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Strategic Operation of a Virtual Energy Hub with the Provision of Advanced Ancillary Services in Industrial Parks

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***Abstract*—Coordinated operation of several industrial energy hubs (IEHs) to realize local energy management concepts at strategic points like industrial parks has attracted the attention of power grid operators worldwide. Deriving an operational model for integrating a large set of IEHs to trade energy in various markets is a fundamental challenge that has not yet been addressed. To overcome this research gap, this paper presents an optimal market participation strategy for a virtual energy hub (VEH) consisting of multiple IEHs and industrial consumers. The proposed strategy seeks to answer two questions: (1) how can a VEH operator (VEHO) minimize its operation cost when participating in different electricity markets, i.e., day-ahead market (DAM), real-time market (RTM), and local electricity market (LEM), as well as natural gas market (NGM)? (2) how can ancillary services affect the economic performance of VEH? To address these questions, a two-stage robust-stochastic optimization model is proposed with the aim of minimizing the total operation cost of VEH and compensating the operational risks associated with the existing uncertainties considering the operational limits of the power grid. To this aim, the advanced ancillary services, i.e., market-based demand response programs (DRPs) and transactive energy management (TEM) mechanism are used in line with the optimization problem. Furthermore, the role of the multi-supply facilities is included in the developed strategy to improve VEH flexibility. The feasibility of the proposed model is validated through a set of case studies on the modified IEEE 14-bus test system. Simulation results demonstrate that the total operation cost of the VEH decreases by at least 9.24% considering ancillary services.**

***Index Terms*—Ancillary services, demand response programs (DRPs), industrial park, transactive energy management (TEM), virtual energy hub (VEH).**

NOMENCLATURE

Indices (Sets)

b ($\mathcal{B}$)	Index (set) of blocks for ASDR program.
e, k, q, v ($\mathcal{E}, \mathcal{K}, \mathcal{Q}, \mathcal{V}$)	Indices (sets) of CAES, CHP, P2H, and PV systems.
h ($\mathcal{H}$)	Index (set) of IEHs.
i, j ($\mathcal{I}$)	Indices (set) of electrical buses located in VEH.
m, n ($\mathcal{M}, \mathcal{N}$)	Indices (sets) of electrical and heat loads.
s ($\mathcal{S}$)	Index (set) of scenarios.
t ($\mathcal{T}$)	Index (set) of time intervals.

Parameters

$\bar{C}^{b}_{m,t}(\bar{E}^{b}_{m,t})$	The submitted capacity (energy) cost of reserve in ASDR program at time t in block b.
$\bar{D}^{b}_{m,t}$	The submitted DR reserve in ASDR program at time t.
$HD^{ini}_{n,t}$, $PD^{ini}_{m,t}$	The forecasted heat and electrical demands.
HR_e	Heat rate of CAES systems for discharging/simple cycle modes.
$KN_{i,\Xi}$, $KN_{h,\Xi}$	Bus-Ξ and hub-Ξ incidence matrices.
$P_{v,t}$	The forecasted PV power generation.
x_{ij}	Reactance of power line ij.
λ^{da}_t, λ^{re}_t, λ^{g}_t	The prices of DAM, RTM, and NGM.
ρ_k, ρ_q	Maintenance cost coefficients of CHP and P2H units.
ρ^{voc}_e, ρ^{voe}_e	Operating and maintenance cost coefficients of compressor and expander.
η^{DLC}_m, η^{DLC}_n	Participation rate of electrical consumer m and heat consumer n in DLC program.
ψ^{in}_m, ψ^{in}_n	Rate of incentive for electrical and heat demands change in DLC program.
π_s	Probability of each scenario.
Γ	Uncertainty budget of DAM price.

Decision variables

$AS_{m,t}$	The amount of capacity committed to participate in ASDR program at time t.
$G^{CAES}_{e,t}$, $G^{CHP}_{k,t}$	Natural gas consumed by CAES and CHP units at time t.
GC^{wh}_t, $\Delta GC^{wh}_{s,t}$	Scheduled/adjusted gas consumption by IEHs at time t.
$H_{k,t}$, $\Delta H_{k,s,t}$	Scheduled/adjusted heat production by CHP unit k at time t.
$H^{ch}_{q,t}$, $\Delta H^{ch}_{q,s,t}$	Scheduled/adjusted heat consumption by P2H storage q in charging mode at time t.
$H^{dis}_{q,t}$, $\Delta H^{dis}_{q,s,t}$	Scheduled/adjusted heat production by P2H storage q in discharging mode at time t.
$H^{dir}_{q,t}$, $\Delta H^{dir}_{q,s,t}$	Scheduled/adjusted heat production by P2H storage q in direct mode at time t.
$HD^{fin}_{n,t}$, $PD^{fin}_{m,t}$	Heat and electricity demands profile after implementing DRPs at time t.
P^{da}_t, $\Delta P^{re}_{s,t}$	Scheduled/adjusted power exchange between the VEH and DAM/RTM at time t.
$P^{ch}_{e,t}$, $\Delta P^{ch}_{e,s,t}$	Scheduled/adjusted power consumption by CAES system e in charging mode at time t.
$P^{dis}_{e,t}$, $\Delta P^{dis}_{e,s,t}$	Scheduled/adjusted power production by CAES system e in discharging mode at time t.
$P^{si}_{e,t}$, $\Delta P^{si}_{e,s,t}$	Scheduled/adjusted power production by CAES system e in simple cycle mode at time t.
$P_{h,t}$	Power generated (or consumed) by IEH h at time t.
$P_{k,t}$, $\Delta P_{k,s,t}$	Scheduled/adjusted power production by CHP unit k at time t.
$PF_{ij,t}$	Power flow between buses i and j at time t.
$PT^{in}_{h,t}$, $PT^{out}_{h,t}$	The amount of power transmitted from/to LEM to/from IEH h at time t.
R^{ASDR}_t, R^{DLC}_t	The revenue from participation in ASDR and DLC programs at time t.
$\delta_{i,t}$	Voltage angle of bus i at time t.

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$\beta_{s,t}$, ξ_s	Dual variables in the robust optimization model.
$u_{h,t}^{in}$, $u_{h,t}^{out}$	Binary variables to indicate the status of IEH *h* in TEM.
$u_{m,t}^{b}$, $y_{m,s,t}^{b}$	The binary variable to indicate the status of each block in ASDR program.
$\Lambda_{m,t}^{dw}$, $\Lambda_{n,t}^{dw}$	Electrical and heat demands change after DLC program execution at time *t*.

I. Introduction

A. Motivation and Aim

Nowadays, industrial parks have an undeniable role in the sustainable development of the electric power industry. The strategic role of industrial parks in the national economy, on the one hand, and the pressure of the energy crisis, on the other hand, have prompted power system operators to seriously reconsider selective approaches to supply the required demand of industrial consumers. To overcome these concerns, the theory of localization of sustainable power generation and consumption has been proposed to increase the security of energy supply [1]. From another standpoint, this theory can relieve the threats posed by the unscheduled outage of the components, thereby increasing the reliability and resiliency of power grids [2]. This motivates the power system operators to use industrial energy hubs (IEHs) with incentives to counterbalance the net-load, inherit the advantages of flexible consumers, and increase the flexibility of power systems at strategic locations, e.g., industrial parks [3]. For example, a large-scale energy hub has recently been launched in Orkney, Scotland by National Grid Electricity System Operator (ESO) to relieve pressure on the power system components in industrial areas [4].

Not long ago, the concept of virtual energy hubs (VEHs) was born as a supportive structure to avert the negative effects of using IEHs in restructured power systems [5]. A VEH can manage a large set of IEHs, which are equipped with renewable energy sources (RESs), energy conversion facilities, and energy storage systems (ESSs), to meet the required energy demands in reliable and economical manners. In addition, a VEH can provide unique ancillary services in various electricity markets by establishing a single operating strategy. According to some strong evidence, it is conceivable that VEHs would decrease the overall cost of operation for IEHs and industrial consumers while mitigating the effects of uncertain parameters without jeopardizing the integrity of the power grid operation. Thus, it is essential to draw up a more realistic scheduling framework to derive the optimal participation strategy of a VEH in energy markets, which allows the VEH operator (VEHO) to use advanced ancillary services considering the technical restrictions as well as the uncertainty associated with various parameters.

B. Literature Survey

The existing literature is rich in addressing the optimal operation strategy for IEHs to incorporate them into different energy markets. The available studies have predominantly used a variety of mathematical optimization approaches to achieve diverse targets with respect to the various distributed ancillary services and operational constraints. For instance, authors of [6] concentrated on a profit-driven strategy for optimal energy management of a VEH with the aim of solving the self-scheduling optimization problem in the context of the day-ahead market (DAM). In the same work, the variable RESs were considered as the main generation sources and the uncertainty related to these resources was modeled by the information gap-decision theory (IGDT). A deterministic model was developed in [7] where large-scale energy hubs submit their bid packages that are embodied pairs of quantities and prices for the provision of the pay-as-bid market model. Likewise, authors of [8] suggested a bi-level stochastic model for IEHs' participation in the day-ahead pool market based on both revenue and cost functions of IEHs' owners and industrial consumers. A multi-objective optimization model was presented in [9], which avails a promoted collaborative scheme to determine the optimal operation of multiple energy stations in the form of the IEHs. However, there is no guarantee that the strategies used in [6]–[9] perform optimally in the real-time market (RTM). In [10], a two-stage distributionally robust optimization problem was developed to analyze the economic performance of IEHs for active participation in the DAM and RTM by considering the influence of ESSs and RESs. An integrated chance-constrained stochastic model was proposed in [11] for multiple IEHs, where risk-averse operators seek to minimize the operation cost incurred in day-ahead and real-time trading. Additionally, the real-time scheduling problem was formulated in [12] as a dynamic pricing market to reach an economic interaction between the independent system operator (ISO) and the IEHs. The main target of [12] is to satisfy consumers' needs at a minimum operating cost with regard to the robust bidding mechanism.

On the other hand, the multi-supply facilities, e.g., combined heat and power (CHP), compressed air energy storage (CAES), and power-to-heat (P2H) units, as well as various ancillary services, e.g., demand response programs (DRPs), were widely scrutinized for identifying economic opportunities and enhancement of operational efficiency of IEHs under various uncertainties [13]. For example, in [14], the cooperative trading framework was proposed to determine the optimal scheduling of the renewable-based IEHs under the background of community-level energy systems. In the same work, the automatic DRP capability was used as an ancillary service between the IEHs and ISO to create a stable situation in the networked IEHs with respect to a real-time energy management model. Authors of [15] presented a robust optimization problem for the optimal energy management of a large-scale energy hub in the presence of CHP, boiler, and P2H units to cover electrical, cooling, and heating demands. In [16], a hybrid robust-stochastic approach was established to derive the optimal self-scheduling of a multi-energy retailer, which was in the role of an IEH, by considering the various flexibility options, e.g., CAES system, P2H storage, and DRP. There are other studies in this field, e.g., in [17], [18], modeling the possible interactions among IEHs to participate in the electricity markets with dynamic energy pricing. In these studies, each IEH tries to minimize its own optimization problem with regard to the practical DRPs. Furthermore, authors of [19], [20] focused on the optimal energy flow problem in an integrated energy system in the presence of multiple IEHs, industrial consumers, and RESs.

Table I summarizes the relevant literature in which the difference of each reference compared to the present study is highlighted. According to Table I, the technical background for optimal exploitation of VEHs is still in immature stages. To sum up, the following shortcomings (**Shs**) can be identified in the existing literature:

(**Sh1**) There is no study that has presented a holistic structure for deriving an optimal operation policy for the VEH to participate in various energy markets at the same time, taking into account grid constraints. Ignoring operational limitations of the power grid when exploiting VEH through a self-scheduling problem might lead to technically infeasible solutions in practice.

(**Sh2**) Most of the proposed structures only considered the role of DRP as an ancillary service, and hence, the emerging options such as transactive energy management (TEM) were neglected. Therefore, a promoted decision-making framework is required for enabling the VEHO to scrupulously determine the optimum scheduling strategy for the VEH by considering all available options.

(**Sh3**) A wide majority of these studies did not consider the role of CAES and P2H units within IEHs to investigate the resilient operation of the VEH.

(**Sh4**) Eventually, the effect of various uncertain parameters on the proposed decision-making strategies for optimal operation of VEHs was not considered in [7], [9], [17], [18].

C. Technical Contributions and Paper Organization

In light of the strategies considered in the literature for the optimal operation of VEHs, it is fair to say that designing a strategic operating structure for a VEH to participate in various energy markets is still an open problem. Also, there are currently no acceptable and scalable approaches to solve such relevant large-scale problems. To overcome these limitations, the main objectives of the proposed strategy are to minimize the operation cost of the VEH, which includes IEHs and multi-energy industrial consumers, to mitigate the operational risks, and to compensate the effect of existing uncertainties. The operation cost of the VEH can be minimized through designing an energy management strategy for each IEH as well as managing the energy consumption of industrial consumers by relying on advanced ancillary services. To the best of the authors' knowledge, this study contributes to state of the art in the following ways:

- On the modeling aspect, an optimal market participation strategy is presented for deriving the optimal operation of a VEH with IEHs and multi-energy consumers that captures the operational constraints to trade energy in the DAM, RTM, local electricity market (LEM), and natural gas market (NGM). The uncertainties arising from the DAM price, energy demands, and RESs are modeled through a two-stage robust-stochastic optimization model.
- The TEM mechanism is applied as a novel ancillary service to develop a free energy trading platform for IEHs that enables the VEHO to perform power dispatch scheduling in an integrated manner for all IEHs in the framework of LEM.
- Unlike previous studies, the incorporation of correlated market-based DRPs, i.e., direct load control (DLC) and ancillary service demand response (ASDR) programs, are considered in the proposed strategy as the ancillary services for economic participation of the VEH in the DAM and RTM according to the activity schedules of industrial consumers. From this standpoint, the proposed strategy contributes to the literature by adding realism to the scheduling problem to ensure that the implementation of DRPs will not jeopardize the welfare level of industrial consumers.
- In addition to CHP units and photovoltaic (PV) systems, the multi-supply facilities, i.e., CAES systems and P2H storages, are employed within the framework of IEHs to overcome the technical and economic risks by establishing a coordinated communication between energy supply sources and exploiting economic opportunities in different energy markets.

The rest of this paper is organized as follows. Section II describes the VEH structure, and then the proposed operational model of VEH in the form of a mixed-integer linear programming (MILP) problem is formulated in this section. The simulation results are presented in Section III, and eventually, the conclusions of this paper are drawn in Section IV.

TABLE I
TAXONOMY OF THE RELATED LITERATURE.

References	Modeled electricity markets			Ancillary services	Upgraded ECF	Uncertainty modelling
	DAM	RTM	LEM			
[6]	✓	-	-	-	CAES	IGDT
[7]	✓	-	-	-	-	Deterministic
[8]	✓	-	-	-	-	Stochastic
[9]	✓	-	-	-	-	Deterministic
[10]	✓	✓	-	-	-	Robust-Stochastich
[11]	✓	✓	-	-	-	Stochastic
[12]	✓	✓	-	-	-	Robust
[14]	-	✓	-	DRP	-	Stochastic
[15]	✓	-	-	-	P2H	Robust
[16]	✓	-	-	DRP	CAES, P2H	Robust-Stochastich
[17]	✓	-	-	DRP	-	Deterministic
[18]	✓	-	-	DRP	-	Deterministic
[19]	✓	-	-	DRP	-	Stochastic
[20]	✓	-	-	DRP	-	Robust-Stochastich
Proposed structure	✓	✓	✓	DRP, TEM	CAES, P2H	Robust-Stochastich

*Note: ECF-Energy conversion facilities

II. Problem Description

The proposed framework for the establishment of a VEH in the industrial park is illustrated in Fig. 1. We consider a VEH consisting of the set $h = \{1, ..., \mathcal{H}\}$ of $\mathcal{H}$ IEHs and several industrial consumers, in which VEHO strives to supply the total electrical and heat demands of the responsive/non-responsive consumers with the lowest operating costs and the highest level of flexibility. As depicted in Fig. 1, IEHs include sets of CHP units, P2H storages, CAES systems, and PV systems. As a price-taker entity, VEHO can participate in the DAM, RTM, LEM, and NGM to meet the energy demands and/or to energize IEHs' units. In addition, a savvy VEHO can take advantage of existing economic opportunities in energy markets, e.g., DRPs and TEM mechanism, as advanced ancillary services to decrease the imbalance costs in RTM and increase the VEH security.

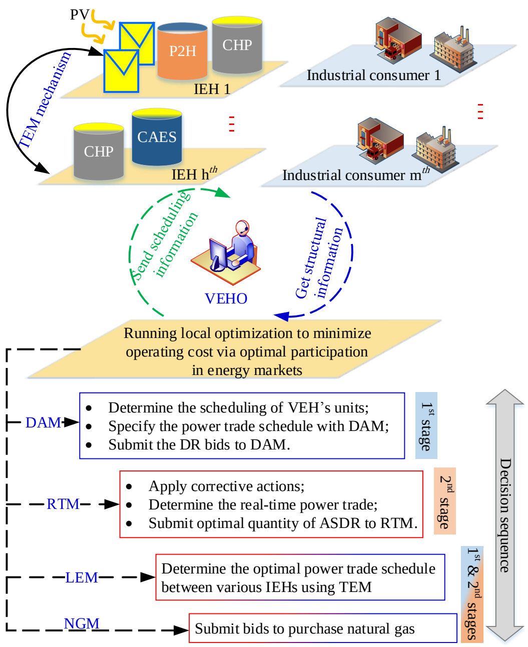

Fig. 1. Schematic illustration of a VEH to participate in various energy markets.

According to the proposed strategy, at first, VEHO gathers the information of IEHs and consumers, e.g., PV power generation, operational limits of each equipment, and activity schedules of responsive consumers. Afterward, VEHO determines the optimal scheduling of the dispatchable units in IEHs, and the deviant between the energy produced by these units and modified demands is compensated via the energy trade with different energy markets by forecasting DAM and NGM prices. The various steps of the proposed strategy are presented in detail in the following sub-sections.

A. Decision Sequence

The VEHO must design an appropriate decision-making structure based on energy markets' framework and various uncertainties to actively participate in the energy markets. This operator faces three major sources of uncertainty, i.e., DAM price, energy demands of industrial consumers, and output power of PV system. The robust approach is applied to handle the uncertainty of DAM price, whereas the stochastic programming model is used to deal with the other uncertain parameters. The sequence of stages in the proposed two-stage robust-stochastic decision-making structure is listed as follows:

- The first-stage decisions, i.e., *here-and-now*, are made by the VEHO regarding the energy bids in the DAM and NGM, online/offline status of generation units, implementation of TEM mechanism in the context of LEM, and participation in DRPs for the entire trading horizon and they do not depend on any scenario. The decisions made in this stage affect the VEHO's operational strategies in the second-stage.
- The second-stage decisions, i.e., *wait-and-see*, appertain to the energy deviations imposed by the VEHO in the RTM. This stage is made after the realization of all stochastic processes.

B. VEH Market Participation Strategy

As it was mentioned, the objective of the proposed market participation strategy for a VEH is to minimize the total operation cost across the trading horizon $t = \{1, ..., \mathcal{T}\}$. The objective function related to the VEH's expected operation cost (*TC*) is manifested in (1) as a two-stage stochastic MILP problem. In (1), ξ_1 expresses the cost (or income) of the scheduled energy trade resulting from the participation of VEH in DAM and NGM. ξ_2 represents the operation cost of the CHP units located in IEHs, whereas ξ_3 stands for the operation cost of P2H storages. ξ_4 accounts for the operation cost of CAES systems. ξ_5 denotes the income resulting from the involvement of the VEHO in the DLC and ASDR programs during the DAM. In line with the second-stage decisions, ξ_6 is related to the cost (or income) of energy exchange deviation in the real-time operation from the scheduled value in the day-ahead process due to the exploitation of VEH under different sources of uncertainty. In the proposed model, P_t^{da} and $\Delta P_{s,t}^{re}$ can have positive or negative values depending on the purchasing, i.e., $P_t^{da}, \Delta P_{s,t}^{re} \geq 0$, or selling, i.e., $P_t^{da}, \Delta P_{s,t}^{re} < 0$, power modes in the DAM and RTM. Hence, to encourage the VEHO to maintain the consistency of the scheduled power in the real-time operation, the RTM price, i.e., λ_t^{re} is determined as a two-stage settlement process, which is given in (2), where σ^+ and σ^- demonstrate the relative differences among the DAM and RTM prices in the up-regulation or down-regulation status. ξ_7-ξ_9 account for the operation cost of CHP units, P2H storages, and CAES systems in the second-stage, respectively. Eventually, ξ_{10} models the earnings associated with implementing the ASDR program in the RTM.

$$\lambda_t^{re} = \begin{cases} (1+\sigma^+) \cdot \lambda_t^{da}; & \Delta P_{s,t}^{re} \geq 0 \\ (1-\sigma^-) \cdot \lambda_t^{da}; & \Delta P_{s,t}^{re} < 0 \end{cases} \tag{2}$$

In (1), the uncertainty of DAM price was neglected and this parameter was perfectly forecasted. Since the uncertainty of DAM price is more vital than the other parameters, the VEHO prefers to use a robust approach to handle this uncertain parameter. The presented structure in [21], [22] is used to develop the two-stage stochastic model, which is defined in (1), as the hybrid robust-stochastic optimization problem. To make the modeling more understandable, the desired uncertain parameter, i.e., λ_t^{da}, is maintained in the objective function and the other terms of the objective function are replaced with $\Phi(\varphi) + \Upsilon(s, \varphi)$, which can be rewritten as (3). The uncertainty set of the DAM price can be described as (4)-(6) with regards to the budget of uncertainty, i.e., Γ. In (4), $\bar{\lambda}_t^{da}$ and $\tilde{\lambda}_t^{da}$ represent the forecasted DAM price and the maximum deviation of the forecasted value, respectively. To create the worst possible conditions for the VEHO to trade power in the DAM, the purchasing and selling power modes are adjusted as (7).

$$TC = \sum_{t \in \mathcal{T}} \sum_{s \in \mathcal{S}} \pi_s \left[(\lambda_t^{da} \cdot P_t^{da}) + \Phi(\varphi) + \Upsilon(s, \varphi) \right], \tag{3}$$

$$\lambda_t^{da} \in \left[\bar{\lambda}_t^{da} - \vartheta_{s,t} \cdot \tilde{\lambda}_t^{da}, \bar{\lambda}_t^{da} + \vartheta_{s,t} \cdot \tilde{\lambda}_t^{da} \right], \tag{4}$$

$$0 \leq \vartheta_{s,t} \leq 1, \qquad \forall s, t, \qquad : \beta_{s,t} \tag{5}$$

$$\sum_{t \in \mathcal{T}} \vartheta_{s,t} \leq \Gamma, \qquad \forall s, \qquad : \xi_s \tag{6}$$

$$\text{Min}: TC$$
$$TC=\sum_{t\in\mathcal{T}}\left[\begin{array}{l}\underbrace{(\lambda_t^{da}\cdot P_t^{da})+(\lambda_t^{g}\cdot GC_t^{wh})}_{\xi_1}+\underbrace{\sum_{k\in\mathcal{K}}\rho_k\cdot P_{k,t}}_{\xi_2}+\underbrace{\sum_{q\in\mathcal{Q}}\rho_q\cdot(H_{q,t}^{ch}+H_{q,t}^{dis})}_{\xi_3}+\\ \underbrace{\sum_{e\in\mathcal{E}}\left(\rho_e^{voc}\cdot(P_{e,t}^{ch}+P_{e,t}^{si})+(\rho_e^{voe}+\lambda_t^{g}\cdot HR_e)\cdot(P_{e,t}^{dis}+P_{e,t}^{si})\right)}_{\xi_4}-\underbrace{R_t^{DLC}-R_t^{ASDR}}_{\xi_5}\end{array}\right]+$$
$$\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\begin{array}{l}\underbrace{(\lambda_t^{re}\cdot\Delta P_{s,t}^{re})+(\lambda_t^{g}\cdot\Delta GC_{s,t}^{wh})}_{\xi_6}+\underbrace{\sum_{k\in\mathcal{K}}\rho_k\cdot\Delta P_{k,s,t}}_{\xi_7}+\underbrace{\sum_{q\in\mathcal{Q}}\rho_q\cdot(\Delta H_{q,s,t}^{ch}+\Delta H_{q,s,t}^{dis})}_{\xi_8}+\\ \underbrace{\sum_{e\in\mathcal{E}}(\rho_e^{voc}\cdot(\Delta P_{e,s,t}^{ch}+\Delta P_{e,s,t}^{si})+(\rho_e^{voe}+\lambda_t^{g}\cdot HR_e)\cdot(\Delta P_{e,s,t}^{dis}+\Delta P_{e,s,t}^{si}))}_{\xi_9}-\underbrace{R_{s,t}^{ASDR}}_{\xi_{10}}\end{array}\right] \quad (1)$$

$$\lambda_t^{da}=\begin{cases}\bar{\lambda}_t^{da}+\vartheta_{s,t}\cdot\tilde{\lambda}_t^{da}; & P_t^{da}\geq 0.\\ \bar{\lambda}_t^{da}-\vartheta_{s,t}\cdot\tilde{\lambda}_t^{da}; & P_t^{da}<0.\end{cases} \quad (7)$$

By using the defined robust model for the DAM price, the initial version of the objective function, which is presented in (3), can be converted to (8). To obtain a robust solution, the deviation from the forecasted value must be maximized using the defined auxiliary continuous variable, i.e., $\vartheta_{s,t}$.

$$\text{Min}: TC$$
$$TC=\begin{cases}\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\begin{array}{l}\underset{\vartheta_{s,t}}{\text{Max}}\left\{\bar{\lambda}_t^{da}+\vartheta_{s,t}\cdot\tilde{\lambda}_t^{da}\right\}\cdot P_t^{da}+\\ \Phi(\varphi)+\Upsilon(s,\varphi)\end{array}\right]; P_t^{da}\geq 0.\\ \sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\begin{array}{l}\underset{\vartheta_{s,t}}{\text{Max}}\left\{\bar{\lambda}_t^{da}-\vartheta_{s,t}\cdot\tilde{\lambda}_t^{da}\right\}\cdot P_t^{da}+\\ \Phi(\varphi)+\Upsilon(s,\varphi)\end{array}\right]; P_t^{da}<0.\end{cases} \quad (8)$$

s.t. (5) and (6)

By doing this process, the VEHO will face a bi-level min-max optimization problem. To deal with the created complexity in the optimization problem, the duality theory can be used to transfer the maximization part of the objective function into a minimization problem. Due to the existence of a conditional term in (8), the developed robust stochastic optimization problem has become a MILP problem. In order to use the conventional duality theory, which applies to linear programming problems, the developed MILP structure should be divided into two sub-problems (SPs) as (9) and (10). At this point, the duality theory must be applied separately to the maximization part of each SP to convert the bi-level min-max optimization problem into a single-level min-min problem.

$$\begin{aligned}&\text{SP1}:\\ &\text{Min}\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\underset{\vartheta_{s,t}}{\text{Max}}\left\{\bar{\lambda}_t^{da}+\vartheta_{s,t}\cdot\tilde{\lambda}_t^{da}\right\}\cdot P_t^{da}+\Phi(\varphi)+\Upsilon(s,\varphi)\right],\\ &\quad s.t.\quad (5)-(6),\end{aligned} \quad (9)$$

$$\begin{aligned}&\text{SP2}:\\ &\text{Min}\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\underset{\vartheta_{s,t}}{\text{Max}}\left\{\bar{\lambda}_t^{da}-\vartheta_{s,t}\cdot\tilde{\lambda}_t^{da}\right\}\cdot P_t^{da}+\Phi(\varphi)+\Upsilon(s,\varphi)\right],\\ &\quad s.t.\quad (5)-(6),\end{aligned} \quad (10)$$

After applying the duality theory, the final state of the robust-stochastic optimization problem can be modeled by (11)-(13).

$$\text{Min}: TC$$
$$TC=\begin{cases}\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\begin{array}{l}\bar{\lambda}_t^{da}\cdot P_t^{da}+(\beta_{s,t}+\xi_s\cdot\Gamma)\\ +\Phi(\varphi)+\Upsilon(s,\varphi)\end{array}\right]; P_t^{da}\geq 0,\\ \sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}}\pi_s\left[\begin{array}{l}\bar{\lambda}_t^{da}\cdot P_t^{da}-(\beta_{s,t}+\xi_s\cdot\Gamma)\\ +\Phi(\varphi)+\Upsilon(s,\varphi)\end{array}\right]; P_t^{da}<0,\end{cases} \quad (11)$$

$$\beta_{s,t}+\xi_s\geq\tilde{\lambda}_t^{da}\cdot P_t^{da},\qquad\forall s,t, \quad (12)$$

$$\beta_{s,t},\xi_s\geq 0,\qquad\forall s,t. \quad (13)$$

where $\beta_{s,t}$ and ξ_s are the auxiliary dual variables of the original hybrid robust-stochastic problem, which are applied for using the duality theory. After making this mathematical process, the hybrid robust–stochastic model can be solved using commercial optimization packages.

C. VEH Operational Constraints

The operational constraints related to the first-stage are presented in (14)-(16). The net active power injection equality in each bus can be formulated as (14). In (14), P_t^{da} represents the power exchange between the VEH and DAM at the point of common coupling (*PCC*). Based on (15), the DC power flow equation is used to model the VEH power flow. Equation (16) states the lower and upper limits of the branch flow to ensure reliable operation. In addition, the equalities/inequalities presented in (14)-(16) must be established for each scenario in the second-stage. To this end, (14)-(16) must be redefined in the optimization process according to the conditions stated in (17). Based on (17), P_t^{da}, $P_{h,t}$, $PF_{ij,t}$, and $\delta_{i,t}$ must be respectively replaced with $P_{s,t}^{re}-\Delta P_{s,t}^{re}$, $P_{h,s,t}$, $PF_{ij,s,t}$, and $\delta_{i,s,t}$ in (14)-(16) as the second-stage decision variables (DVs).

$$P_t^{da}\Big|_{i\in PCC}+\sum_{h\in\mathcal{H}}KN_{i,h}\cdot P_{h,t}-\sum_{m\in\mathcal{M}}KN_{i,m}\cdot PD_{m,t}^{fin}=\sum_{j\in\mathcal{I}}KN_{i,j}\cdot PF_{ij,t},\qquad\forall i,t, \quad (14)$$

$$PF_{ij,t}=\frac{\delta_{i,t}-\delta_{j,t}}{x_{ij}}\quad,\quad\forall i,j,t, \quad (15)$$

$$-\overline{PF_{ij}}\leq PF_{ij,t}\leq\overline{PF_{ij}}\quad,\quad\forall i,j,t, \quad (16)$$

$$(14)-(16),\quad\forall s,t\;\left|\;\begin{array}{c}DVs:\{P_{s,t}^{re}=P_t^{da}+\Delta P_{s,t}^{re};\\ P_{h,t}\rightarrow P_{h,s,t};\\ PF_{ij,t}\rightarrow PF_{ij,s,t};\\ \delta_{i,t}\rightarrow\delta_{i,s,t}.\}\end{array}\right. \quad (17)$$

D. IEHs Model

The available IEHs in the VEH are equipped with PV systems, CHP units, CAES systems, and P2H storages to cover a big part of the whole electrical demand and supply the heat demand of the industrial consumers. All of the operational constraints related to the available equipment in IEHs are considered in the proposed mathematical model, which can be found in [13], [16]. Based on the constraints provided in these references, the minimum/maximum power and heat generation limits and heat-power feasible operating region are used for modeling CHP units. Also, the charging/discharging rates and reservoir energy level constraints are taken into account for modeling CAES systems and P2H storages.

1) Energy Balance Constraints: Constraints (18)-(20) guarantee the multi-energy balance in each IEH in the first-stage decisions. It is important to remark that all operational limits and energy balance constraints must also be met in real-time session. To this end, constraints (18)-(20) must be updated for real-time operation decisions using (21). The set of second-stage decision variables involved in the scheduling of IEHs is given in (21). These variables should be replaced with the corresponding term in the first-stage decisions and the created equations should be applied in the optimization process.

$$P_{h,t} = \sum_{e \in \mathcal{E}} KN_{h,e} \cdot (P^{dis}_{e,t} + P^{si}_{e,t} - P^{ch}_{e,t}) + \sum_{k \in \mathcal{K}} KN_{h,k} \cdot P_{k,t} - \sum_{q \in \mathcal{Q}} KN_{h,q} \cdot P_{q,t} + \sum_{v \in \mathcal{V}} KN_{h,v} \cdot P_{v,t} + PT^{in}_{h,t} - PT^{out}_{h,t}, \quad \forall h,t, \tag{18}$$

$$\sum_{k \in \mathcal{K}} KN_{h,k} \cdot H_{k,t} + \sum_{q \in \mathcal{Q}} KN_{h,q} \cdot (H^{dis}_{q,t} - H^{ch}_{q,t} + H^{dir}_{q,t}) - \sum_{n \in \mathcal{N}} KN_{h,n} \cdot HD^{fin}_{n,t} = 0, \quad \forall h,t, \tag{19}$$

$$GC^{wh}_{t} = \sum_{e \in \mathcal{E}} G^{CAES}_{e,t} + \sum_{k \in \mathcal{K}} G^{CHP}_{k,t}, \quad \forall t, \tag{20}$$

$$(18)-(20), \quad \forall h,s,t \quad \left| \begin{array}{l} DVs: \{P_{h,t} \rightarrow P_{h,s,t}; \\ P_{k,s,t} = P_{k,t} + \Delta P_{k,s,t}; \\ P_{q,s,t} = P_{q,t} + \Delta P_{q,s,t}; \\ H_{k,s,t} = H_{k,t} + \Delta H_{k,s,t}; \\ H^{dis}_{q,s,t} = H^{dis}_{q,t} + \Delta H^{dis}_{q,s,t}; \\ H^{ch}_{q,s,t} = H^{ch}_{q,t} + \Delta H^{ch}_{q,s,t}; \\ H^{dir}_{q,s,t} = H^{dir}_{q,t} + \Delta H^{dir}_{q,s,t}; \\ G^{CAES}_{e,t} \rightarrow G^{CAES}_{e,s,t}; \\ G^{CHP}_{k,t} \rightarrow G^{CHP}_{k,s,t}; \\ GC^{wh}_{t} \rightarrow GC^{wh}_{s,t}.\} \end{array} \right. \tag{21}$$

E. TEM Mechanism Model

TEM mechanism provides a set of economic and control mechanisms to the VEHO as an advanced ancillary service to satisfy the dynamic power balance constraint in DAM and also to deal with the unexpected power mismatches in RTM by consolidating the potential capacity of IEHs [23]. Fig. 2 shows a schematic of the implementation process of the TEM mechanism for several IEHs, which are composed of different types of energy sources. According to the concept of the TEM mechanism, IEHs can trade power with each other in a free energy sharing platform within the framework of LEM. In practice, not all IEHs have the same energy conversion facilities and energy storage systems. In the proposed structure, the TEM mechanism enables the VEHO to perform power dispatch scheduling in an integrated manner to optimally utilize the available equipment in different IEHs. So that VEH has the lowest energy exchange rate with the DAM and RTM during the scheduling period and steps towards the realization of the theory of localization of sustainable power generation and

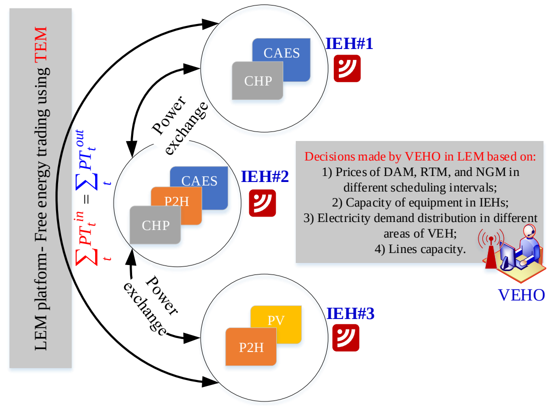

Fig. 2. Schematic illustration of the TEM mechanism.

consumption. The most important advantage of using the TEM mechanism is that there is no price fluctuation in the LEM and VEHO can develop the scheduling schemes for the VEH regardless of the economic arbitrage in the DAM and RTM. It is necessary to mention that the implementation of the TEM mechanism by VEHO depends on the operational constraints of the VEH, the distribution of industrial consumers over the different areas of the VEH, as well as the DAM, RTM, and NGM price signals. To motivate the IEHs to participate in this mechanism, an assumption based on economic policies is defined as below:

Assumption 1: *It is assumed that IEHs can communicate with the VEHO using a two-way communication platform to perform the TEM mechanism. This action provides a free power trading possibility between IEHs by using the LEM infrastructures.*

The mathematical model of the TEM mechanism can be expressed as (22)-(26) considering the provided assumption. The inequality (22) indicates that each IEH cannot simultaneously receive/transmit power from/to the LEM. Based on (23), the amount of traded power should not exceed the allowable limit. The power balance limitations in the form of the TEM mechanism for each IEH and during the scheduling horizon are enforced by (24) and (25). To avoid violating the rules of the TEM mechanism in real-time operation decisions, the limitations set out in (23)-(25) must also be satisfied for each scenario using (26). Based on (26), $PT^{in}_{h,s,t}$ and $PT^{out}_{h,s,t}$ belong to the set of second-stage decision variables. In (26), $\Delta PT^{in}_{h,s,t}$ and $\Delta PT^{out}_{h,s,t}$ demonstrate the adjusted power transmitted from/to LEM to/from IEHs during the second-stage decisions.

$$u^{in}_{h,t} + u^{out}_{h,t} \leq 1, \quad \forall h,t, \tag{22}$$

$$PT^{X}_{h,t} \leq \overline{PT_h} \cdot u^{X}_{h,t}, \quad \forall h,t,X \in \{in, out\}, \tag{23}$$

$$\sum_{t \in \mathcal{T}} PT^{in}_{h,t} = \sum_{t \in \mathcal{T}} PT^{out}_{h,t}, \quad \forall h, \tag{24}$$

$$\sum_{h \in \mathcal{H}} PT^{in}_{h,t} = \sum_{h \in \mathcal{H}} PT^{out}_{h,t}, \quad \forall t, \tag{25}$$

$$(23)-(25), \quad \forall h,s,t \quad \left| \begin{array}{l} DVs: \{PT^{in}_{h,s,t} = PT^{in}_{h,t} + \Delta PT^{in}_{h,s,t}; \\ PT^{out}_{h,s,t} = PT^{out}_{h,t} + \Delta PT^{out}_{h,s,t}.\} \end{array} \right. \tag{26}$$

F. Market-Based DRPs Model

In this study, the VEHO is considered as the demand response (DR) aggregator to implement the market-based DRPs. Among various options of market-based DRPs, DLC and ASDR programs are considered as ancillary services. These options are very useful for the VEHO to harness existing opportunities in the DAM and RTM with regard to the industrial customers' activity schedules. One of the important advantages of the proposed mechanism is to prevent the reduction of the welfare level of consumers when participating in various DRPs. It should be noted that there are no preconditions for industrial consumers to participate in these programs, and volunteer consumers of any size can participate in these programs and help advance the targets of the VEHO. More details about these programs can be found in [13], [24]. The formulation of these programs is as follows:

1) DLC Program: In the context of the DLC program, the participation rate, i.e., $\eta^{DLC}_{(\cdot)}$, and the activity schedule of each volunteer consumer, i.e., $[T^s_{(\cdot)}, T^f_{(\cdot)}]$, are delivered to the VEHO as DR signals so that the VEHO implements the proposed market participation strategy for the VEH based on the tradable DR volume during the scheduling period [13]. The optimal amount of reduced demands in the context of the DLC program can be calculated according to the participation rate of each consumer by (27). This equation must be adjusted according to the activity schedule of each consumer and is strictly valid only in this interval. The modified electrical and heat profiles are obtained using (28). Furthermore, the reward of customers' participation in the DLC program can be calculated with the defined function in (29).

$$\begin{cases} 0 \le \Lambda^{dw}_{m,t} \le \eta^{DLC}_m \cdot PD^{ini}_{m,t}, & \forall m,t \in [T^s_m, T^f_m], \\ 0 \le \Lambda^{dw}_{n,t} \le \eta^{DLC}_n \cdot HD^{ini}_{n,t}, & \forall n,t \in [T^s_n, T^f_n], \end{cases} \tag{27}$$

$$\begin{cases} PD^{fin}_{m,t} = PD^{ini}_{m,t} - \Lambda^{dw}_{m,t}, & \forall m,t \in [T^s_m, T^f_m], \\ HD^{fin}_{n,t} = HD^{ini}_{n,t} - \Lambda^{dw}_{n,t}, & \forall n,t \in [T^s_n, T^f_n], \end{cases} \tag{28}$$

$$R^{DLC}_t = \sum_{m\in\mathcal{M}} (\psi^{in}_m \cdot \Lambda^{dw}_{m,t}) + \sum_{n\in\mathcal{N}} (\psi^{in}_n \cdot \Lambda^{dw}_{n,t}), \quad \forall t. \tag{29}$$

2) ASDR Program: The ASDR program operates as a reserve source. In this program, industrial consumers submit their bid to ISO through the VEHO to curtail their load as operational reserve. If their bid is accepted, ISO will reward the industrial consumers located in VEH for the commitment as a standby reserve capacity. The ASDR contracts can be defined by a stepwise function, as shown in Fig. 3. It should be noted that this program is considered in both decision sequences and applied only to the electrical demands. The required formulations to understand this program are presented by (30)-(35) [24]. Equation (30) represents the total amount of the participated DR volume in the form of the ASDR program in the DAM. The capacity reward of ASDR program deployment in the DAM is given in (31). The total amount of reserve capacity that calls in the RTM, i.e., $\widehat{AS}_{m,s,t}$, can be calculated by (32) and (33). The final electrical profile after running the ASDR program is determined using (34). Eventually, the income resulting from the involvement of VEH in the ASDR program in the RTM is calculated by (35).

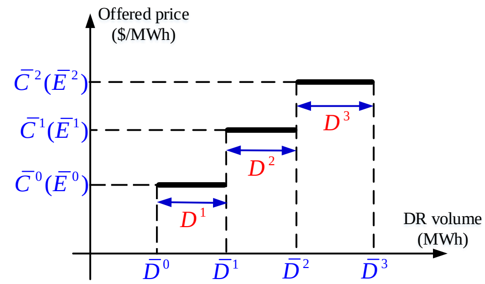

Fig. 3. The stepwise curve for the ASDR program.

$$AS_{m,t} = \bar{D}^0_{m,t} \cdot u^0_{m,t} + \sum_{b=1}^{\mathcal{B}} (\bar{D}^b_{m,t} \cdot u^b_{m,t}), \forall m,t \in [T^s_m, T^f_m], \tag{30}$$

$$R^{ASDR}_t = \sum_{m\in\mathcal{M}} \left[\begin{array}{c} (\bar{D}^0_{m,t} \cdot \bar{C}^0_{m,t} \cdot u^0_{m,t}) + \\ \sum_{b=1}^{\mathcal{B}} (\bar{D}^b_{m,t} \cdot \bar{C}^{b-1}_{m,t} \cdot u^b_{m,t}) \end{array} \right], \forall t \in [T^s_m, T^f_m], \tag{31}$$

$$\widehat{AS}_{m,s,t} = \bar{D}^0_{m,t} \cdot y^0_{m,s,t} + \sum_{b=1}^{\mathcal{B}} (\bar{D}^b_{m,t} \cdot y^b_{m,s,t}), \forall m,s,t \in [T^s_m, T^f_m], \tag{32}$$

$$0 \le \widehat{AS}_{m,s,t} \le AS_{m,t}, \quad \forall m,s,t \in [T^s_m, T^f_m], \tag{33}$$

$$PD^{fin}_{m,s,t} = PD^{ini}_{m,s,t} - \widehat{AS}_{m,s,t}, \quad \forall m,s,t \in [T^s_m, T^f_m], \tag{34}$$

$$R^{ASDR}_{s,t} = \sum_{m\in\mathcal{M}} \left[\begin{array}{c} (\bar{D}^0_{m,t} \cdot \bar{E}^0_{m,t} \cdot y^0_{m,s,t}) + \\ \sum_{b=1}^{\mathcal{B}} (\bar{D}^b_{m,t} \cdot \bar{E}^{b-1}_{m,t} \cdot y^b_{m,s,t}) \end{array} \right], \forall s,t. \tag{35}$$

III. Case Studies

A. Simulation Setup

In this section, the effectiveness of the proposed strategy was assessed based on the extended IEEE 14-bus test system in [25], as an industrial park. As seen in Fig. 4, the VEH comprises of four IEHs, i.e., $\mathcal{H} = 4$, four heat loads, i.e., $\mathcal{N} = 4$, and 11 electrical loads, i.e., $\mathcal{M} = 11$. Bus 1 was considered as the PCC. Detailed information about the original test system can be found in [25]. Table II outlines the units available in each IEH. The technical constraints and characteristics of each unit are given in [6], [13], [16]. The forecasted PV power production and energy demands are shown in Fig. 5. The maximum capacity of each PV system was set to 15 MW. In addition, the electrical and heat peak demands of the VEH were considered to be 175.8 MW and 53.5 MW, respectively. The distribution of electrical loads in each bus was taken from [25]. Whereas the heat loads connected to the buses 2, 3, 6, 8 had 18%, 54%, 12%, and 16% share of the total heat demand, respectively. The utilized energy prices for DAM and NGM were adopted from [16]. The RTM prices for the up-regulation and down-regulation status were set to be 1.2 and 0.8 of the DAM prices, respectively. The assumptions and information used to run DLC and ASDR programs were adapted from [13], [26]. The activity schedules of flexible consumers to participate in various DRPs are specified in Table III. The length of the operational horizon was considered 24 hours, i.e., $\mathcal{T} = 24$, and the time resolution was set to 1 hour. The proposed mathematical model was coded in the GAMS software, and all cases were implemented using CPLEX solver [27] on a laptop with Intel 7-core 1.8 GHz and 6 GB of

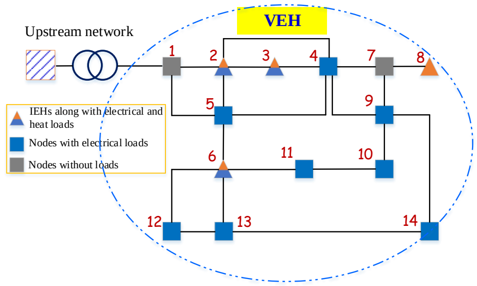

Fig. 4. One-line diagram of studied VEH.

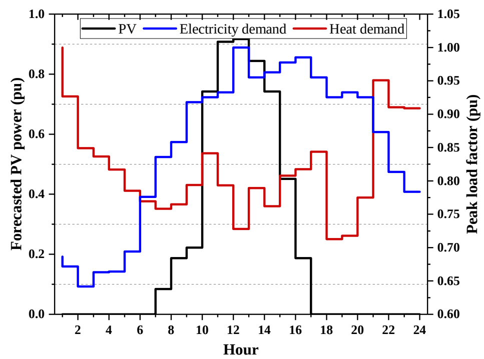

Fig. 5. Forecasted multi-energy demands and output power of PV system.

RAM. The computation time was less than 20 s considering all introduced tools. Since the proposed structure is designed as a MILP problem, there are no restrictions on the scalability of the proposed strategy. Therefore, the researchers can be expanded the dimensions of the test system by maintaining a proper scale between the system equipment, e.g., line capacity and characteristics of IEHs, and energy demands.

B. Results and Discussion

To verify the effectiveness of the proposed market participation strategy for the VEH, four different case studies were analyzed as follows:

- *Base case*: The robust performance of the VEH was analyzed without considering any ancillary service under the presented two-stage robust-stochastic problem;
- *Case 1*: *Base case* was developed by considering the role of the TEM mechanism in achieving the desired aims;
- *Case 2*: Similar to *Case 1*, but the impact of the DLC program along with the TEM mechanism on the robust performance of the VEH was evaluated;
- *Case 3*: Similar to *Case 2*, but the ASDR program was replaced by the DLC program.

TABLE II
AVAILABLE ENERGY SOURCES IN IEHS.

	Located at bus	CHP	P2H	CAES	PV
IEH1	2	✓	-	✓	-
IEH2	3	✓	✓	-	✓
IEH3	6	-	✓	-	✓
IEH4	8	✓	-	✓	-

TABLE III
CONSUMER ACTIVITY SCHEDULE IN EACH DRP.

		Bus No.	Activity schedules (hour)
DLC program	Electrical loads	2-4	6-9, 22-24
		5, 6, 9, 10	11-19
		11-14	8-10, 13-16, 21-23
	Heat loads	2, 3, 6, 8	8-18
ASDR program	Electrical loads	2-4, 9, 13	11-14

To implement the developed two-stage robust-stochastic optimization model, the Monte-Carlo simulation (MCS) was used to consider the uncertain behavior of PV systems and energy demands in real-time operation decisions. A total of one thousand scenarios were generated using MCS in the form of the normal probability distribution function (PDF) with a deviation of 10% and a mean of zero. Then, the generated scenarios were reduced to ten scenarios by the GAMS/SCENRED tool [27]. The robust approach was also applied to address the uncertainty associated with the DAM price with regards to the various amounts of the budget of uncertainty, i.e., Γ, and different ranges for the maximum deviation between the predicted and actual values, i.e., $\tilde{\lambda}_t^{da}$. Fig. 6 demonstrates the effects of Γ and $\tilde{\lambda}_t^{da}$ on the total operation cost of the VEH for the base case. As can be observed, as the budget of uncertainty increases, the expected operation cost of the VEH increases as well, given the fact that the VEHO tries to deal with more severe forecasting violations. Similarly, increasing deviation from the predicted DAM price has led to significant increases in the total operation cost.

To examine the effects of ancillary services on the operation cost, Γ and $\tilde{\lambda}_t^{da}$ were fixed to 4 and 15%, respectively. To get a better understanding of what happens in the presence of each service, the details of the cost/revenue terms are summarized in Table IV. Based on Table IV, it is clear that the day-ahead cost is higher than the real-time cost in all case studies. In terms of the operation cost of IEHs, the base case had placed in the worst situation compared with other case studies. Generally, the operation cost of the VEH was decreased by up to 9.24% in case 1, 12.42% in case 2, and 55.75% in case 3 compared to the base case by adding different combinations of ancillary services to the proposed market participation strategy. It can also be seen that case 3 is superior, as the coordinated use of the TEM mechanism and ASDR program incurs the lowest imbalance cost, earns the highest revenue (\$163.19k), as well as the lowest operation cost of the VEH (\$143.27k).

The amount of power trading of VEH in the DAM and LEM for case 3 are plotted in Fig. 7. As seen from this figure, the exchanged power between VEH and DAM decreases from 145.7 MW, at 10 o'clock, to 82 MW, at 13 o'clock, when

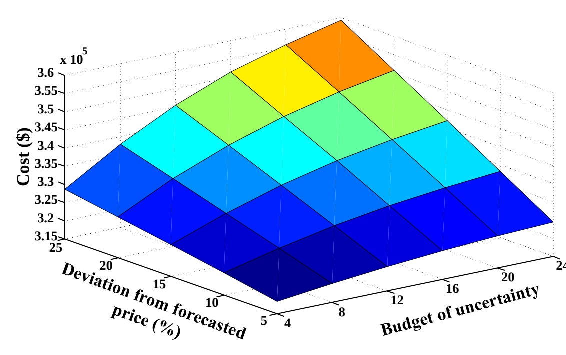

Fig. 6. Impact of Γ and $\tilde{\lambda}_t^{da}$ on total operation cost of VEH for base case.

TABLE IV
COST/REVENUE ALLOCATION FOR EACH CASE STUDY (NOTE $K=$1000).

	Base case	Case 1	Case 2	Case 3
Power purchase cost from DAM ($k)	180.57	186.11	178.43	185.51
Power purchase cost from RTM ($k)	0.298	0.248	5.06	0
Gas purchase cost from NGM ($k)	127.22	100.91	94.35	101.89
Operation cost of IEHs ($k)	27.44	18.31	17.76	19.06
Revenue from power sales to RTM ($k)	11.78	11.74	7.36	145.31
Revenue from DRPs ($k)	_	_	4.69	17.88
Total operation cost ($k)	323.748	293.838	283.55	143.27
Decremented cost (%)	_	-9.24	-12.42	-55.75

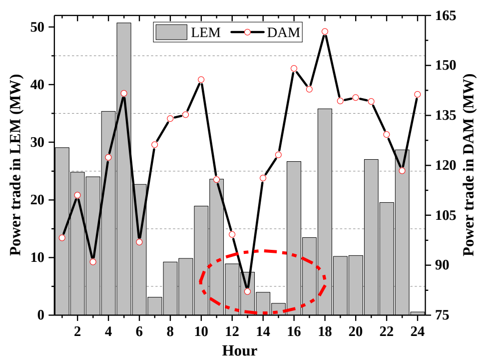

Fig. 7. The amount of traded power in the LEM and DAM for case 3.

the VEHO's commitment to implement the ASDR program is communicated to the ISO. So, the implementation of the ASDR program in the real-time session was the principal reason for the VEHO's desire to have more power deviations in the RTM in the hope of gaining a greater profit. This fact is clearly seen in the fifth line of Table IV where the revenue from power trading in the RTM has increased from $11.78k in the base case to $145.31k in case 3. From the perspective of VEH participation in the LEM, due to the decrease in power demand as well as the implementation of the ASDR program during time intervals 7-9 and 12-15, respectively, the lowest amount of power was traded in the LEM by means of TEM mechanism. The presence of multi-supply facilities within the framework of IEHs in the diverse locations of the industrial park had a profound effect on the exchanged power in the LEM, particularly during the peak price period. The hourly scheduling of CHP units, CAES systems, and P2H storages for case 3 are shown in Fig. 8. The VEHO can use the capabilities of multi-supply facilities to distribute the consumers' demand among different sources as well as to enhance the flexibility of the VEH against various uncertain sources or cyber-attacks.

Moreover, the effects of DLC and ASDR programs in coordination with the TEM mechanism on the electrical demands of VEH are demonstrated in Fig. 9. As can be seen, the VEHO participates in limited hours, i.e., during time slot 11-14, in the ASDR program by considering the activity schedules of volunteer consumers, as given in Table III. On the contrary, the VEHO has participated in extended hours in the DLC program with regard to the activity schedules of each consumer. It can be found that the total electrical demands of the industrial consumers were reduced by up to 6.05% and 3.01% in the form of the DLC and ASDR programs, respectively, which was one of the reasons for reducing the operation cost of the VEH. According to the obtained results, it can be claimed that the VEHO can overcome the existing potential risks associated with different players by creating a coordinated communication process between the TEM mechanism and DRPs.

C. Sensitivity Analysis

To further analyze the effect of the key input parameters on the performance of the VEH, several sensitivity analyses were conducted in this sub-section. These analyses pave the way for the VEHO to take advantage of existing opportunities in different markets. All assumptions were the same as those of the third case study. At first, the sensitivity of the total operation cost of the VEH to the relative differences among the DAM and RTM prices in the up-regulation, i.e., $(1+\sigma^+)$, and down-regulation, i.e., $(1-\sigma^-)$, status was analyzed. To this end, σ^+ and σ^- were changed from 0.05 to 0.35 applying seven equal steps. As can be seen from Fig. 10, the operation cost of the VEH is increased linearly by increasing the values of σ^+ and σ^-. This analysis shows that the total operation cost of the VEH strongly depends on the price difference between the DAM and RTM, which highlights the need to use a robust strategy to deal with the uncertainty of the DAM price.

Furthermore, the sensitivity of the amount of traded power in the DAM as well as the performance of the CAES system to variations of the robustness parameters was investigated. From an economic point of view, the VEHO should strive to have the least amount of power exchanges with the DAM during the

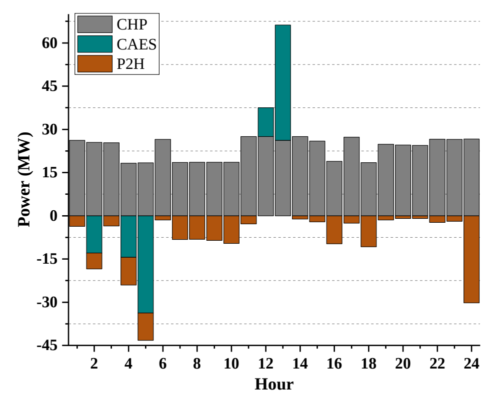

Fig. 8. Hourly scheduling of CHP, CAES, and P2H units for case 3.

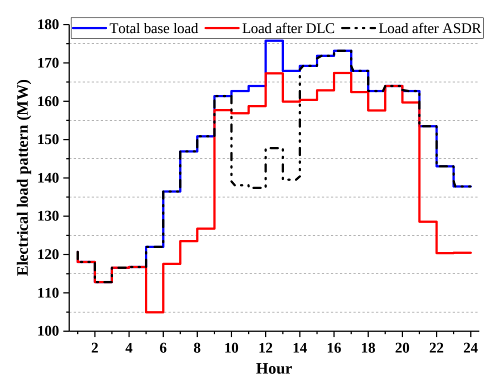

Fig. 9. The effect of DRPs on the profile of electricity loads for cases 2 and 3.

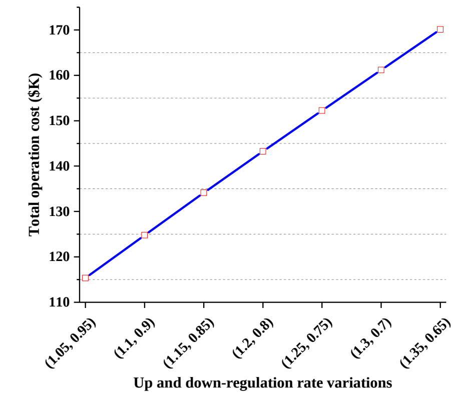

Fig. 10. Sensitivity of the total operation cost of VEH to σ^+ and σ^-.

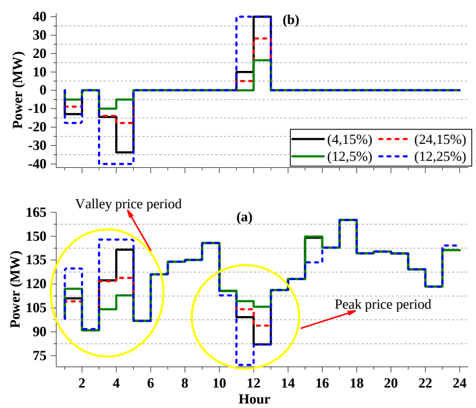

Fig. 11. Sensitivity of (a) the traded power in the DAM; (b) performance of CAES systems to variations of the robustness parameters.

peak price period and to make the most of the VEH's internal capabilities, e.g., CAES system, to cover electrical demands. This trend can be intensified depending on the robustness degree, i.e., (Γ , $\tilde{\lambda}_t^{da}$), intended for the DAM price. To evaluate this issue, four different (Γ , $\tilde{\lambda}_t^{da}$) combinations, i.e., (4, 15%), (24, 15%), (12, 5%), and (12, 25%), were selected to repeat the performed simulations in case 3. The variation in the amount of traded power between the VEH and DAM for each combination is shown in Fig. 11a. As can be seen from Fig. 11a, the traded power between the VEH and DAM has a similar range for different combinations throughout the entire time period, except the peak and valley periods. Also, Fig. 11b gives more information on the performance of CAES systems with respect to different robustness degrees. It can be observed that the participation of CAES systems in the peak and valley periods has also increased by changing the robustness degree and in direct proportion to the traded power in the DAM. From Figs. 11a and 11b, it can be seen that $\tilde{\lambda}_t^{da}$ has a greater effect on the fluctuations in the traded power in the peak and valley periods than Γ. So, the highest and lowest amounts of the traded power between the VEH and DAM in the valley and peak periods as well as the highest participation rate of CAES systems in the proposed strategy belonged to the highest range of $\tilde{\lambda}_t^{da}$, i.e., 25%. These results confirm the effectiveness and competence of the proposed market participation strategy to deal with increasing the robustness degree of the DAM price uncertainty.

D. After the Fact Analysis

As mentioned earlier, the robust optimization approach is referred to as a "maximum performance" method, where the total operation cost is maximized according to Γ and $\tilde{\lambda}_t^{da}$. On the other hand, stochastic approaches try to deal with the uncertain behavior of different parameters based on a limited number of scenarios. In this sub-section, the effectiveness and usefulness of the proposed hybrid strategy compared to the pure stochastic method were evaluated using an "after the fact" analysis. For this purpose, the actual DAM price of the Iberian electricity market on 13 January 2021 [28] was used to repeat the third case study based on $\Gamma = 4$ and $\tilde{\lambda}_t^{da} = 15\%$. After solving the proposed robust-stochastic optimization model using the actual DAM price, the total operation cost of the VEH was equal to \$152.46k. In the next step, the uncertainty of the DAM price was modeled with several scenarios, like other uncertain parameters, to execute the pure stochastic approach. To this end, one thousand scenarios were generated for the DAM price alongside the produced scenarios for the PV systems and energy demands using the MCS. It should be noted that the actual DAM prices selected from the Iberian electricity market were the base values for the generation of the DAM price scenarios. Then, the proposed two-stage stochastic optimization problem was solved for each scenario to obtain the total operation cost of the VEH. To this end, equations (3)-(13) were removed from the optimization process. The results of the after the fact analysis are shown in Fig. 12. As can be observed in Fig. 12, the total operation cost of the VEH is always less than that obtained by the hybrid robust-stochastic model (i.e., \$152.46k). Therefore, it can be confirmed that the proposed hybrid model is always robust against the uncertainty of DAM price and guarantees the maximum operation cost under the condition that the other uncertain sources fall inside their uncertainty sets. To achieve the most conservative state, the VEHO must increase Γ, which leads to increasing the expected operation cost of the VEH.

E. Price-Making Role of the VEH

In the proposed market participation strategy, it was considered that the formed VEH was connected to a large-scale power system through a *PCC*. Furthermore, it was assumed that the amount of power generated/consumed by the VEH could not affect the behavior of other entities in the power

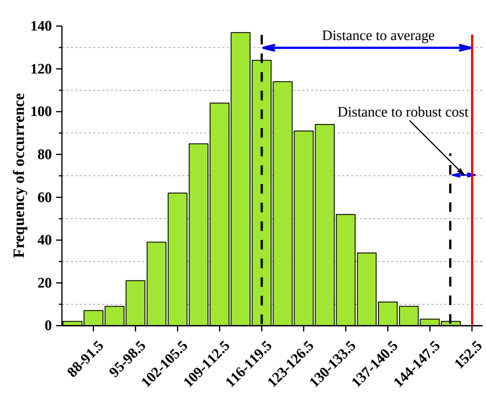

Fig. 12. Results of after the fact analysis for robustness justification.

system as well as the market clearing price. Hence, the proposed structure was developed in the form of a self-scheduling problem for VEHO, and VEHO tried to forecast energy prices for day-ahead energy markets.

From another perspective, it can be assumed that in the developed market participation strategy, multiple VEHs are connected to each other through energy sharing mechanisms and cover a wider range of the system under study. In this case, the amount of energy consumed/generated by different VEHs will affect the energy prices as well as the scheduling of other entities involved with the test system, e.g., thermal units, other dispatchable units, gas turbines. In this state, the VEHs must be considered as the price-maker entities, and the infrastructures of the power system, gas network, and district heating network should be modeled to determine the optimal performance of each VEH. Therefore, the proposed strategy can be extended under an integrated security-constrained unit commitment (SCUC) problem from the perspective of the VEHOs and energy system operators. To this end, a bi-level decision-making model needs to be developed to determine the optimal operation of the VEHs in different energy markets along with other entities involved in energy systems. It should be noted that in this situation, one of the main outcomes of the developed structure will be the market clearing prices.

IV. Conclusion and Future Work

This paper proposed a novel optimal market participation strategy for a VEH containing IEHs and multi-energy industrial consumers for energy trading in the DAM, RTM, LEM, and NGM. The presented strategy was organized and formulated as a two-stage robust-stochastic optimization problem based on the advanced ancillary services to handle the day-ahead and real-time operation decisions. Uncertainties arising from various sources of different nature, such as DAM price, energy demands, and PV systems, were considered under a realistic power system model that involves all operational constraints to address the concerns of the VEHO. Simulation results revealed that the proposed strategy in coordination with the TEM mechanism and market-based DRPs could help manage the VEH's behavior by decreasing the total operation cost by 55.75%. To sum up, the use of ancillary services was able to provide affordable solutions to identify optimal operation schemes.

The authors' future research endeavor will concentrate on analyzing the price-making role of the VEH in the presence of peer-to-peer energy trading mechanisms.

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