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Short-term Self-Scheduling of Virtual Energy Hub Plant within Thermal Energy Market

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Abstract— Multi-carrier energy systems create new challenges as well as opportunities in future energy systems. One of these challenges is the interaction among multiple energy systems and energy hubs on different energy markets. By the advent of the local thermal energy market in many countries, energy hubs' scheduling becomes more prominent. In this paper, a new approach to energy hubs scheduling is offered, called virtual energy hub (VEH). **The proposed concept of the energy hub, which is named as the VEH in this paper, is referred to an architecture based on the energy hub beside the proposed self-scheduling approach. The VEH is operated,** based on the different energy carriers and facilities as well as maximization its revenue by participation on the various local energy markets. The proposed virtual energy hub (VEH) optimizes its revenue from participating in the electrical and thermal energy markets by examining both local markets. Participation a player in the energy markets by using the integrated point of view can be reached to a higher benefit and optimal operation of the facilities in comparison with independent energy systems. In a competitive energy market, a VEH optimizes its self-scheduling problem in order to maximize its benefit considering uncertainties related to renewable resources. To handle the problem under uncertainty, a non-probabilistic information gap method is implemented in this study. The proposed model enables the VEH to pursue two different strategies concerning uncertainties, namely risk-averse strategy and risk-seeker strategy. For effective participation of the renewable-based VEH plant in the local energy market, compressed air energy storage (CAES) unit is used as a solution for the volatility of the wind power generation. Finally, the proposed model is applied to a test case and the numerical results validate the proposed approach.

Index Terms— Virtual energy hub, local thermal energy market, information gap decision theory, wind power generation, compressed air energy storage.

NOMENCLATURE

Indices:

t	Time period index, from 1 to T .
c	CHP units index, from 1 to C .
b	Boilers index, from 1 to B .

Parameters:

$\lambda^{E/H,ex}$	The price of the exported electricity/heat.
$\lambda^{E/H,im}$	The price of imported electricity/heat.
λ^G	Price of input fuel (natural gas).
$\rho_{CHP/boiler}$	Maintenance coefficient of the CHP/boiler unit.
$Cost^{su/sh}$	Startup/shutdown cost.
HV	Natural gas heat value.
HPR_{CHP}	Each CHP units' heat to power ratio.
η_{HE}	Heat exchanger efficiency.
$P_{Min/Max}^{E,CHP/Boiler}$	Minimum/maximum range of the CHP/boiler units' generations.
$\eta_{CHP/boiler}$	CHP/boiler units' efficiency.
$P_{Max}^{E,CS_{ch/dch}}$	Maximum capacity of compressor/expander.
$\phi^{exp/c}$	Maintenance and operation costs' variable of the expander/compressor.
CP	EHP system coefficient of performance.
$P_{Min/Max}^{H,EHP}$	Minimum/maximum output of the EHP unit.
$P_{Min/Max}^{sg^{ch}}$	Minimum/maximum rate of the charging state of the energy storage units.
$P_{Min/Max}^{sg^{dch}}$	Minimum/maximum rate of the discharging state of the energy storage units.
$PS_{Min/Max}^{sg}$	Minimum/maximum stored energy in the energy storages.
η_{sg}	Standby efficiency of the energy storage units.
$\eta_{sg}^{ch/dch}$	Charging/discharging efficiency of the energy storages.
$\tilde{P}^{E,wind}$	Forecasted wind power generation (WPG).
κ	Benefit deviation factor of the robustness function.
ω	Benefit deviation factor of the opportunity function.
B_e	Expected benefit.

Variables:

Revenue / Cost	VEH plant's revenue/cost.
$P^{E/H,ex}$	Amount of exported electricity/heat.

$P^{E/H,im}$	Amount of imported electricity/heat.
$R^{E/H}$	Revenue from exporting electricity/heat.
$C^{E/H}$	Cost of the imported electricity/heat.
$C^{CHP/boiler}$	The operation cost of CHP/boiler units.
$P^{E/H,CHP}$	Electrical/thermal generation of the CHP units.
$P^{H,Boiler}$	Generation of the boilers.
$P^{E,CS_{ch/dch}}$	Power consumption/generation of the CAES in charging/discharging mode.
E^{CS}	Amount of stored energy in the CAES unit.
$P^{E/H,EHP}$	Electrical/thermal input/output of EHP.
$P^{sg_{ch/dch}}$	Input/ output of the energy storages.
PS^{sg}	Amount of stored energy in the energy storages.
$P^{E,wind}$	Power generation of WPG.
α	Deviation factor of the WPG (uncertain variable of the IGDT method).

Functions:

$U(\tilde{P}^{E,wind}, \alpha)$	IGDT methodology's uncertainty.
$\tilde{\alpha}(P, B_r)$	IGDT method's robustness function.
$\tilde{\beta}(P, B_o)$	IGDT method's opportunity function.
$C^{su/sh}$	Startup/shutdown cost of the CHP units.
C^{CS}	The operation cost of the CAES system.

I. INTRODUCTION

A. Motivation and Problem Description

RECENTLY, the integration of various energy carriers and the penetration of distributed energy generation have resulted in a more efficient operation of the power systems. With this background, energy hub concept represented as an interface between different energy infrastructures [1]. In this environment, the issues of the impact of various energy carriers on the energy market become important. Providing a service using different energy systems will make the service provider more flexible and more opportunities for the end-users. Due to low operating costs and energy efficiency, wind power generation (WPG) is a reliable resource among renewable energy technologies [2]. Despite the uncertain parameters in the problem, the unfavourable risk of different parameters should be reduced. Energy storages are one of the important components of the renewable-based multi-carrier energy systems. In one hand, energy storage systems provide more optimal and flexible operation for power systems. On the other hand, storages enable participation in the energy market for virtual energy hub (VEH) plants. **The proposed VEH plant is referred to as an architecture based on the energy hub concept beside the proposed self-scheduling approach. The idea of the VEH is a concept based on the energy hub architecture to make more revenue by participation in the various energy markets.** In addition, different equipment such as generating, converting and storage systems make **the proposed system more flexible for more optimal operation and participation on the energy**

markets in comparison with virtual power plants which are operated only based on the electrical energy systems and can participate only on the electrical energy market. Therefore, the local thermal energy market besides electrical energy market has an impact on self-scheduling of the proposed VEH plant.

B. Literature Review

Multi-energy systems are presented in diverse studies. Energy hub concept is proposed in [1] that receives, stores and converts the various forms of energy. A huge contribution of studies in the field of multi-carrier energy systems is about planning [3] and scheduling [4] of the multi-energy systems in the smart grid. A stochastic model to design an energy hub is presented in [3], which candidate equipment are combined heat and power (CHP) unit, storage devices, boiler unit and renewable resources. In addition, the uncertain parameters that are considered in this study are WPG, outages of the facilities and consumers' demands

Authors of [4] have proposed a mathematical model for optimal scheduling of energy hubs considering the conditional value-at-risk (CVaR) methodology. An optimization model for a residential energy hub is examined in [5], which minimize the total cost of energy consumption, emission and the peak load of the system. Reference [6] introduced an optimization framework for online economic dispatch of the multi-carrier energy systems, where the energy hubs economic dispatch problem is solved by a multi-agent genetic algorithm (MAGA). Moreover, the computational volume of the optimization problem is reduced by the nomination of a decomposed model. Obtaining energy carriers for energy hubs direct affected from external markets, therefore multi-agent systems can be employed for controlling energy carriers [7].

One of the features that the energy hub created for the power system is providing flexibility to the operator to manage the effects of volatility of renewable resources. In this regard, an optimization model for home energy management in a residential scale energy hub is presented in [8]. The renewable-based energy hub model includes a CHP unit, a thermal storage system, a plug-in hybrid electric vehicle (PHEV) and a rooftop photovoltaic system. Two-point estimate method is applied to model the solar panels' power generation as an uncertain parameter.

Authors of [9] proposed a renewable-based energy hub to study the interactions of gas, electrical and thermal energy flows. This system is implemented on the stand-alone microgrid and cannot exchange energy with the network. Energy management for the residential energy hubs is presented in [10], which studied the impacts of the coupling constraints and energy purchasing behaviours of demand sides. The mentioned study considers only purchasing electricity from the network. In [11], a probabilistic model is developed for the planning of the solar system in an energy hub. This model supplies the demands by using a CHP unit, gas boiler, thermal storage, solar system and importing electricity from the network and cannot export electricity to the network. A two-stage stochastic method is proposed to model the uncertain parameters in [12]. The uncertainties of the proposed energy hub model are price, electrical demands and ambient temperature. This system can exchange electrical energy with network.

A multi-objective method is presented in [13] for energy management problem, which the proposed approach is focused on the minimization both the risk level and energy cost in multi

TABLE I
COMPARISON OF THE PROPOSED VEH SELF-SCHEDULING STRATEGY WITH EXISTING METHODS IN THE RELATED LITERATURE

References	Study field	Exchanging energy with local networks		Uncertainty modelling	Risk management	Optimization strategies	
		Electrical	Thermal			Risk-averse	Risk-seeker
[9]	Scheduling	✗	✗	✗	✗	✗	✗
[10]	Scheduling	Importing	✗	✗	✗	✗	✗
[11]	Designing	Importing	✗	Probabilistic	✗	✗	✗
[12]	Scheduling	Importing & exporting	✗	Stochastic	✗	✗	✗
[4]	Scheduling	Importing & exporting	✗	Stochastic	✓	✗	✗
[14]	Scheduling	Importing	Importing	Stochastic	✗	✗	✗
The proposed VEH	Scheduling	Importing & exporting	✓	IGDT	✓	✓	✓

carrier energy system. A mixed-integer linear programming (MILP) model for energy management of multi-carrier energy systems is introduced in [15]. The objective is minimizing both the energy procurement cost and commercial risks in the energy hub. Also, the information gap decision theory (IGDT) method is applied as the risk management model. Electricity procurement problem of a large consumer is developed in [16]. Moreover, risk levels for this consumer are assessed using an IGDT method.

The multi-carrier energy system which is proposed in [14], focuses on satisfying the electrical and thermal demands of the system. The mentioned system's uncertainties are modelled by pure stochastic optimization programming. This model only can imports electrical and thermal energies from the networks to satisfy its energy demands. In [17], wind-based energy hub systems are proposed to enhance voltage stability. The energy hub systems only can import electrical energy from the network to satisfy the electrical demands. Uncertainties of the proposed system are modelled by using a pure stochastic optimization method. A renewable-based multi-carrier energy system is proposed in [18]. The price uncertainty of this system is modelled by an IGDT method.

A solution for volatility and unpredictability problem of the renewable generations is employing the storage systems for the more efficient operation of the renewable technologies in the power system. In recent years, diverse technologies of energy storage systems are provided, that amongst the various energy storage technologies only compressed air energy storage (CAES) [19] and pumped hydro storage (PHS) [20] systems are capable to cooperate by large scale power plants. The presence of energy storage in the power system not only increases the reliability of the use of renewable resources but also allows the power generation system to participate in the local energy markets.

In some previous works, the models that are proposed for retail energy market consider only one energy carrier's parameters as an influential parameter in the market. Reference [21] considers electricity as the only energy carrier in the

operation problem of the multi-energy systems in the microgrids. In addition, in [22] only electrical energy market is considered that presents a model to interaction electrical energy prosumers in the market.

In the noted studies, little attentions are paid to the impact of the energy hub on the various local energy markets. While large scale energy hubs can participate and effect on the diverse markets which are called VEH in the current paper. In this regard, integration of various energy carriers (e.g., district heat, natural gas and electricity) can affect different energy markets (e.g., electrical and local thermal energy markets). Therefore, VEHs can take part in the electricity and local thermal energy market. Due to the fluctuation of renewable resources, it is essential to investigate the risk levels regarding VEH's generation strategies.

To summarize, the following shortcomings can be identified in the existing literature related to the scheduling and operation of the multiple power plants:

1. Lack of opportunities to participate in the energy system in the various energy markets such as local thermal energy market [21-23].
2. Not-existence an optimization method for the investment of the proposed energy systems' strategy and behaviour against the uncertainty of the renewable power generations in the energy market [3, 24, 25].
3. Not paying attention to the ability of energy hub systems to participate in the local energy markets in the form of virtual power plants [6, 8, 13, 26].
4. Not considering the use of storage systems such as CAES units which are capable to cooperate with large scale energy hub systems [5, 7, 24, 25].

Table I summarizes taxonomy of proposed models in the optimization of the multi-carrier energy systems.

C. Contributions

In this paper, a risk-constrained self-scheduling model is proposed for a virtual energy hub using the concept of IGDT method, which can participate in the local energy markets. The

proposed VEH plant can participate in the local thermal and electrical energy markets. To the best of authors' knowledge, no similar integrated model for virtual power plant (VPP) self-scheduling model has been proposed in the past literature. In this paper, the participation in the various energy markets by a multiple energy system by using the integrated point of view to reach a maximum benefit by examining both electrical and thermal markets is proposed as a model that can be used for the practical local multi-carrier energy systems which want to operate based on the VPPs concept. The main contributions of this paper can be summarized as follows:

- 1) Participation of the VEH plant in the local thermal and electrical energy markets by examining both electrical and thermal markets, simultaneously.
- 2) Handle the uncertainty and risk of wind resource as renewable energy in the proposed VEH plant.
- 3) The maximum benefit for VEH plant while modelling the error between the forecasted and actual amount of the unpredictable WPG is provided based on IGDT method.
- 4) Two different strategies can be taken by the proposed VEH plant to face with WPG uncertainty in the energy market, i.e., risk-averse and risk-seeker strategies.

D. Paper Organization

The remainder of the current paper is organized as follows. Section II demonstrates the mathematical model of VEH plant self-scheduling and the IGDT methodology. The IGDT-based robustness and opportunity function of the proposed optimization problem are introduced in Section III. Numerical simulation and results are discussed in Section IV. Finally, the conclusion is given in Section V.

II. BACKGROUND

A. VEH plant Self-Scheduling Problem

The proposed VEH plant is fed by a natural gas network and connected to an electrical grid. WPG, CAES unit, energy storage systems, electrical heat pump, boiler and CHP units are considered in the proposed system as shown in Fig. 1. As it is mentioned previously, the energy hubs brought the coupling among various energy carriers up. In other words, the interaction among different facilities of the energy hubs and various operational parameters became a challenge. The coupling among various energy carriers in the energy hub occurred by using some facilities which are fed by one type of energy resource and generate one or two different types of energies. For example, the CHP unit, as one of the main equipment of the energy hub system, is fed by natural gas and generates electrical and thermal energies. The boiler is fed by natural gas and generates thermal energy. EHP system uses electrical energy to exchange the thermal energy between different areas.

In addition, the proposed VEH can import various energies from the local network in the low price periods and stores them in the different storage systems such as CAES system, EES and TES, and export them to the local networks in the high price periods. Exchanging electrical and thermal energies are illustrated in detail in the proposed mathematical model. Figure 1 illustrates the interaction among different types of energies and the facilities in the proposed VEH. The aforementioned equipment provides the ability for VEH to participate in the

local electrical and heat energy markets. It should be noted that the proposed self-scheduling model is for

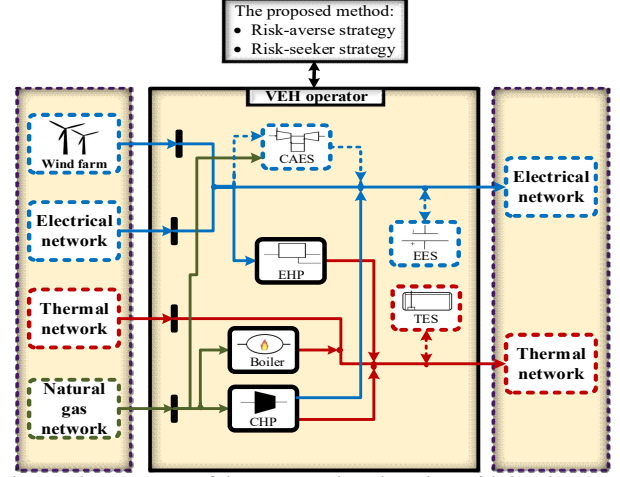


Fig. 1. The structure of the VEH and exchanging with local networks.

next 24-hours. In other words, the proposed model is for the day-ahead market.

1) Objective Function

The objective function for the self-scheduling of the VEH is to maximize benefit through energy arbitrage as a participant in the electricity and local thermal energy markets in each time blocks of the self-scheduling horizon. The objective function of the VEH is as follows:

$$\text{Max Benefit} = \sum_{t=1}^T \{ \text{Revenue}_t - \text{Cost}_t \} \quad (1)$$

$$\text{Revenue}_t = R_t^E + R_t^H \quad (2)$$

$$\text{Cost}_t = C_t^E + C_t^H + C_t^{\text{CHP}} + C_t^{\text{Boiler}} + C_t^{\text{CAES}} + C_t^{\text{su}} + C_t^{\text{sh}} \quad (3)$$

The terms of the objective function (Eq. 1) are the revenue from exporting electricity and heat and the costs of the imported energies from electrical and thermal energy markets, the operation costs of the CHP units and boilers, CHP units' startup cost and shutdown cost.

2) Exchange Energy with the Energy Markets

Eqs. (4) and (5) represent the revenues from selling electricity and heat in the local energy markets.

$$R_t^E = \lambda_t^{E,ex} \times P_t^{E,ex} \quad (4)$$

$$R_t^H = \lambda_t^{H,ex} \times P_t^{H,ex} \quad (5)$$

Likewise, the costs of the purchased electrical and thermal energies are given as follows:

$$C_t^E = \lambda_t^{E,im} \times P_t^{E,im} \quad (6)$$

$$C_t^H = \lambda_t^{H,im} \times P_t^{H,im} \quad (7)$$

3) VEH plant's Energy Balancing

Eqs. (8) and (9) are electrical and thermal power balance equations, respectively. It should be mentioned that the energy provided by equipment and energy purchased from the market should be equal to inputs of the components and energy sold in the electrical and local heat energy markets.

$$P_t^{E,ex} = \left\{ \sum_{c=1}^C P_t^{E,CHP_c} \right\} + P_t^{E,wind} - P_t^{E,CAES_{ch}} + P_t^{E,CAES_{dch}} - P_t^{E,storage_{ch}} + P_t^{E,storage_{dch}} - P_t^{E,EHP} + P_t^{E,im} \quad (8)$$

$$P_t^{H,ex} = \left\{ \sum_{c=1}^C P_t^{H,CHP_c} \right\} + \left\{ \sum_{b=1}^B P_t^{H,Boiler_b} \right\} + P_t^{H,EHP} - P_t^{H,storage_{ch}} + P_t^{H,storage_{dch}} + P_t^{H,im} \quad (9)$$

4) CHP units

The operation costs of the CHP units are formulated as follows [27]:

$$C_t^{CHP_c} = \sum_{c=1}^C (F_t^{CHP_c} + M_t^{CHP_c}) \quad (10)$$

$$F_t^{CHP_c} = P_t^{E,CHP_c} \times \left(\frac{\lambda_t^G}{\eta_{CHP_c} \times HV} \right) \quad (11)$$

$$M_t^{CHP_c} = \rho_{CHP_c} \times P_t^{E,CHP_c} \quad (12)$$

where, $F_{CHP_c}(t)$ and $M_t^{CHP_c}$ are fuel cost and maintenance cost of the CHP units, which are given by Eqs. (11) and (12), respectively.

The costs related to startup and shutdown states of the CHP units are expressed as Eqs. (13) and (14), respectively.

$$C_t^{su} = \sum_{c=1}^C (m_t^{CHP_c} \times \text{Cost}^{su}) \quad (13)$$

$$C_t^{sh} = \sum_{c=1}^C (n_t^{CHP_c} \times \text{Cost}^{sh}) \quad (14)$$

where $m_t^{CHP_c}$ and $n_t^{CHP_c}$ are binary variables that define startup and shutdown status of the CHP units. Also, $\text{Cost}^{su/sh}$ is CHP units' startup/shutdown cost.

It should be mentioned that the CHP units' electrical and thermal generations are interdependent, which are limited by:

$$P_t^{H,CHP_c} = P_t^{E,CHP_c} \times HPR_{CHP_c} \times \eta_{HE} \quad (15)$$

$$P_{Min}^{E,CHP_c} \leq P_t^{E,CHP_c} \leq P_{Max}^{E,CHP_c} \quad (16)$$

The proposed CHP units' ramp-up and ramp-down constraints are shown in Eqs. (17) and (18). The CHP units' performance status is characterized by binary variable, $i_t^{CHP_c}$, which is equal to 0 if each of the CHP units is in the *off* state and 1 otherwise.

$$P_t^{E,CHP_c} - P_{t-1}^{E,CHP_c} \leq i_{t-1}^{CHP_c} \times P^{RU} + m_t^{CHP_c} \times P_{Min}^{E,CHP_c} \quad (17)$$

$$P_{t-1}^{E,CHP_c} - P_t^{E,CHP_c} \leq i_t^{CHP_c} \times P^{RD} + n_t^{CHP_c} \times P_{Min}^{E,CHP_c} \quad (18)$$

where, $P^{RU/RD}$ is the CHP units' ramp-up/ramp-down rate.

5) Boiler units

The boiler units' operation costs contain the maintenance and fuel costs summation which are formulated by [28]:

$$C_t^{Boiler} = \sum_{b=1}^B (F_t^{Boiler_b} + M_t^{Boiler_b}) \quad (19)$$

$$F_t^{Boiler_b} = P_t^{H,Boiler_b} \times \left(\frac{\lambda_t^G}{\eta_{Boiler_b} \times HV} \right) \quad (20)$$

$$M_t^{Boiler_b} = \rho_{Boiler_b} \times P_t^{H,Boiler_b} \quad (21)$$

The outputs of the boiler units are limited by:

$$P_{Min}^{H,Boiler_b} \leq P_t^{H,Boiler_b} \leq P_{Max}^{H,Boiler_b} \quad (22)$$

6) CAES unit

The CAES unit uses electrical energy during low electricity price periods to compress air into the underground chamber using compressors [29]. The energy ratio is used to express the efficiency of the CAES unit. The energy ratio illustrates the amount of energy that the compressor of the CAES unit consumes per-unit of energy that is generated by expander [30]. The compressed air into the chamber is related to pressure limits and the valves' size. Therefore, the stored energy in the CAES system is limited by the storage size. The limitation of the charging and discharging of CAES can be formulated by (23) and (24), respectively. To withhold the CAES from simultaneous charging and discharging states, binary variables f_t and h_t are considered in Eq. (25).

$$0 \leq P_t^{E,CS_{ch}} \leq f_t \times P_{Max}^{E,CS_{ch}} \quad (23)$$

$$0 \leq P_t^{E,CS_{dch}} \leq h_t \times P_{Max}^{E,CS_{dch}} \quad (24)$$

$$f_t + h_t \leq 1 \quad (25)$$

Eq. (26) specifies the capacity of the CAES unit. The constraints related to stored energy in each time blocks and the initial energy level expressed as (27) and (28), respectively.

$$E_{Min}^{CS} \leq E_t^{CS} \leq E_{Max}^{CS} \quad (26)$$

$$E_{t+1}^{CS} = E_t^{CS} + (P_t^{E,CS_{ch}} \times \eta_{CS}^{ch}) - (P_t^{E,CS_{dch}} / \eta_{CS}^{dch}) \quad (27)$$

$$E_t^{CS} = E_{init}^{CS} \quad (28)$$

where $E_{Min/Max}^{CS}$ and E_{init}^{CS} are minimum/maximum energy limit and initial level of air storage. The operation cost of the CAES is provided by (29). The terms of the CAES unit related to the operation cost are operation cost of discharging state and the cost of the compressor in charging state.

$$C_t^{CS} = (\phi^c \times P_t^{E,CS_{ch}}) + (\phi^{exp.} \times P_t^{E,CS_{dch}}) \quad (29)$$

7) EHP unit

Eqs. (30) and (31) indicate the constraints of the electric heat pump (EHP) [4]. It should be noted that the output limitation of the EHP is given by (31).

$$P_t^{H,EHP} = P_t^{E,EHP} \times CP \quad (30)$$

$$P_{Min}^{H,EHP} \leq P_t^{H,EHP} \leq P_{Max}^{H,EHP} \quad (31)$$

where, $P_{Min}^{H,EHP}$ and $P_{Max}^{H,EHP}$ are the minimum and maximum output of the EHP unit.

8) Energy Storage unit

The energy capacity of the energy storages is explained in Eq. (32). Charging and discharging limitations are shown in Eqs. (33) and (34), respectively. In this paper, the following equations imply both electrical and thermal energy storages,

which generally are specified for both units with (sg_s) index. In the constraints, if the variables or parameters are related to electrical storage, they are characterized by (sg_E) subscript in front of its symbol, and else if they are related to thermal storage, are characterized by (sg_H) subscript. For example, the electricity output of the electrical storage is written as $P_t^{sg_E^{dch}}$, while $P_t^{sg_H^{dch}}$ denotes the output of the thermal storage. Likewise, $\eta_{sg_E}^{ch}$ and $\eta_{sg_H}^{ch}$ indicate the charging efficiency of the electrical and thermal storages.

$$PS_{Min}^{sg_s} \leq PS_t^{sg_s} \leq PS_{Max}^{sg_s} \quad (32)$$

$$P_{Min}^{sg_s^{ch}} \leq P_t^{sg_s^{ch}} \leq P_{Max}^{sg_s^{ch}} \quad (33)$$

$$P_{Min}^{sg_s^{dch}} \leq P_t^{sg_s^{dch}} \leq P_{Max}^{sg_s^{dch}} \quad (34)$$

where, $P_{Min/Max}^{sg_s^{ch}}$ and $P_{Min/Max}^{sg_s^{dch}}$ are minimum/maximum rates of the charging state and discharging state of the energy storage units, respectively.

Eq. (35) corresponds to the energy balance of the storage units.

$$PS_t^{sg_s} = (PS_{t-1}^{sg_s} \times \eta_{sg_s}) + (P_t^{sg_s^{ch}} \times \eta_{sg_s}^{ch}) - (P_t^{sg_s^{dch}} / \eta_{sg_s}^{dc}) \quad (35)$$

9) Wind Power Generation (WPG)

Type of turbine, rotor and gearbox are parameters that effect on power generated by a WPG. In the current paper, a simplified relation between wind speed and generated power by WPG is approximated by [31-33]:

$$P_v^{E,wind} = \begin{cases} (a+b*v+c*v^2)P_{wind}^r & \text{if } v_{in}^c \leq v \leq v_r \\ P_{wind}^r & \text{if } v_r \leq v \leq v_{out}^c \\ 0 & \text{otherwise} \end{cases} \quad (36)$$

where a , b and c are explained as:

$$a = \frac{1}{(v_{in}^c - v_r)^2} \left[v_{in}^c (v_{in}^c + v_r) - 4v_{in}^c v_r \left(\frac{v_{in}^c + v_r}{2v_r} \right)^3 \right] \quad (37)$$

$$b = \frac{1}{(v_{in}^c - v_r)^2} \left[4(v_{in}^c + v_r) \left(\frac{v_{in}^c + v_r}{2v_r} \right)^3 - (3v_{in}^c + v_r) \right] \quad (38)$$

$$c = \frac{1}{(v_{in}^c - v_r)^2} \left[2 - 4 \left(\frac{v_{in}^c + v_r}{2v_r} \right)^3 \right] \quad (39)$$

where, P_{wind}^r is the rated power generated by WPG. In Eqs.

(37)-(39), v_{in}^c , v_{out}^c and v_r are cut in, cut out and rated wind speeds, respectively.

In the current paper, the VEH plant is assumed to be a price taker. Therefore, no strategic bidding is considered here. Moreover, it is assumed that the VEH's optimal scheduling is occurred by using energy market prices obtained by market clearing process.

B. IGTD Method

The IGDT method maximizes the horizon of error between the feasible and forecasted uncertain parameters [34]. In other words, the decision-maker selects the targets and the IGDT theory maximizes the uncertainty horizon to guarantee the objective. It can be used to carry out a robust decision against intense uncertain nature of the problem parameters [35]. IGDT is a non-probabilistic method that optimizes in a way to be immune again low benefits and windfall gains [36]. In this paper, an IGDT model is developed for dealing with the VEH plant with WPG uncertainty. By the proposed approach, the VEH decision-maker can adopt two various strategies to face uncertain WPG which are risk-averse and risk-seeker strategies. Different uncertainty models can be used in the IGDT method [37]. An uncertain model, i.e., $U(\tilde{P}_t^{E,wind}, \alpha)$,

shows the information-gap between the known, i.e., $\tilde{P}_t^{E,wind}$ and what needs to be known, i.e., $P_t^{E,wind}$. In the proposed model, the uncertain parameter is WPG. Also, the set of uncertainty can be mathematically formulated by:

$$U(\tilde{P}_t^{E,wind}, \alpha) = \{P_t^{E,wind} : |P_t^{E,wind} - \tilde{P}_t^{E,wind}| \leq \alpha \tilde{P}_t^{E,wind}\} \quad (40)$$

$\alpha \geq 0$

where, α is the uncertainty horizon parameter, $\tilde{P}_t^{E,wind}$ and $P_t^{E,wind}$ are the forecasted power and uncertain WPG, respectively.

This model is a type of an envelope bound uncertainty model, which a known parameter, i.e., $\tilde{P}_t^{E,wind}$ specifies the formation of the envelope. In the proposed method, the maximal variation is proportional to the prognosticated value.

Risk-averse VEH desires to operate in a way to be immune against low benefit owing to undesirable deviations of uncertain WPG from the forecasted values. This can be formulated by:

$$\tilde{\alpha}(P, B_r) = \text{Max} \left\{ \alpha : \left(\text{Min}_{P^{E,wind} \in U(\tilde{P}_t^{E,wind}, \alpha)} Z(P, P^{E,wind}) \geq B_r \right) \right\} \quad (41)$$

where B_r is determined as a benefit target for the robustness function. Furthermore, the risk-seeker strategy determines the immunity against windfall benefits. The opportunity function can be mathematically formulated by:

$$\tilde{\beta}(P, B_o) = \text{Min} \left\{ \alpha : \left(\text{Max}_{P^{E,wind} \in U(\tilde{P}_t^{E,wind}, \alpha)} Z(P, P^{E,wind}) \geq B_o \right) \right\} \quad (42)$$

where, B_o is a benefit that the VEH hopes to obtain as a target benefit in the event of favourable WPG.

III. THE PROPOSED IGDT-BASED METHODOLOGY

A. Risk-Averse Strategy

In the IGDT model, if the risk-averse strategy is taken by decision-maker, the objective of the self-scheduling in this mode is to maximize the uncertain variable (i.e. α). This is while the indispensable constraints of the system are satisfied and the minimum predesignated benefit, $B_r = (1-\kappa)B_e$ is guaranteed. B_e is expected benefit which is obtained from VEH scheduling problem based on the forecasted WPG. Let rewrite (1) using (8), (4) and (2) as follows:

$$\text{Max} \sum_{t=1}^T \left\{ \left(\lambda_t^{E,ex} \times P_t^{E,wind} \right) + \text{Revenue}'_t - \text{Cost}_t \right\} \quad (43)$$

where $\text{Revenue}'_t$ is the revenue of the VEH plant derived from selling of power without the contribution of the WPG.

The robustness function of the self-scheduling optimization problem can be formulated by:

$$\hat{\alpha}(P, B_r) = \text{Max} \alpha \quad (44)$$

Subject to:

$$\text{Min} \sum_{t=1}^T \left\{ \left(\lambda_t^{E,ex} \times P_t^{E,wind} \right) + \text{Revenue}'_t - \text{Cost}_t \right\} \geq B_r = (1-\kappa)B_e \quad (45)$$

$$(1-\alpha)\tilde{P}_t^{E,wind} \leq P_t^{E,wind} \leq (1+\alpha)\tilde{P}_t^{E,wind} \quad (46)$$

$$\text{Eqs. (2)-(39)} \quad (47)$$

where α is the uncertain variable, κ is a robustness benefit deviation factor, $\tilde{P}_t^{E,wind}$ and $P_t^{E,wind}$ are the forecasted and uncertain WPG, respectively.

Electrical power generated by WPG does not cost the operation of the VEH plant. Therefore, the benefit of the VEH is dependent on WPG.

In other words, if WPG decreases, then the VEH system's benefit will decrease as well. In the other side, the benefit will certainly increase by increasing the power generated by WPG. Also, the proposed IGDT method can be simplified as a single level problem [38].

As previously mentioned, in the risk-averse strategy the VEH's minimum benefit occurs for the lowest power generated by WPG which is equal to $(1-\alpha)\tilde{P}_t^{E,wind}$. As a result, the bi-level problem pertaining (44) can be reformulated as a single level. This form of the problem can be expressed by:

$$\hat{\alpha}(P, B_r) = \text{Max} \alpha \quad (48)$$

Subject to:

$$\sum_{t=1}^T \left\{ \lambda_t^{E,ex} \times \left((1-\alpha)\tilde{P}_t^{E,wind} \right) + \text{Revenue}'_t - \text{Cost}_t \right\} \geq B_r = (1-\kappa)B_e \quad (49)$$

$$\text{Eqs. (2)-(39)} \quad (50)$$

The solution of the above optimization problem yields the minimum profit if all forecasted errors are less than maximized error, $\hat{\alpha}$.

B. Risk-Seeker Strategy

The risk-seeker VEH is looking at the uncertain events which affect objective function in an optimal positive way.

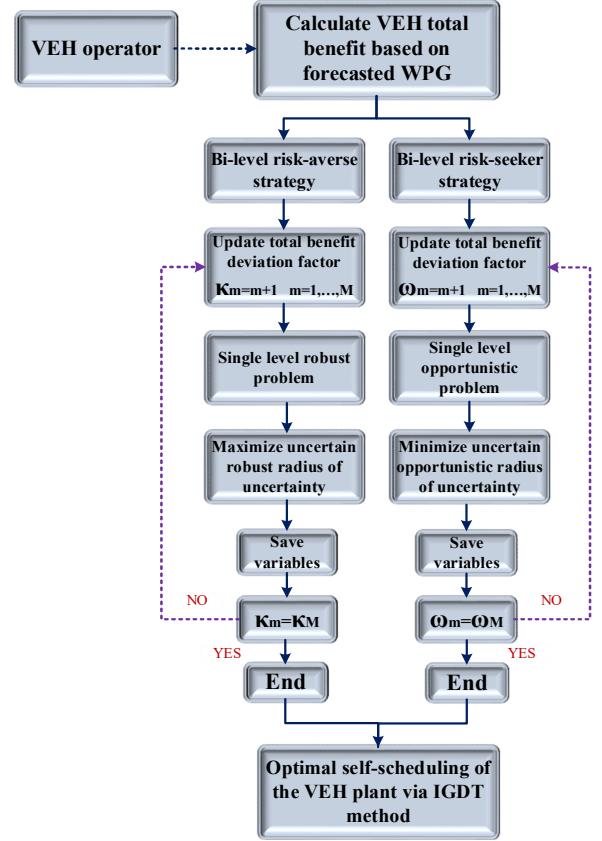


Fig. 2. Flowchart of the proposed IGDT-based methodology.

Unexpected high WPG is a favourable variation for the VEH. The higher WPG makes it possible to export more energy in the local electrical energy market.

Similar to robustness formulation, the opportunity function can also be written as follows:

$$\hat{\beta}(P, B_o) = \text{Min} \alpha \quad (51)$$

Subject to:

$$\text{Max} \sum_{t=1}^T \left\{ \lambda_t^{E,ex} \times P_t^{E,wind} + \text{Revenue}'_t - \text{Cost}_t \right\} \geq B_o = (1+\omega)B_e \quad (52)$$

$$(1-\alpha)\tilde{P}_t^{E,wind} \leq P_t^{E,wind} \leq (1+\alpha)\tilde{P}_t^{E,wind} \quad (53)$$

$$\text{Eqs. (2)-(39)} \quad (54)$$

It should be noted that in the VEH system, if the power generated by WPG increases, the benefit of the VEH will increase, in other words the maximum benefit is obtained with the highest WPG. The highest WPG is equal to $(1+\alpha)\tilde{P}_t^{E,wind}$.

The maximum benefit occurs for the highest WPG, so the bi-level problem (51) can be cast into a single-level problem as follows:

$$\hat{\beta}(P, B_o) = \text{Min} \alpha \quad (55)$$

Subject to:

$$\sum_{t=1}^T \left\{ \lambda_t^{E,ex} \times \left((1+\alpha)\tilde{P}_t^{E,wind} \right) + \text{Revenue}'_t - \text{Cost}_t \right\} \geq B_o = (1+\omega)B_e \quad (56)$$

$$\text{Eqs. (2)-(39)} \quad (57)$$

TABLE II
SPECIFICATIONS OF THE CHP UNITS

CHP	Capacity (kW)	Maintenance cost (\$/kWh)	Elec./ther. conversion efficiency	Startup/shutdown cost (\$)	Elec./ther. ramp-up/ramp-down(kW/h)
#1	10000	0.275	0.36/0.38	60/60	1800/1900
#2	10000	0.275	0.45/0.50	60/60	2250/2500

TABLE III
SPECIFICATIONS OF THE BOILERS

Boiler	Capacity (kW)	Maintenance cost (\$/kWh)	Efficiency	Startup/shutdown cost (\$)
#1	6000	0.275	0.70	12
#2	6000	0.275	0.80	12

TABLE IV
CHARACTERISTICS OF THE CAES SYSTEM

Maximum charging/discharging range (kW)	Maximum energy (kWh)	Charging/discharging efficiency	Operating and maintenance cost of compressor/expander (\$/kWh)
500	2500	0.90	0.04

TABLE V
CHARACTERISTICS OF THE EHP SYSTEM

Maximum capacity (kW)	Minimum capacity (kW)	coefficient of performance
1500	0	2.5

The $\hat{\beta}$ is the minimum favourable wind power deviation that makes the target benefit, B_o , accessible.

Figure 2, shows the schematic of the proposed IGDT-based method.

IV. SIMULATION RESULTS AND DISCUSSIONS

This section assesses the effectiveness of the proposed robust and opportunistic self-scheduling method for VEH plant. The proposed VEH plant consists of two CHP units, two boiler units, a CAES unit, an EHP unit, thermal and electrical storage and WPG. The presented VEH can exchange electrical and thermal energy with local energy markets. The proposed self-scheduling model is for the day-ahead market.

A. Assumptions

The specifications of the CHP units and boilers are provided in Tables II and III [3], respectively. The WPG's parameters are taken from [39]. In addition, the WPG range is considered 2500 kW. In this paper, a short-term forecasting algorithm based on the support vector regression (SVR) is used to forecast the wind data for the 24-hour of the self-scheduling horizon [40]. The SVR model is employed to forecast wind speed. It should be noted that the basic idea of SVR is to map the feature vector into a high dimensional space by using a nonlinear mapping [41]. Figure 3 shows the hourly wind speeds related to the VEH plant 24-hours self-scheduling horizon.

TABLE VI
PARAMETERS OF THE ENERGY STORAGES

Storage type	Maximum discharging/charging range (kW)	Maximum stored energy (kWh)	Discharging/charging efficiency	Standby efficiency
Electrical	2500	10000	0.97	0.95
Thermal	1500	5000	0.94	0.90

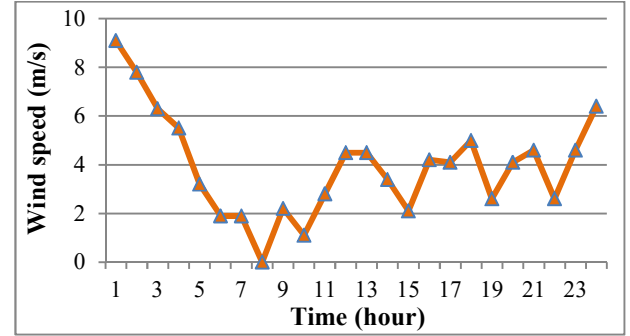


Fig. 3. Wind speeds of the VEH scheduling horizon.

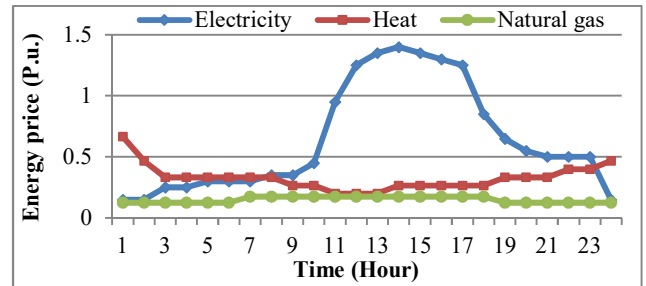


Fig. 4. Variations of electrical energy, heat and natural gas prices.

Table IV and Table V show the CAES and EHP system characteristics [4, 29, 42], respectively. The electrical storage and thermal storage parameters are determined by Table VI [43].

The base values of the electricity, thermal energy and natural gas prices are chosen 0.2\$/kWh, 0.15\$/kWh and 0.4\$/m³, respectively. Also, the price variations of electrical energy, thermal energy and natural gas in 24-hours of a sample day are provided in Fig. 4 [44]. It should be noted that the electricity prices for 24-hours are based on the data, which are taken from the Tabriz electric power distribution company (TEPDC). In addition, the natural gas price is based on the data, which is taken from the East-Azarbaijan gas company (EAGC). The thermal energy prices are assumed based on the energy prices of the thermal generation facilities inputs. The prices are converted from local currency (Rial) to the US dollar.

It should be mentioned that the selling price of electrical energy ($\lambda^{E,ex}$) and heat ($\lambda^{H,ex}$) in the local energy markets are assumed to be $3 * \lambda^{E,im}$ and $2 * \lambda^{H,im}$, respectively.

Finally, considering all the above assumptions, the CPLEX solver is employed to handle the proposed mixed-integer linear programming problem in the GAMS environment [45]. In addition, the overview of the proposed optimization problem is demonstrated in Fig. 5. The computational time of the proposed optimization problem is about 62 seconds. The explored MILP

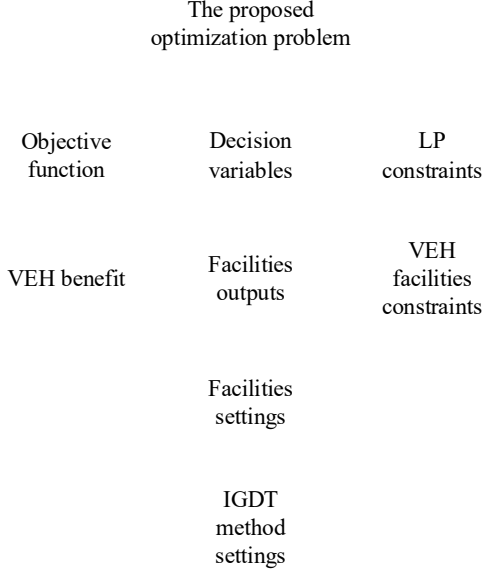


Fig. 5. The overview of the proposed optimization problem.

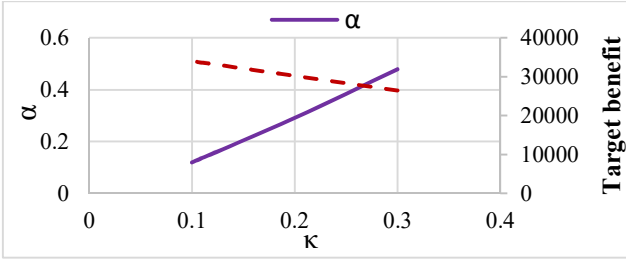


Fig. 6. Optimal values of robustness function versus benefit deviation factor.

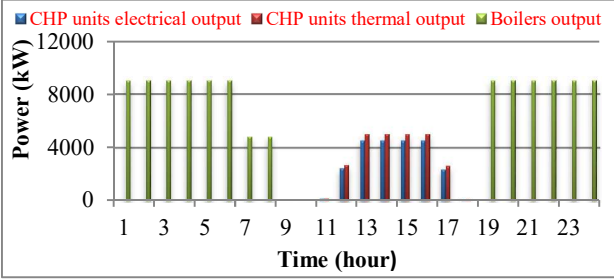


Fig. 7. Robust scheduling of CHP and boiler units for $\kappa = 0.1$.

problem in this paper has been executed by CPLEX solver of GAMS software which is one of the strongest solvers of MILP problems. Based on GAMS software report, the proposed optimization problem includes 99 blocks of equation (1870 single equations) and 66 blocks of variables (1101 single variables).

B. Risk-Averse VEH plant Self-Scheduling

At first, the deterministic problem based on forecasted WPG, (1)-(39), is solved. The result shows the expected benefit is equal to $B_e = 37775.59\$$.

Then, by solving the IGDT-based optimization problem for $\kappa = 0.1$ to $\kappa = 0.3$, the robustness function, $\hat{\alpha}$, and target

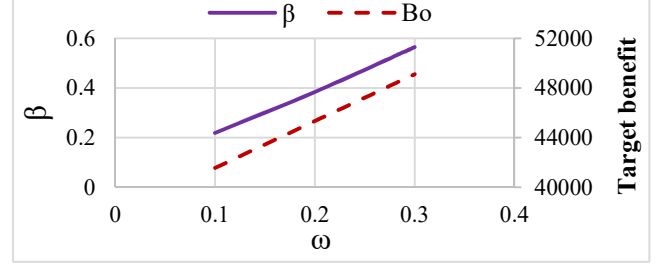


Fig. 8. Optimal opportunity function value versus benefit deviation factor.

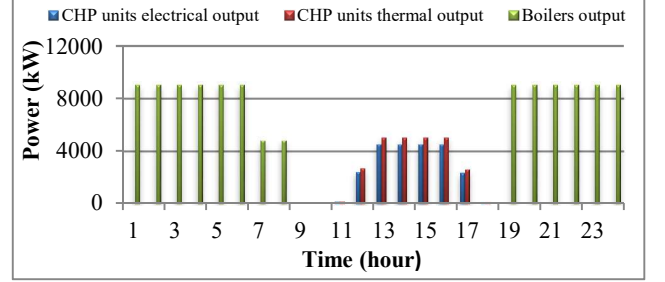


Fig. 9. Opportunistic scheduling of CHP and boilers units for $\omega = 0.1$

benefit, B_r , are founded as shown in Fig. 6. It is clear that for $\kappa = 0.2$, if the forecasted error, $\hat{\alpha}$, be less than 0.291, an expected target benefit is guaranteed.

Figure 7 shows the robust schedule of the CHP and boiler units for $\kappa = 0.1$. It is clear that in hours 11-17 that the electricity market price starts to rise, CHP units are in *ON* state and generate electrical and thermal power. But in hours 1-8 and 19-24 in which the local thermal energy market price is high, the boilers generate thermal power. The CHP units' highest generation is in hour 14, which the electricity market price is the highest amount.

C. Risk-Seeker VEH plant Self-Scheduling

As earlier mentioned, the expected benefit is equal to $B_e = 37775.59\$$. Figure 8 Shows the opportunity function expected value, $\hat{\beta}$, and target benefit, B_o , for $\omega = 0.1$ to $\omega = 0.3$. As shown in Fig. 8, in order to reach to higher target benefits, higher favourable WPG deviations from the forecasted values are needed. To gain a benefit 20% higher than the expected benefit, B_e , the power generated by WPG must be at least 38.4% higher than the forecasted generation.

The opportunistic schedule of boilers and CHP units for $\omega = 0.1$ are illustrated in Fig. 9. As seen in Fig. 9, CHP units generate electrical and thermal power in hours 12-17. But in hours 1-7 and 19-24 the boilers generate thermal power. By comparing Figs. 7 and 9, it can be seen that the robust scheduling of the CHPs and boilers are similar to their opportunity scheduling for the benefit deviation factor of 0.1. This fact can be explained by the fact that the time periods of the operation of the CHPs and boilers are determined by the energy market prices patterns in the different hours of the scheduling horizon. Therefore, the time periods of the CHPs and boilers robust scheduling are similar to the time periods of

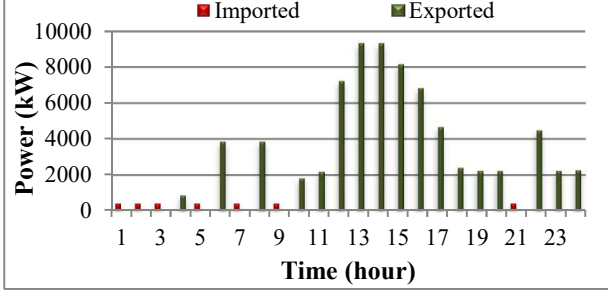


Fig. 10. Exchanged electrical energy with the network for risk-averse VEH.

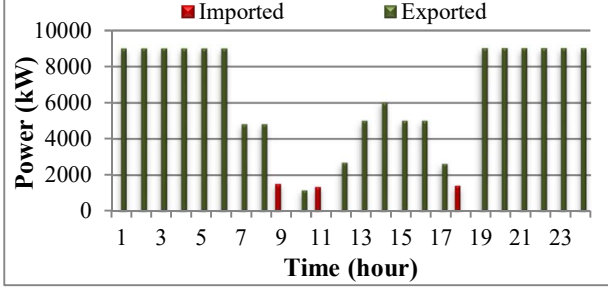


Fig. 11. Exchanged thermal energy with the network for risk-averse VEH.

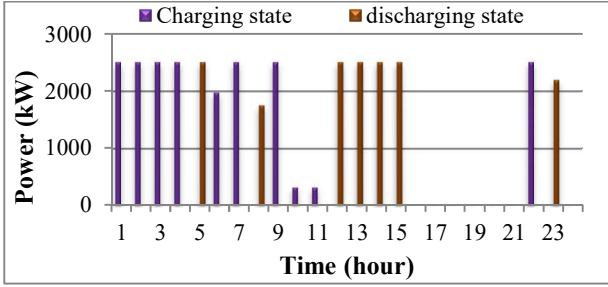


Fig. 12. Electrical storage scheduling states.

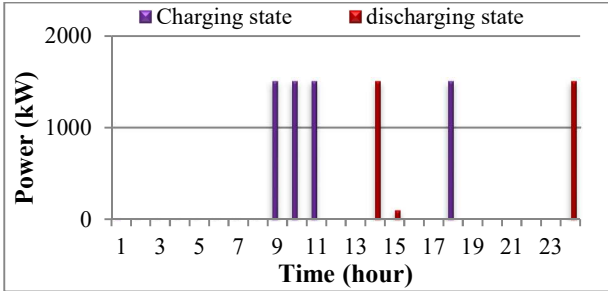


Fig. 13. Thermal storage scheduling states.

their opportunity scheduling. Furthermore, there is a difference between the output values of robust and opportunity scheduling. On the other hand, the values of the deviation factors of the robust and opportunity functions are low. Also, the outputs of the CHPs and boilers in the robust condition are close to their output values in the opportunity condition.

D. Exchanging electrical and thermal energies with local networks

In this subsection, the exchanged electricity and thermal energy are evaluated for the risk-averse VEH.

TABLE VII
ROBUST SCHEDULING OF THE VEH PLANT FOR
 $\kappa = 0.2$

	Total benefit (\$)	Imported electricity cost (\$)	Exported electricity revenue (\$)
With CAES	30220.47	261.45	40823.08
Without CAES	29295.59	846.11	38172.53

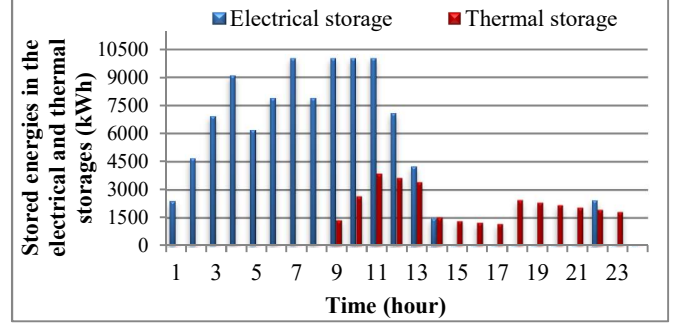


Fig. 14. Stored energies in the electrical and thermal storages.

The imported/exported electrical and thermal energies from/to the local networks for $\kappa = 0.1$ are shown in Figs. 10 and 11, respectively. It should be noted that the energy exchanging behaviour of the VEH is mainly affected by market price patterns. As can be clearly seen, VEH purchases electrical energy from the local network in the low price periods such as hours 1-3. However, VEH exports electricity to the network during hours 11-19, due to the electrical market high prices in these times. Similarly, in the hours 9, 11 and 18 thermal energy is imported by the VEH and during hours 1-6 and 19-24 VEH export the higher thermal energy to the local thermal network, compared to the rest of the times.

E. Energy storage systems scheduling

The charging and discharging states of the electrical and thermal storages of the VEH in the risk-neutral condition are illustrated in the Figs. 12 and 13, respectively. As can be clearly seen, the charging and discharging states follow the markets prices. For example, the electrical storage is in the charging state during hours 1-4 due to the low prices of the electricity in these times and it is in the discharging state during hours 12-15 due to the high electrical market prices. Similarly, the thermal storage system is in the charging during hours 9-11 and it also discharges during hours 14-15 because the thermal market prices are relatively higher than previous hours. **In other words, the electrical storage is operated in the maximum capacity during hours 1-2 and 12-15. Similarly, the thermal storage is operated in the maximum capacity during hours 9-11.**

The electrical and thermal stored energies in the electrical and thermal storages are present in Fig. 14. As it is clear from Fig. 14 the stored electrical and thermal energies increase during the charging states of the electrical and thermal storage, respectively. It should be noted that the minimum stored electrical and thermal energies in the storages are 50 kWh and 10 kWh.

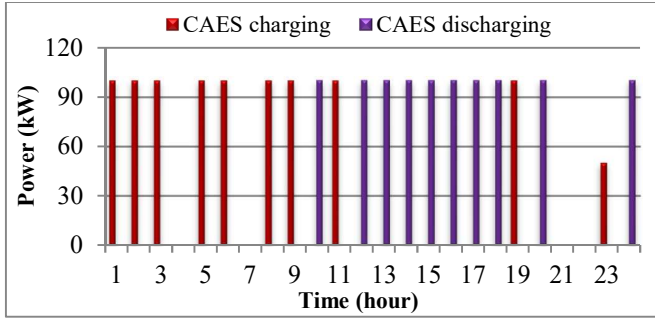


Fig. 15. Robust scheduling of the CAES system for $\kappa = 0.2$.

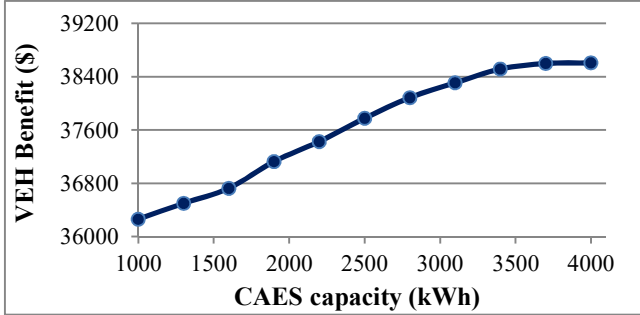


Fig. 16. Sensitivity analysis for VEH benefit based on different CAES sizes.

F. Impact of the scheduling of the CAES Unit on the VEH

Table VII provides an overall comparison between a risk-averse VEH plant with CAES system and without CAES for $\kappa = 0.2$. The results of risk-averse VEH plant self-scheduling for $\kappa = 0.2$ show the benefit of the VEH with CAES unit from exporting of electricity is higher than the benefit of the proposed VEH plant without CAES system. Moreover, the cost of electricity imported from the energy market is reduced from 846.11\$ to 261.45\$, a decrease of about 69%.

Furthermore, Fig. 15 shows the robust scheduling of the CAES system. It is clear that the scheduling plan follows the electricity market price pattern. In other words, during off-peak periods when the market prices are low, VEH plant imports electricity to store the compressed air and vice versa, the VEH exports electrical energy during peak which the prices are high.

G. Sensitivity analysis for VEH benefit

In this subsection, the sensitivity analysis procedure is applied to study the effect of CAES system size on the total benefit of the VEH. The impact of the CAES size changes on the objective function of the proposed concept is presented in Fig. 16. As it is clear from Fig. 16, the size of CAES system is changed from 1000 kWh to 4000kWh. According to the results, it can be concluded that the total benefit is increased significantly by increasing of CAES system size until 3400 kWh. Therefore, the high capacity of the CAES system has higher revenue for the VEH than its operation cost. But it can be seen that the CAES capacities which are more than 4000 kWh have no effect on the total benefit growth. Therefore, high CAES capacity up to 3400 kWh has a significant positive effect on the total benefit of the proposed VEH plant.

TABLE VIII
BENEFIT COMPARISON FOR DIFFERENT MODELS
BASED ON THE ACTUAL WPG VALUES

Number of days	Deterministic benefit (\$)	Stochastic benefit (\$)	Risk-seeker benefit (\$)	Risk-averse benefit (\$)
1	30913.75	30620.82	38757.90	38084.81
2	31089.25	30965.23	38933.40	38260.31
3	29743.87	29314.56	36914.81	37587.90
4	30523.32	30159.32	37694.93	38367.64
5	31615.98	31325.74	38786.76	39459.13
6	28885.71	28698.86	36056.08	36729.90
7	27910.25	27498.20	35081.42	35754.98
Total benefit	210682.13	208582.73	262225.30	264244.67

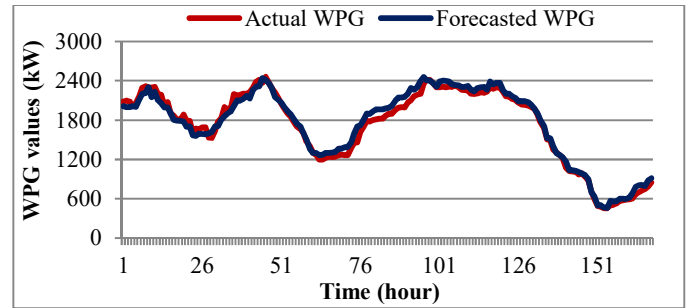


Fig. 17. Hourly WPG values for an arbitrary week.

H. Performance evaluation of the proposed model under the actual WPG values based on the after the fact analysis

In order to evaluate the effectiveness of the applied proposed method on the VEH system, stochastic and deterministic methodologies are implemented on the proposed model based on the actual WPG. It should be noted that the prediction errors are not taken into consideration in the deterministic based optimization problem. Also, various strategies are not considered in the stochastic problem and only the uncertainties are considered in the pure stochastic model.

The self-scheduling of the proposed VEH system is analyzed once again based on the forecasted and actual values of the WPG. The Monte Carlo simulation is used to generate the forecasted values. Figure 17 shows the actual and forecasted values for the 7 days of a sample week. The VEH benefit of the deterministic, scenario-based stochastic, risk-seeker and risk-averse strategies are calculated for the actual WPG values and are illustrated in Table VIII. The values of the WPG in Fig. 17 show that during the 2 days of the mentioned week, WPG values are underestimated which the results in the Table VIII confirm that the benefit of the opportunity model is higher than the other models, while, during the rest of 5 days, the values of the WPG are mostly overestimated. Therefore, for these 5 days, the robust model yields economic benefits.

It is clear from the noted results, the total weekly benefit of the risk-averse strategy is higher than the other methods. This lies in the fact that in 5 out of seven days of the week, the WPG values are mostly overestimated by the forecasting model. Therefore, the risk-averse strategy makes the VEH system robust against the worst cases of the WPG values.

V. CONCLUSION

In the current paper, a risk-constrained self-scheduling of a VEH plant based on IGDT optimization is proposed. An IGDT method is applied to find an interval for WPG to investigate the opportunity and robustness models. By implementing the proposed methodology, the VEH plant can pursue two various strategies in the local energy market to face the volatility of the WPG. The proposed robust model guarantees the minimum target benefit of the risk-averse VEH if WPG generation is lower than forecasted value. For a risk-seeker VEH, the proposed opportunistic function guarantees the VEH plant gain the target benefit from unpredictable high WPG. Moreover, this paper by introducing the VEH plant as a price taker examines the capability of the proposed concept to participate in the heat energy market. Hence, for more effective participation of the WPG integrated VEH plant in the electrical energy market, CAES unit is considered as a solution for the unpredictability of the wind farm generation. The numerical results show a reduction by about 69% for the cost of the electricity imported from the local market for a risk-averse VEH plant with CAES system for $\kappa = 0.2$ compared to a plant without CAES unit.

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