2)–(5) based on a convex combination of extreme points in the polyhedral feasible operating region [13]. $\mathcal{S}_i = \{1, \dots, N_i^{reg}\}$ is the set of sub-regions, $\mathcal{D}_{i,s} = \{1, \dots, D_{i,s}\}$ is the set of extreme points, $\alpha_{i,t}^{d_{i,s}}$ is coefficient of extreme points, $(x^{d_{i,s}}, y^{d_{i,s}})$ is the coordination of extreme points, $m_{i,t}^s$ is a binary variable to determine the operating region and $h_{i,t}^{chp}$ is the generated heat.

$$p_{i,t}^{chp} = \sum_{s_i \in \mathcal{S}_i} \sum_{d_{i,s} \in \mathcal{D}_{i,s}} \alpha_{i,t}^{d_{i,s}} \cdot x^{d_{i,s}} \quad (2)$$

$$h_{i,t}^{chp} = \sum_{s_i \in \mathcal{S}_i} \sum_{d_{i,s} \in \mathcal{D}_{i,s}} \alpha_{i,t}^{d_{i,s}} \cdot y^{d_{i,s}} \quad (3)$$

$$\sum_{d_{i,s} \in \mathcal{D}_{i,s}} \alpha_{i,t}^{d_{i,s}} = m_{i,t}^s \quad (4)$$

$$\sum_{s_i \in \mathcal{S}_i} m_{i,t}^s = V_{i,t} \quad (5)$$

C. Electric vehicles

EHs operators facilitate both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) options for the EVs, which participate in the power market. The state-of-charge (SoC) of EVs at each hour is demonstrated by (6), whereas (7), (8) and (9) are represented the limitations of SoC, G2V and V2G power of parked EVs, respectively. The V2G and G2V operations cannot be performed simultaneously, as described in (10). Further, (11) expresses that the EVs must be fully charged when departing the EHs.

$$E_{t,i,n,m}^{EV} = E_{t-1,i,n,m}^{EV} + \eta_n^{chr,EV} \cdot p_{t,i,n,m}^{chr,EV} - \frac{p_{t,i,n,m}^{dch,EV}}{\eta_n^{dch,EV}} \quad (6)$$

$$\underline{E}_n^{EV} \leq E_{t,i,n,m}^{EV} \leq \overline{E}_n^{EV} \quad (7)$$

$$\underline{P}_n^{chr,EV} \cdot I_{t,i,n,m}^{chr,EV} \leq p_{t,i,n,m}^{chr,EV} \leq \overline{P}_n^{chr,EV} \cdot I_{t,i,n,m}^{chr,EV} \quad (8)$$

$$\underline{P}_n^{dch,EV} \cdot I_{t,i,n,m}^{dch,EV} \leq p_{t,i,n,m}^{dch,EV} \leq \overline{P}_n^{dch,EV} \cdot I_{t,i,n,m}^{dch,EV} \quad (9)$$

$$I_{t,i,n,m}^{chr,EV} + I_{t,i,n,m}^{dch,EV} \leq 1 \quad (10)$$

$$E_{t_{dep},i,n,m}^{EV} = \overline{E}_n^{EV} \quad (11)$$

In defined relations, $t \in [t_{arr}, t_{dep}]$; $n \in \mathcal{N} = \{1, \dots, N\}$ and $m \in \mathcal{M} = \{1, \dots, M\}$ denote type and cluster of EVs, respectively; $E_{t,i,n,m}^{EV}$ is state of charge (SoC); $\underline{E}_n^{EV} / \overline{E}_n^{EV}$ are min/max of the SoC; $p_{t,i,n,m}^{chr,EV} / p_{t,i,n,m}^{dch,EV}$ are charging/discharging power; $\underline{P}_n^{chr,EV} / \overline{P}_n^{chr,EV}$ are min/max of the charging power; $\underline{P}_n^{dch,EV} / \overline{P}_n^{dch,EV}$ are min/max of the discharging power; $\eta_n^{chr,EV} / \eta_n^{dch,EV}$ are charging/discharging efficiencies and $I_{t,i,n,m}$ is a binary variable indicates charging or discharging mode.

D. Energy storage systems

Energy storage systems (ESSs) are included in this model to increase the efficiency of EHs. This study proposed three types of energy storage such as electrical storage (ES), heat storage (HS), cool storage (CS). The quantity of stored energy is described in (12), while the limitations is presented in Eq(13). In addition, the lower and upper boundaries of charging and discharging is determined by (14)-(15), respectively. (16) ensures that the charging and discharging should not be performed simultaneously, whereas (17) describes that the initial and final quantity of energy in the ES should be equal.

$$SoC_{t,i}^{\Omega} = SoC_{t-1,i}^{\Omega} + \eta_i^{ch,\Omega} \cdot p_{t,i}^{ch,\Omega} - p_{t,i}^{dch,\Omega} / \eta_i^{dch,\Omega} \quad (12)$$

$$\underline{SoC}_i^{\Omega} \leq SoC_{t,i}^{\Omega} \leq \overline{SoC}_i^{\Omega} \quad (13)$$

$$\underline{P}_i^{ch,\Omega} \cdot I_{t,i}^{ch,\Omega} \leq p_{t,i}^{ch,\Omega} \leq \overline{P}_i^{ch,\Omega} \cdot I_{t,i}^{ch,\Omega} \quad (14)$$

$$\underline{P}_i^{dch,\Omega} \cdot I_{t,i}^{dch,\Omega} \leq p_{t,i}^{dch,\Omega} \leq \overline{P}_i^{dch,\Omega} \cdot I_{t,i}^{dch,\Omega} \quad (15)$$

$$I_{t,i}^{ch,\Omega} + I_{t,i}^{dch,\Omega} \leq 1 \quad (16)$$

$$SoC_{(t=0),i}^{\Omega} = SoC_{t=24,i}^{\Omega} \quad (17)$$

Where, $\Omega \in \{ES, HS, CS\}$ refer to different types of storages; $SoC_{t,i}^{\Omega}$ SoC level; $\underline{SoC}_i^{\Omega} / \overline{SoC}_i^{\Omega}$ are min/max of the SoC; $p_{t,i}^{ch,\Omega} / p_{t,i}^{dch,\Omega}$ are charging/discharging power; $\underline{P}_i^{ch,\Omega} / \overline{P}_i^{ch,\Omega}$ are min/max of the charging power; $\underline{P}_i^{dch,\Omega} / \overline{P}_i^{dch,\Omega}$ are min/max of the discharging power and $\eta_i^{ch,\Omega} / \eta_i^{dch,\Omega}$ are charging/discharging efficiencies.

E. Electrical chiller and boiler

This model has applied an electrical boiler and chiller to satisfy the heat and cool demand in each EH. The constraints of output power production in the electrical boiler (B) and chiller (C) are determined through (18)-(19). $p_{t,i}^{B/C}$ is output heat/cool; $p_{t,i}^{e,B/C}$ is consumed power; $\eta^{B/C}$ is conversion efficiency and $\overline{P}_{t,i}^{B/C}$ is maximum capacity.

$$p_{t,i}^{B/C} = p_{t,i}^{e,B/C} \cdot \eta^{B/C} \quad (18)$$

$$0 \leq p_{t,i}^{B/C} \leq \overline{P}_{t,i}^{B/C} \quad (19)$$

F. Integrated demand response program

End-users could participate in demand response (DR) programs to maximize ultimate profits. This study has suggested an integrated electrical and heat demand response programs (IDRP) to manage the power consumption of consumers with regards to the energy price. The limitations correspond to electrical DR (E_{dr}) and heat DR (T_{dr}) are presented as a general form in (20)-(23). In (20), the new electrical/heat load after the DR program is defined. In addition, the constraints of electrical/heat load increment and reduction are determined in (21) and (22), respectively. Finally, the total of shifted up and shifted down loads must be equal as described in (23). $p_{t,i}^{E_{dr}/T_{dr}}$ is electrical/heat demand after demand response program; $P_{t,i}^{El/Tl}$ are basic electrical/heat demand; $p_{t,i}^{E_{dr}/T_{dr},up} / p_{t,i}^{E_{dr}/T_{dr},dwn}$ are shifted up/shifted down load and $D_i^{E_{dr}/T_{dr},inc}$ is the percentage of electrical/heat flexible load.

$$p_{t,i}^{E_{dr}/T_{dr}} = P_{t,i}^{El/Tl} - p_{t,i}^{E_{dr}/T_{dr},up} + p_{t,i}^{E_{dr}/T_{dr},dwn} \quad (20)$$

$$0 \leq p_{t,i}^{E_{dr}/T_{dr},up} \leq D_i^{E_{dr}/T_{dr},inc} \cdot p_{t,i}^{E_{dr}/T_{dr},up} \quad (21)$$

$$0 \leq p_{t,i}^{E_{dr}/T_{dr},dwn} \leq D_{i,n}^{E_{dr}/T_{dr},dwn} \cdot p_{t,i}^{E_{dr}/T_{dr},dwn} \quad (22)$$

$$\sum_{t=1}^{Nt} p_{t,i}^{E_{dr}/T_{dr},up} = \sum_{t=1}^{Nt} p_{t,i}^{E_{dr}/T_{dr},dwn} \quad (23)$$

G. Multi-energy balance of the VEHP

Power, heat and cool generation must match consumption in each EH, which are stated by (24)-(26), respectively. Relation (27) declares that sum of the manager's exchanged power with EHs must be equal to the exchanged power with the power grid. Finally, (28) is the coupling constraint between microgrids and manager. $p_{t,i}^{M2EH}$ is the power supplied by manager to the EH i ; $p_{t,i}^{EH2M}$ is the power supplied from EH i to the manager; $P_{t,i}^W / P_{t,i}^{PV}$ are wind/PV output power; π_i is number of EVs; $U_{i,n}$ is a coefficient for determining EV types and $Q_{i,m}$ is scenario of clusters.

$$p_{t,i}^{EH2M} + p_{t,i}^{chp} + P_{t,i}^W + P_{t,i}^{PV} + p_{t,i}^{dch,ES} - p_{t,i}^{ch,ES} - p_{t,i}^B + \sum_{n \in \mathcal{N}} \sum_{m \in \mathcal{M}} \pi_i U_{i,n} Q_{i,m} (p_{t,i,n,m}^{dch,EV} - p_{t,i,n,m}^{chr,EV}) - p_{t,i}^C - p_{t,i}^{Edr} = 0 \quad (24)$$

$$h_{t,i}^{chp} + p_{t,i}^B + p_{t,i}^{dch,TS} - p_{t,i}^{ch,TS} = p_{t,i}^{Tdr} \quad (25)$$

$$p_{t,i}^C + p_{t,i}^{dch,TS} - p_{t,i}^{ch,TS} = p_{t,i}^{Cdr} \quad (26)$$

$$\sum_{i \in \mathcal{I}} p_{t,i}^{M2EH} = p_t^{sell} - p_t^{buy} \quad (27)$$

$$p_{t,i}^{M2EH} + p_{t,i}^{EH2M} = 0 \quad (28)$$

H. Robust optimization

The presented model suggests robust optimization approach to optimize the intermittent nature of RESs, i.e., wind and PV. The uncertainty set of wind and PV sources is described in (29). In fact, $\tilde{P}_{t,i}$ denotes as the forecasted output power of RESs. Further, $\hat{P}_{t,i}$ defines the maximum deviation of renewable sources from the predicted value. The level of uncertainty could vary according to $\beta_{t,i} \in [0, 1]$. For instance, when $\beta_{t,i} = 0$ the uncertainty level is zero and when $\beta_{t,i} = 1$ the uncertainty is in its maximum degree of renewable sources. The term $\Gamma_{t,i} \in [0, 2]$ in (30) expresses the robust parameter which could restrict the maximum considered uncertainty. By considering the uncertainty for renewables, (24) can be restated as (31), which ϕ denotes other terms in (24). In order to linearize this relation, the duality theory is applied. In doing so, (32)-(34) are achieved, where $\alpha_{t,i}, \sigma_{t,i}$ are auxiliary variables.

$$P_{t,i}^{W/PV} \in [\tilde{P}_{t,i}^{W/PV} - \beta_{t,i}^{W/PV} \hat{P}_{t,i}^{W/PV}, \tilde{P}_{t,i}^{W/PV} + \beta_{t,i}^{W/PV} \hat{P}_{t,i}^{W/PV}] \quad (29)$$

$$\beta_{t,i}^W + \beta_{t,i}^{PV} \leq \Gamma_{t,i} \quad (30)$$

$$\tilde{P}_{t,i}^W - \beta_{t,i}^W \hat{P}_{t,i}^W + \tilde{P}_{t,i}^{PV} - \beta_{t,i}^{PV} \hat{P}_{t,i}^{PV} + \phi \geq 0 \quad (31)$$

$$\tilde{P}_{t,i}^W - \alpha_{t,i}^W + \tilde{P}_{t,i}^{PV} - \alpha_{t,i}^{PV} - \sigma_{t,i} \Gamma_{t,i} + \phi \geq 0 \quad (32)$$

$$\sigma_{t,i} + \alpha_{t,i}^W \geq \hat{P}_{t,i}^W \quad (33)$$

$$\sigma_{t,i} + \alpha_{t,i}^{PV} \geq \hat{P}_{t,i}^{PV} \quad (34)$$

I. Hybrid MEC-ATC based decentralized algorithm

Since the VEHP contains independent EHs, with the aim of preserving data privacy, security and scalability of the proposed model, the MEC system is proposed to render the optimization problems locally at each agent premise. The MEC system has been introduced by European Telecommunications Standard Institute [14]. By implementing this system, computation is moved from a centralized cloud-based system into multiple edge servers. In doing so, not only the computational burden is reduced, but also the data privacy of entities is preserved. However, coupling constraints (28) make the problem complicate to decompose. In order to tackle these complicating constraints, the ATC algorithm is proposed as a decentralized computation [11]. To do so, firstly the augmented Lagrangian function is constructed as (35). In this function \mathcal{X} denotes all the decision variables of the centralized

problem and $\omega_{i,t}, \zeta_{i,t}$ are Lagrangian multipliers. In doing so, the complicating constraints are relaxed and the objective functions associated with the manager of the VEHP and each EH are extracted as (36)-(37), respectively. $\tilde{p}_{i,t}^{M2EH}, \tilde{p}_{i,t}^{EH2M}$ are parameters that are updated at each iteration by the corresponded agent. Afterwards, an iterative process is began in a way that the cloud and edge-servers solve their local problems then Lagrangian multipliers are updated by the cloud according to equations (38)-(39) and broadcast to the EHs for the next iteration. In (39), β is a parameter that takes a value within the interval $[2, 3]$. At each iteration, the convergence criteria, i.e., relations (40)-(41), are checked by the cloud and the iterative process will continue till these constraints are met. ϵ_1, ϵ_2 represent the accepted error.

$$\mathcal{L}(\mathcal{X}, \omega_{i,t}, \zeta_{i,t}) = f_c + \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} \omega_{i,t} (p_{i,t}^{EH2M} + p_{i,t}^{M2EH}) + \zeta_{i,t} \|p_{i,t}^{EH2M} + p_{i,t}^{M2EH}\|_2^2 \quad (35)$$

$$\text{Max } f_M = \sum_{t \in \mathcal{T}} \left[\lambda_t^p (p_t^{sell} - p_t^{buy}) + \sum_{i \in \mathcal{I}} [\omega_{i,t} (\tilde{p}_{i,t}^{EH2M} + p_{i,t}^{M2EH}) + \zeta_{i,t} \| \tilde{p}_{i,t}^{EH2M} + p_{i,t}^{M2EH} \|_2^2] \right] \quad (36)$$

$$\text{Max } f_i = \sum_{t \in \mathcal{T}} \left[C_t^p \cdot EL_{i,t}^{dr} + C_t^h \cdot HL_{i,t}^{dr} + C_t^c \cdot CL_{i,t} - \lambda_t^{gas} \cdot p_{i,t}^{CHP} / \eta^{CHP} - C^{CHP} \cdot p_{i,t}^{CHP} + \omega_{i,t} (p_{i,t}^{EH2M} + \tilde{p}_{i,t}^{M2EH}) + \zeta_{i,t} \|p_{i,t}^{EH2M} + \tilde{p}_{i,t}^{M2EH}\|_2^2 \right] \quad (37)$$

$$\omega_{i,t}^k = \omega_{i,t}^{k-1} + 2(\zeta_{i,t}^{k-1})^2 (p_{i,t}^{EH2M,k-1} + p_{i,t}^{M2,k-1}) \quad (38)$$

$$\zeta_{i,t}^k = \beta \zeta_{i,t}^{k-1} \quad (39)$$

$$\|p_{i,t}^{EH2M,k} + p_{i,t}^{M2EH,k}\| \leq \epsilon_1 \quad (40)$$

$$\left| \frac{(f_m^{k-1} + \sum_{i \in \mathcal{I}} f_i^{k-1}) - (f_m^k + \sum_{i \in \mathcal{I}} f_i^k)}{f_m^k + \sum_{i \in \mathcal{I}} f_i^k} \right| \leq \epsilon_2 \quad (41)$$

III. SIMULATION RESULTS

The proposed scheduling model for the VEHP has been rendered on the test system illustrated in Fig. 1(a). Multiple energy demands for EHs and techno-economic data for utilized technologies have been obtained from [15], [16] while renewable power and power prices have been depicted in Fig. 2. In order to deliver a comprehensive discussion as well as to show the impact of the uncertainty, the obtained results are discussed through two case studies. In the first case, the uncertainty of renewable power is ignored and the problem has been solved in the deterministic manner, while the second case study will focus on the impact of the uncertainty. The decentralized optimization is a mixed-integer nonlinear programming (MINLP), which all simulations have been done on a standard PC with Intel® Core™ i7-4710HQ CPU @ 2.5 GHz and 8GB RAM using SBB solver in GAMS software.

A. Case study I: Deterministic approach

As mentioned before, in this case, the results are reported in deterministic manner. Fig. 3 demonstrates power dispatch among different technologies for EHs. With a general look, it is perceived that exchanged power with the power grid has a correlation with the power market prices. Closely looking,

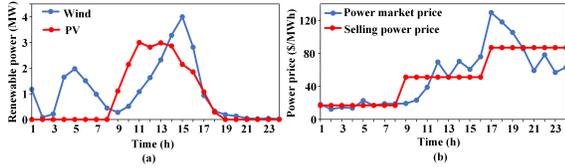


Fig. 2: Hourly predicted (a)-renewable power (b)-power prices

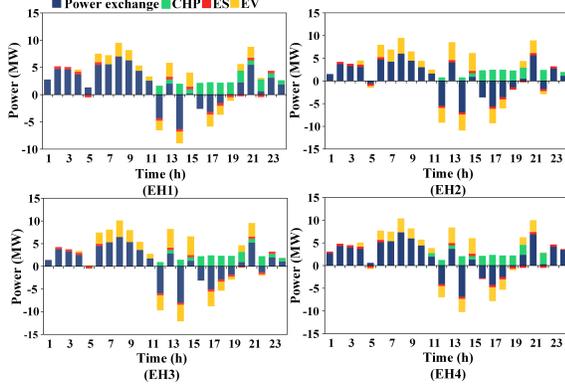


Fig. 3: Optimal power dispatch

EHs have purchased power during off-peak power price hours; however, during on-peak hours they have sold power. Further, the CHP unit has assisted EHs throughout the period from $t = 12$, which the power prices start climbing, to the end of the day. The electrical storage systems have been applied in charging mode during $t = 2 - 4, 6, 13, 15, 21$ and they have been discharged when power prices are high. A similar pattern with the ESs is obvious for electric vehicles since they are mobile electrical storage systems from the power system point of view. Hence, EHs' operators have charged EVs where the power market experience low prices, and they have benefited from the vehicle-to-grid ability of EVs at high power prices period.

Fig. 4 depicted heat and cool dispatch among technologies for EHs. As is shown in the illustration, the heat loads during the period $t = 12 - 24$ are supplied via the CHP unit on the ground that it is online during that period. However, during low power price period, the electrical boilers are operated to meet demands. Moreover, it is interesting to note that the operation of heat storages, in addition to the heat load, depends on the power market since the operation of heat suppliers, both CHP and EB, depend on the power market. Further, regarding cool dispatch, since ECs are main cool demand suppliers, they are online during the whole day. Besides ECs, have been discharged throughout hours $t = 5, 12, 17 - 20, 22$ in order to reduce the ECs operation where the power market prices are high.

Fig. 5 shows the impact of the implemented IDR program. It is apparently seen that the IDR has affected demand profiles positively. Overall, the performance of the IDR is correlated with the power market. As the IDR is a price-based program, end-users have reduced their electrical loads by receiving high power prices and increased their loads during low price hours. Turning to the heat demand profiles, end-users have shifted their flexible heat loads from the first half of the day to the second half, especially $t = 16 - 20$. This is because of the

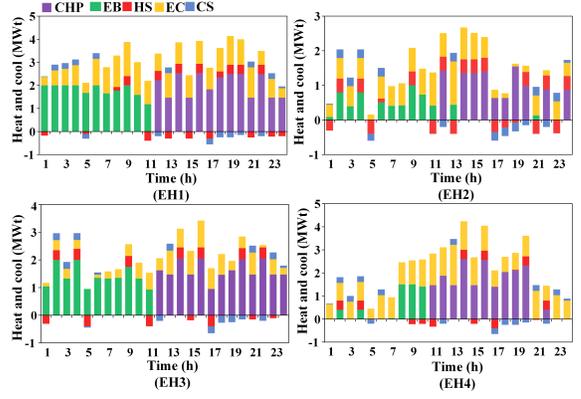


Fig. 4: Optimal heat and cool dispatch

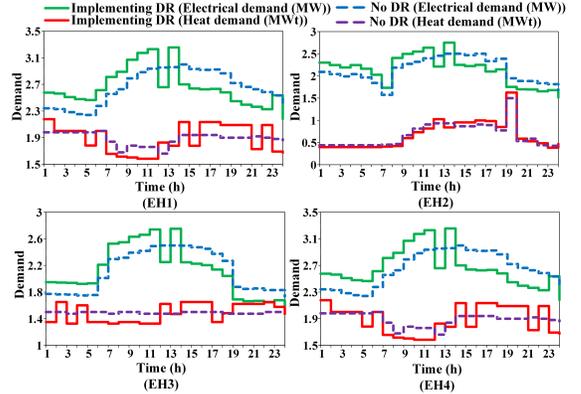


Fig. 5: Impact of the IDR program on demand profiles
TABLE I: Economic analysis of the flexible technologies

	Storage \times IDR \times V2G \times	Storage \checkmark IDR \times V2G \times	Storage \checkmark IDR \checkmark V2G \times	Storage \checkmark IDR \checkmark V2G \checkmark
Purchased power cost (\$)	5188.521	5204.711	5520.619	7501.153
Sold power cost (\$)	3433.331	4461.538	4982.258	8433.064
CHP units operation cost (\$)	6041.941	5895.09	5777.745	5777.745
Profit (\$)	14217.103	15375.970	15794.460	17264.732

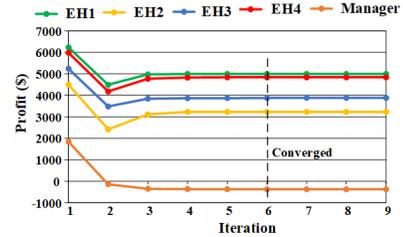


Fig. 6: The MEC-ATC algorithm performance

potential heat generation by CHP units.

Furthermore, the economic analysis of the utilized flexible technologies is provided through Table I for the VEHP. As enumerated, the V2G ability of the EVs has the most impact on the profit by an increasing of \$1470.27(9.3%). Furthermore, storage systems and IDR have accounted for \$1158.87(8.15%) and \$418.49(2.7%), respectively, growth in the profit. As the final part of this case study, the performance of the ATC algorithm is analyzed. Hence, Fig. 6 has been provided, which shows the objective functions for EHs and manager. As illustrated, the ATC algorithm has been converged at iteration six with 35 seconds execution time.

B. Case study II: Robust approach

This case study focuses on impact of the uncertainty on

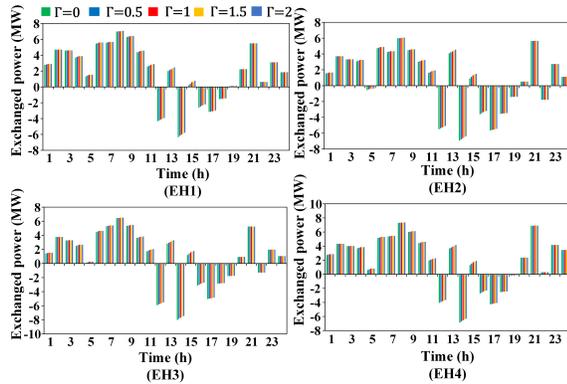


Fig. 7: Impact of the uncertainty on exchanged power

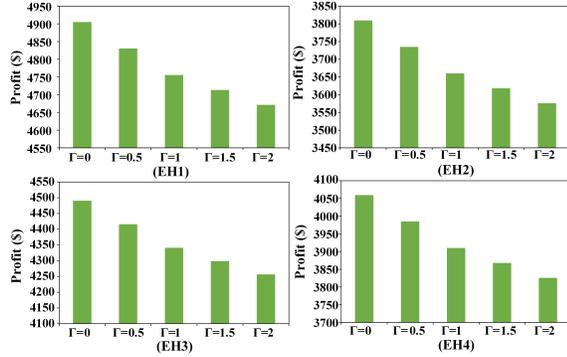


Fig. 8: Impact of the uncertainty on profit

the scheduling problem. Fig. 7 shows EHs trading strategy with the power grid for different amounts of Γ . As depicted in this figure, the amount of imported power has been increased at $t = 10, 11, 13, 15$, which are on-peak power market period. The reason for rise in the imported power during the mentioned hours is that the robust optimization finds the worst hours that the uncertainty can affect the scheduling. Hence, according to the risk-averse behaviour, more power is imported to compensate the predicted renewable power error. In addition, considering an error in the predicted renewable power in a risk-averse manner when EHs sell power, which enforce to schedule less renewable power, cause a drop in the exported power during $t = 12, 14, 16 - 18$. Moreover, the profit of EHs for different amounts of Γ is shown in Fig. 8. By increasing the value of uncertainty budget, the robustness of the scheduling increases; therefore, the profit decreases. The total profit of the VEHP is decreased from \$17264.732 to \$16329.319 for $\Gamma = 0$ and $\Gamma = 2$, respectively.

IV. CONCLUSION

The presented paper contributed a day-ahead scheduling of a virtual energy hub plant (VEHP). The considered VEHP includes four energy hubs (EHs) with the aim of maximizing profit. A hybrid decentralized model composed of mobile edge computing and analytical target cascading theory (MEC-ATC) was proposed to preserve data privacy of EHs. Furthermore, in order to tackle the uncertainty of renewable sources, a robust optimization method was taken into consideration. The obtained results verified the effectiveness of the proposed model. Firstly, the utilized flexible technologies accounted for

21.4% rise in the total profit of the VEHP. The MEC-ATC model showed a good performance and converged at iteration six. Further, the VEHP could reduce the risk level of decision-making against the uncertainty of renewable energy resources as a result of the robust optimization, although it achieved less profit.

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