Optimal Operation of a Multi-Energy System Considering Renewable Energy Sources Stochasticity and Impacts of Electric Vehicles

Mustafa Ata[1], Ayşe Kübra Erenoğlu[1], İbrahim Şengör[1], Ozan Erdinç[1], Akın Taşcıkaraoğlu[2], João P. S. Catalão[3,*]

[1] *Electrical Engineering Department, Yıldız Technical University, İstanbul, Turkey*
[2] *Electrical and Electronics Engineering Department, Muğla Sıtkı Koçman University, Muğla, Turkey*
[3] *Faculty of Engineering of the University of Porto and INESC TEC, Porto, Portugal*
[*] *catalao@fe.up.pt*

Abstract

Electrical, heating and cooling energy demands of the end users are increasing day by day. For the sake of using fewer fossil fuels, decreasing the energy costs and gas emissions as well as increasing the efficiency and flexibility of the traditional energy systems, multi-energy systems (MESs) have begun to be used. In this study, a MES structure which also includes renewable-based generation units as suppliers together with combined heating and power (CHP) and heat pumps (HPs) is presented. The proposed MES structure is modelled as a mixed integer linear programming problem with the objective of minimizing total gas and electricity costs in daily operation. Furthermore, electric vehicles (EVs) as a new type of electrical load with inherently different characteristics are evaluated considering different end-user types as residential and commercial together with the capability of offering operational flexibility. In order to tackle with the intermittent structure of the renewable energy sources, a scenario oriented stochastic programming concept is taken into account by addressing real radiation, temperature, and wind data. Moreover, actual time-of-use (TOU) tariffs for electricity prices along with the real gas prices are evaluated. The simulation results of the devised model are given for different case studies and the effectiveness of the system is demonstrated via a comparative study. As a result, it is found that the operational costs are decreased nearly 5.49% by integrating only PV production according to the case which has no additional sources. Also, a substantial reduction of 13.45% is achieved by considering both PV and wind generation. Moreover, the flexibility was increased with taking EVs into account on the demand side and this leads to a cost reduction of 8.81% even if EVs are integrated to the system as an extra load.

Keywords: electric vehicles; energy costs; heating and cooling; multi energy systems; renewable energy sources.

1. Nomenclature

1.1. Sets and Indices

m	Set of CHP units.
n	Set of HP units.
t	Set of time periods.
e	Set of EVs.
v	Set of PV generation scenarios.
w	Set of wind generation scenarios.

1.2. Parameters

COP_n	Coefficient-of-performance of nth HP unit.
EER_n	Energy efficiency ratio of nth HP unit.
N	Sufficiently big number.
$P_{m,t}^{CHP,elec,max}$	Maximum electricity supply level of mth CHP unit in period t [kW].
$P_{m,t}^{CHP,heat,max}$	Maximum heat supply level of mth CHP unit in period t [kW].
$P_{v,w,t}^{end-user,cool}$	Cooling demand of end-user in period t for scenario v and w [kW].
$P_{v,w,t}^{end-user,elec}$	Electricity demand of end-user in period t for scenario v and w [kW].
$P_{v,w,t}^{end-user,heat}$	Heating demand of end-user in period t for scenario v and w [kW].
$P_{n,t}^{HP,cool,max}$	Maximum cooling supply level of nth HP unit in period t [kW].
$P_{n,t}^{HP,heat,max}$	Maximum heat supply level of nth HP unit in period t [kW].
$P_{v,t}^{pv}$	PV power generation in period t for scenario v [kW].
$P_{w,t}^{wind}$	Wind power generation in period t for scenario w [kW].
$R_{e,t}^{ev,ch}$	Maximum charging power of eth EV in period t [kW].
$SOE_e^{ev,ini}$	Initial SOE of eth EV [kWh].
$SOE_e^{ev,max}$	Maximum SOE of eth EV [kWh].
CE_e^{ev}	Charging efficiency of eth EV.
λ_t^{elec}	Electricity price in period t [\$/kWh].

λ_t^{gas} Marginal cost of the natural gas supplied from gas source in period t [$/kWh].

η_m^{elec} Energy conversion efficiency from gas to electricity at mth CHP unit.

η_m^{heat} Energy conversion efficiency from gas to heat at mth CHP unit.

chp_hp_m Integration multiplier for mth CHP unit.

T_e^a Arrival time of eth EV.

T_e^d Departure time of eth EV.

1.3. Variables

$P_{m,v,w,t}^{CHP,input}$ Input power of mth CHP unit in period t for scenario v and w [kW].

$P_{m,v,w,t}^{CHP,elec}$ Output electricity generation of mth CHP unit in period t for scenario v and w [kW].

$P_{m,v,w,t}^{CHP,heat}$ Output heat generation of mth CHP unit in period t for scenario v and w [kW].

$P_{m,v,w,t}^{CHPel,end-user}$ Injected electricity from mth CHP unit to end-user directly in period t for scenario v and w [kW].

$P_{m,v,w,t}^{CHPel,HP}$ Injected electricity from mth CHP unit to HP unit directly in period t for scenario v and w [kW].

$P_{v,w,t}^{direct-user}$ Injected power from the grid to end-user in period t for scenario v and w [kW].

$P_{v,w,t}^{elec}$ Power supply from grid in period t for scenario v and w [kW].

$P_{v,w,,t}^{elec,HP}$ Electricity taken from grid as one of the inputs for all of the HP units in period t for scenario v and w [kW].

$P_{v,w,t}^{gas}$ Gas input of district from fuel distribution system in period t for scenario v and w [kW].

$P_{n,v,w,t}^{HP,cool}$ Output cooling energy of nth HP unit in period t for scenario v and w [kW].

$P_{n,v,w,t}^{HP,heat}$ Output heating energy of nth HP unit in period t for scenario v and w [kW].

$P_{n,v,w,t}^{HP,input}$ nth HP unit input power in period t for scenario v and w [kW].

$P_{e,v,w,t}^{ev,ch}$ Charging power of eth EV for scenario v and w [kW].

$SOE_{e,v,w,t}^{ev}$ SOE of eth EV in period t for scenario v and w [kW].

$u_{n,v,w,t}^{HP}$ Binary variable. 1 if HP is converting electricity to heat energy in period t for scenario v and w; else 0.

a_v Probability of PV scenario v.

p_w Probability of wind scenario w.

Δt Time granularity.

2. Introduction

2.1. Motivation and Background

In recent years, demand for various types of energy sources such as electricity, natural gas, and heating/cooling have extraordinarily grew with the continuous urbanization, increasing world population density and economic growth. Furthermore, this demand is expected to increase by 48% between the years of 2012 to 2040 according to the Energy Information Agency statistical data [1]. However, all of the mentioned developments cause to undesirable side effects such as greenhouse gas (GHG) emissions and there have already been significant attempts like 2020 climate and energy package by European Union in this manner [2].

In this context, multi energy systems (MESs) are considered to be one of the most promising approaches to deal with the aforementioned problems by providing high efficiency in energy conversion process and some economic benefits [3]. To expand our knowledge, smart MES can be defined as an integrated system combining different networks such as gas, electricity, and heat so as to utilize their collective performances in terms of technical, economic, and environmental aspects [4]. Besides, it presents optimisation capability at both operational and planning stages, and it is possible to convert higher-priced energy into lower-priced energy depending on the need of the consumer [5]. Thus, it is meaningful to indicate that MESs have genuinely vast range of benefits such as providing operational flexibility, sustainability of the energy utilization and enhancing reliability as well as resiliency. Combined heating and power (CHP) and combined cooling, heat and power (CCHP) systems, heat pumps (HPs), boilers, refrigerators, thermal and electricity storage systems, power-to-gas (P2G) converter units are the main components of MES [6,7], which makes it difficult to model and operate this sophisticated architecture. As a solution, the-state-of-art concept of energy hub is presented that can be introduced as an important tool for MES modelling in which multiple carriers can be converted, conditioned, and stored [8].

Besides, integrating renewable energy resources such as photovoltaic (PV) and wind presents good opportunities in system operation of EH and has gained increasing interest in worldwide [10]. In addition, electric vehicles (EVs) have been represented as an attractive solution so as to increase flexibility and to provide fast responding, economic, environmentally friendly energy network. As an outcome, the aforementioned circumstances are drawing attention on operating a MES structure enriched with renewable-based generation units and EVs thanks to the smart grid paradigm.

2.2. Relevant Literature

There are diverse studies in the literature that examine MESs. The germane investigations can be categorized into different groups such as the survey of MESs that gives general information, broad literature review about MESs or economic or environmental evaluations of MESs, power flow applications, integration of renewables or EVs to MESs, operational and stochastic optimization of MESs, etc.

In [3], the needs of MESs that could give enthusiasms about the topic, various models of MESs and hindrances and studies that could be done in the future were described in detail. In [6], the MES layout, and various types of modelling and evaluation techniques of MESs were in depth overviewed. Besides, the control concepts of MES such as energy hub, microgrids and virtual power plants and finally several economic assessments about MES were presented.

Reynolds et al. [7] presented an exhaustive review of modelling techniques for district energy conversion technologies and focused on artificial intelligence based operational optimization of multi carrier systems. In this paper, the MES structure contained P2G systems, HPs, CHPs and boilers, and inputs of the system were electricity from grid, wind and solar energy and gas. Also a P2G schematic was given and a district energy management solution was proposed. Reference [11] performed an operational optimization of a MES consisting of a CHP and a plug-in hybrid EV (PHEV), and electricity, natural gas and electrical and heat demanding loads were respectively used as the inputs and outputs of the system. In this paper the cost given for the charging of the PHEV was minimized with the proposed formulation. Two level time-of-use (ToU) pricing scheme was used and operation of the MES was presented.

In [12], a scenario based operational optimization of a smart energy hub was presented considering the stochastic nature of electricity demand, prices of natural gas and electricity. The objective function of the problem was the minimization of the weighted sum of the energy cost and emission penalty, and conditional value a risk (CVaR) technique was used to control the operation of the system. The smart energy hub included a transformer, a CHP, a battery, a chiller and a boiler for transferring the electricity and gas inputs to the electricity, heating and cooling demands. The demand data of a real office was used in the mentioned study.

In [13], a stochastic MES simulation model for United Kingdom (UK) residential buildings was carried out. It should be stated that the study presented a new stochastic electricity, space heating and domestic hot water model for residential buildings in UK which was called Centre for Renewable Energy Systems Technology (CREST) Heat and Power (CHAP), and various versions of the proposed models were used in this study.

In [14], a multi-agent control technique was used for controlling the proposed multi carrier system. The system composed of an inverter, a microturbine, a battery, a reformer and a fuel cell, and EVs were used as mobile sources in this system. The inputs of the system were DC and AC electric power, hydrogen and natural gas and outputs were AC electric power and heat.

Pazouki et al. [15] proposed a multi carrier energy system which includes a transformer, gasification reformer, CCHP, boiler, thermal storage, absorption chiller, heat exchanger and electrical storage. Wind energy, grid electricity, biomass energy and network gas were used as the inputs of the system while electricity, heating and cooling energies were CONSİDERED as the outputs. Besides, a demand response (DR) approach was adopted in this study. Mixed integer linear programming (MILP) model of the proposed system was built for the purpose of the minimization of the operation costs and General Algebraic Modeling System (GAMS) was used to solve the optimization problem.

Timothee et al. [16] constructed a MES composed of an internal combustion generator, a boiler, a CHP, a battery bank and EVs. Solar and wind energy, grid electricity (with limited interactions) and fuel were used as the inputs, and heating and cooling demand were taken into account as outputs. The study focused on the optimization of the dispatch of the multi energy hub using evolutionary algorithm and the obtained results from the evolutionary algorithm were compared with Particle Swarm Optimisation (PSO) algorithm. Finally, the results were analysed deeply and sensitivity analysis was employed.

In [17], a flexible MES modelling technique that includes PHEVs was presented. The proposed energy hub used hydrogen, electricity and gasoline as its inputs. The PHEVs were modelled in detail (vehicle mass, car front area, tire friction coefficient, etc.) and different driving patterns were also employed. Finally, the system was tested with different simulations, hence the results of the study could clearly state the impacts of the PHEVs to a MES.

Shams et al. [18] formulated two stage stochastic optimization problem for determining the scheduled energy and reserve capacity. The objective of the problem was to minimize the operational costs. The system consisted of a transformer, a CHP, a boiler, a heat storage, a battery and a diesel generator. The proposed system was integrated with solar system and wind turbine and the intermittencies of the wind and solar energy were considered using scenarios with their probabilities. Besides, thermal demand was considered as a stochastic demand.

In [19], a residential microgrid was constructed by including power generation unit (PGU), auxiliary boiler (AB), heat recovery unit (HRU), thermal energy system (TES), electricity storage system (ESS), absorption chiller, electric chiller, CCHP and PHEVs to obtain the optimal scheduling state of the proposed structure. Electricity, gas and PV energy were used as the inputs and the uncertain production of the PV was considered using stochastic method with Normal, Weibull and Beta probability distribution functions. Besides, electricity prices, electrical and thermal demands were stochastic and DR programs were used. The MILP-based optimization problem was solved by the Augmented ε–constraint method and also fuzzy approach was used to determine best possible solution for minimizing both operational costs and total emissions.

In [20], an optimization problem was formulated considering building geometries for MES structure affecting the end-users' energy demand. The presented MES, in the mentioned study, contained CHP and HP units for the conversion of the energy carriers. Multi-energy demand was covered by PV, wind turbine, grid and gas plant with the objective of minimizing the building geometry.

Ref [21] presented a novel modelling technique for MESs which was especially suitable for predictive control applications. In order to meet the heating, cooling and electricity demand, integrated CHP, boiler, HP, heat storage, battery and chiller system components were taken into consideration. Three case studies were carried out for evaluating the effectiveness of the algorithm in terms of minimizing energy purchasing costs.

Table 1 Taxonomy of the relevant literature in the proposed research area

Ref.	CHP	HP	Multiple CHP-HP	RES EV	COM EV	Type of Demand			Type of RES		TOU	Method of Component Modeling			Type of Source		Objective Function
						Heating	Cooling	Electricity	PV	Wind		Deterministic	Sensitivity Analysis	Stochastic Approach	Electricity	Gas	
[7]	✔	✔	—	—	—	✔	—	✔	✔	✔	—	—	—	—	✔	✔	—
[11]	✔	—	—	✔	—	✔	—	✔	—	—	✔	—	—	—	✔	✔	Cost minimization
[12]	✔	—	—	—	—	✔	✔	✔	—	—	✔	—	—	—	✔	✔	Cost minimization
[13]	✔	—	—	—	—	—	—	—	—	—	—	—	—	✔	—	—	—
[14]	✔	—	—	✔	—	✔	—	✔	—	—	—	—	—	—	✔	✔	Minimizing energy input&cost&emission
[15]	✔	—	—	—	—	✔	✔	✔	—	✔	—	—	—	—	✔	✔	Cost minimization
[16]	✔	—	—	✔	—	✔	✔	—	✔	✔	—	—	—	✔	✔	—	Cash flow optimization
[17]	—	—	—	✔	—	—	—	✔	—	—	—	—	—	—	✔	✔	Minimizing propulsion costs
[18]	✔	—	✔	—	—	✔	—	✔	✔	✔	—	—	—	✔	✔	✔	Minimizing operational costs
[19]	✔	—	—	✔	—	✔	✔	✔	✔	—	—	—	—	✔	✔	✔	Energy generation& environmental costs
[20]	✔	✔	—	—	—	✔	✔	✔	✔	—	—	—	—	—	✔	✔	Minimizing building geometry
[21]	✔	✔	—	—	—	✔	✔	✔	—	—	—	✔	—	—	✔	✔	Minimizing energy purchasing cost
[22]	✔	✔	—	—	—	✔	—	✔	✔	—	✔	—	—	✔	✔	✔	Minimizing total fixed investment&variable operating&carbon emission costs
[23]	✔	✔	✔	—	—	✔	—	✔	—	—	—	—	—	✔	✔	✔	—
[24]	—	✔	—	—	—	✔	—	✔	✔	—	—	✔	—	—	✔	✔	Minimizing annual costs or emissions
[25]	✔	✔	—	—	—	✔	✔	✔	✔	✔	✔	—	✔	—	✔	✔	Minimizing total annual costs
This Study	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	—	✔	✔	✔	✔	Cost minimization

MES architecture was presented in [22] consisting of same conversion units like [21] with an extra gas turbine, thermal and electrical storage units. It was aimed to minimize the total fixed investment, variable operating and carbon emission costs in this optimization problem. The electrical output of PV-based power system was modelled stochastically via Monte Carlo simulation technique. Also, Time-of-Use (ToU) tariff was considered for trading electricity with the grid.

In [23], an innovative MES model was constructed considering power flows, point estimate method (PEM) and energy hub. The devised model had different energy converter units such as generators, compressors, CHPs, boilers and HPs. The case studies were conducted to compare Monte Carlo simulation and PEM in terms of their performance effectiveness.

A MILP-based optimization algorithm was represented in [24] for providing a robust MES model with the purpose of matching electrical and heating energy demand of end-users by minimizing total annual costs and carbon emissions.

Multi-energy demand (electrical, cooling and heating) as well as multi-power supply units (PV and wind energy) were considered in [25] for a complicated MES model. Transformer, combustion engine, heat storage and chillers were integrated into the system as an energy conversion vectors.

A detailed taxonomy of the relevant literature in the proposed research area is presented in Table 1. Although the studies in the existing literature were comprehensive studies on MES, they remained incomplete in some respects. First of all, Refs. [11-19] used various energy converter units such as CHPs, CCHPs; however, HPs were not considered as a component. Moreover, one of each energy converter unit was taken into consideration in studies [7-17], [19-22], and [24,25]. Therefore, being having different technical features of the converter units were not addressed. It is worthy to underline that while EVs were never included in the proposed MES structure of the works [7], [12-13], and [15], [18], [20-25] EVs were noticed in [11], [14], [16, 17] and [19] but ignored being residential or commercial types. The indefinite production of wind and solar energies greatly affects systems in real life. However, in only one of the studies [18], [22] wind and solar energy production were evaluated stochastically. In the literature, this issue has not been given enough attention in the scope of MES systems. On the other hand, the ToU pricing scheme, which is widely used nowadays and might be providing efficient operation for a MES, was not taken into account in any, except reference [11,12], [22] and [25].

2.3. Contributions and Organization

This paper aims to present seminal insights into the economic operation of a smart neighbourhood by taking into account network conditions, operational constraints, limitations of integrated electricity, heat and gas services. A MILP-based comprehensive mathematical formulation is presented in order to manage the wide range of multi-energy technologies such as CHP and HP units, distributed RES generation, EVs, multi-energy demand considering the related uncertainties. In the power supply side, the stochasticity due to solar and wind energy is modelled as scenario-based depending on solar radiation and wind speed by making realistic assumptions. An energy management strategy is developed according to the objective function aiming at minimizing total operational cost. It is to be noted that the gas and electricity prices are taken from Fuel Distribution System (FDS) and Electricity Distribution System (EDS), respectively. The major contributions of the study are listed as follows:

- Integrated MES structure consists of CHPs and HPs with different specifications; Renewable-based generation units such as PV and wind along with EVs are taken into consideration for achieving optimal operation in terms of minimizing total energy costs. Also, ToU pricing scheme is considered for electricity prices while the real gas prices are evaluated.
- A scenario-based system modelling is considered for PV and wind power plants for investigating the impact of uncertainties on the system operation. Besides, the impact of fuel prices on the system decision making process is investigated via additional case studies.

- Different usage patterns of EVs are aimed to be evaluated from comprehensive perspective for facilitating EV penetration with proper charging strategies in a complicated MES architecture.

The organization of the paper is prepared as follows: Section 2 gives the proposed layout and the optimization problem which is based on MILP with detailed explanations. Section 3 shows the simulation results and review of the results using different cases and comparisons. Then, Section 4 provides the conclusions and the possible future studies.

3. Methodology

3.1. An Overview of the Proposed Structure

The structures of the MESs might be demonstrated with the black box representation easily, because MES can contain detailed units and presentation of these units with their details in one scheme would be difficult for readers or researchers. In this paper, the layout of the proposed MES is shown using the black box representation. The system consists of units that can generate electricity, heating and cooling energy. The scheme of the system is presented in Fig. 1.

The proposed layout uses electricity and gas that are both obtained from related grids to meet the needed demand of the end users. In the system CHPs and HPs are used as the main components of the system, which are capable of integrating electricity and gas inputs and providing electricity, heating and cooling energy to the demand side. CHPs take gas inputs and transform the gas energy to electrical heating energy and efficiencies to convert gas to electricity and heat are different from each other. On the other hand, HPs utilize the electricity inputs and convert it to heating energy or cooling energy. However, they cannot produce the cooling and heating energy carriers at the same time.

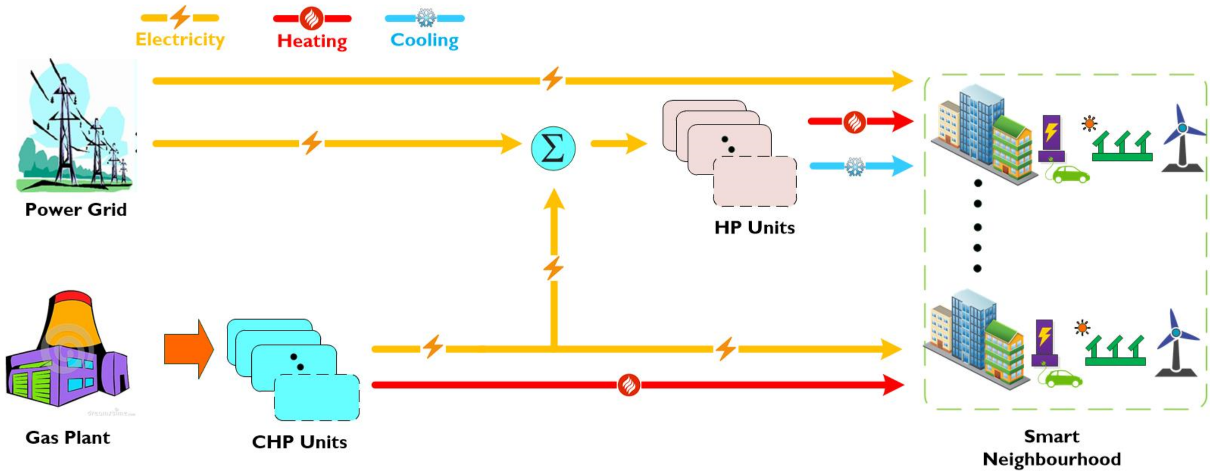

Fig. 1. *Proposed smart multi-energy neighbourhood.*

As in CHPs, HPs also use different efficiencies for the conversion of electricity to heating and cooling. Besides, HPs can also be integrated with the electricity output of the CHPs in the proposed model. The stochastic generation of PV and wind energy and commercial and residential EVs are integrated at the same time to present the effects of the intermittency of renewables and changing charging demands of the EVs with the operation of the system. Therefore, electricity and gas distribution systems are combined in the devised model and this model can enable the flexible operation of different energy carriers. The mathematical explanations of the utilized units, sources and the optimization problem are shown in the next section.

3.2. Mathematical Formulation

In this subsection, MILP-based mathematical formulation is presented considering various forms of energy inputs, outputs and multilevel energy conversion process. Also, each specific component is modelled by taking into consideration their operational limits under the network constraints and uncertainties in order to manage MES optimally. In the following subsections, the objective function and constraints are presented sequentially.

3.2.1. Objective Function:

$$Minimize\ Total\ Cost = \sum_{t}\sum_{v}\sum_{w} a_v . p_w . (P^{elec}_{v,w,t} \cdot \lambda^{elec}_{t} + P^{gas}_{v,w,t} \cdot \lambda^{gas}_{t}), \qquad \forall v, \forall w, \forall t \tag{1}$$

The objective function of the optimization problem is formulated as in Eq. (1) with the aim of minimizing the total operational cost. The injected electric and gas power from the outer energy network are represented as $P^{elec}_{v,w,t}$ and $P^{gas}_{v,w,t}$ during the period t for scenario v and w, respectively. In this formulation, the energy prices are denoted as λ^{elec}_{t} for electricity and λ^{gas}_{t} for gas. The stochasticity caused by the generation units of PV and wind formulated as scenario based along with their probabilities are coupled on the objective function $a(v)$ and $p(w)$, respectively.

3.2.2. Modelling of CHPs:

$$P^{gas}_{v,w,t} = \sum_{m} P^{CHP,input}_{m,v,w,t}, \forall m, \forall v, \forall w, \forall t \tag{2}$$

$$P^{CHP,input}_{m,v,w,t} \leq \frac{P^{CHP,elec,max}_{m,t}}{\eta^{elec}_{m}} + \frac{P^{CHP,heat,max}_{m,t}}{\eta^{heat}_{m}}, \forall m, \forall v, \forall w, \forall t \tag{3}$$

$$P^{CHP,input}_{m,v,w,t} = \frac{P^{CHP,elec}_{m,v,w,t}}{\eta^{elec}_{m}} + \frac{P^{CHP,heat}_{m,v,w,t}}{\eta^{heat}_{m}}, \forall m, \forall v, \forall w, \forall t \tag{4}$$

$$P^{CHP,elec}_{m,v,w,t} = P^{CHPel,end-user}_{m,v,w,t} + P^{CHPel,HP}_{m,v,w,t}, \forall m, \forall v, \forall w, \forall t \tag{5}$$

It is important to highlight that outer gas network is responsible for supplying natural gas demand of EH. The input of all the CHP units $\left(\sum_{m} P^{CHP,input}_{m,v,w,t}\right)$ is gas power which met by the gas network ($P^{gas}_{v,w,t}$) as described in Eq. (2). There are two conversion processes occurring in CHP units, which are gas to the power and gas to heat. The inequality constraint associated to capacity of equipment which indicates that mth CHP input power ($P^{CHP,input}_{m,v,w,t}$) strongly depends on maximum electricity ($P^{CHP,elec,max}_{m,v,w,t}$) and heat ($P^{CHP,heat,max}_{m,v,w,t}$) outputs through its efficiencies as denoted in Eq. (3). The efficiencies are supposed as the known parameters and indicated as η^{elec}_{m}, η^{heat}_{m}. In Eqs. (4) and (5), the output power of a CHP and integration of HP units are denoted in period t for scenario v and w. It is worth noting that CHP can supply electric energy for the HPs ($P^{CHPel,HP}_{m,v,w,t}$)

and to the end users $\left(P_{m,t}^{CHPel,end-user}\right)$. Moreover, the heating demand of the end-users can be satified by CHP's output $(P_{m,v,w,t}^{CHP,heat})$.

3.2.3. Modelling of HPs:

$$P_{v,w,t}^{elec} = P_{v,w,t}^{elec,HP} + P_{v,w,t}^{direct-user}, \forall v, \forall w, \forall t \quad (6)$$

$$\sum_{n} P_{n,v,w,t}^{HP,input} = \sum_{m} P_{m,v,w,t}^{CHPel,HP} \cdot chp\_hp_m + P_{v,w,t}^{elec,HP}, \forall m, \forall n, \forall v, \forall w, \forall t \quad (7)$$

$$P_{n,v,w,t}^{HP,input} = \frac{P_{n,v,w,t}^{HP,heat}}{COP_n} + \frac{P_{n,v,w,t}^{HP,cool}}{EER_n}, \qquad \forall n, \forall v, \forall w, \forall t \quad (8)$$

$$P_{n,v,w,t}^{HP,input} \leq \frac{P_{n,t}^{HP,heat,max}}{COP_n} + \frac{P_{n,t}^{HP,cool,max}}{EER_n}, \forall n, \forall v, \forall w, \forall t \quad (9)$$

$$P_{n,v,w,t}^{HP,heat} \leq N \cdot u_{n,v,w,t}^{HP}, \forall n, \forall v, \forall w, \forall t \quad (10)$$

$$P_{n,v,w,t}^{HP,cool} \leq N \cdot \left(1 - u_{n,v,w,t}^{HP}\right), \forall n, \forall v, \forall w, \forall t \quad (11)$$

The purchased electricity from the outer network $(P_{v,w,t}^{elec})$ can be directly used in order to meet the electricity demand of end-users and HP units which are stated in Eq. (6) as $P_{v,w,t}^{direct-user}$, $P_{v,w,t}^{elec,HP}$, respectively. The input power of the HPs can also be supplied from the produced electricity from CHPs $(\sum_m P_{m,v,w,t}^{CHPel,HP})$ by using integration multiplier (chp_hp_m) indicating if there is a connection between CHP and HP as expressed in Eq. (7). HPs are capable of providing heating $(P_{n,t}^{HP,heat})$ and cooling $(P_{n,t}^{HP,cool})$ demand of the end-users through energy efficiency ratio (EER_n) and coefficient of performance (COP_n) as denoted in Eq. (8). The electricity input $(P_{n,v,w,t}^{HP,input})$ is limited considering the maximum capacity heating $(P_{n,t}^{HP,heat,max})$ and cooling outputs $(P_{n,t}^{HP,cool,max})$ as presented in Eq. (9). Equations (10) and (11) control the flow of heating and cooling in one direction at the same time. More clearly, these inequalities restrict the producing of heating and cooling energy simultaneously as stated earlier.

3.2.4. Modelling of EVs:

$$0 \leq P_{e,v,w,t}^{ev,ch} \leq R_e^{ev,ch} \quad \forall t \in [T_e^a, T_e^d] \quad (12)$$

$$SOE_{e,v,w,t}^{ev} = SOE_e^{ev,ini} + CE_e^{ev} \cdot P_{e,v,w,t}^{ev,ch} \cdot \Delta t \quad if\ t = T_e^a \quad (13)$$

$$SOE_{e,v,w,t}^{ev} = SOE_{e,v,w,t-1}^{ev} + CE_e^{ev} \cdot P_{e,v,w,t}^{ev,ch} \cdot \Delta t \quad \forall t \in (T_e^a, T_e^d] \quad (14)$$

$$SOE_e^{ev,min} \leq SOE_{e,v,w,t}^{ev} \leq SOE_e^{ev,max} \quad \forall t \in [T_e^a, T_e^d] \quad (15)$$

$$SOE^{ev}_{e,v,w,t} = SOE^{ev,max}_{e} \ , t = T^{d}_{e} \tag{16}$$

The following formulations (12)-(16) are presented for EVs' dynamic nature and modelling constraints. The charging limitation of EV is stated in Eq. (12) indicating that charging power depends on the maximum power capacity ($R^{ev,ch}_{e,}$) and should be lower than this value during the simulation between arrival (T^{a}) and departure (T^{d}) times. In Eqs. (13) and (14), the state of energy (SOE) dynamics are given by taking into account charging efficiencies (CE^{ev}_{e}) and charging power ($P^{ev,ch}_{e,v,w,t}$) of each EV. The upper ($SOE^{ev,max}_{e}$) and lower limitations ($SOE^{ev,min}_{e}$) of the SOE are formulated as follows in Eq. (15) to avoid deep-discharging as much as possible which may reduce battery lifetime. The last equation ensures that SOE is to be maximum when the EV leaves for a safe travel to prevent the so-called range anxiety.

3.2.5. Modelling of End-users:

$$\begin{aligned} P^{end-user,elec}_{t} &= P^{direct-user}_{v,w,t} + P^{pv}_{v,t} + P^{wind}_{w,t} + \sum_{m} P^{CHPel,end-user}_{m,v,w,t} \\ &- \sum_{e} P^{ev}_{e,v,w,t}, \quad \forall m, \forall e, \forall v, \forall w, \forall t \end{aligned} \tag{17}$$

$$P^{end-user,heat}_{t} = \sum_{m} P^{CHP,heat}_{m,v,w,t} + \sum_{n} P^{HP,heat}_{n,v,w,t} , \forall m, \forall n, \forall v, \forall w, \forall t \tag{18}$$

$$P^{end-user,cool}_{t} = \sum_{n} P^{HP,cool}_{n,v,w,t} , \forall n, \forall v, \forall w \tag{19}$$

In Eq. (17), the electric generation and consumption balance is presented in each period of scenario v and w. The electricity demand of the end users ($P^{end-user,elec}_{t}$) and also charging demand of EVs ($\sum_{e} P^{ev}_{e,v,w,t}$) are satisfied from directly outer energy network $\left(P^{direct-user}_{v,w,t}\right)$ from CHPs ($\sum_{m} P^{CHPel,end-user}_{m,v,w,t}$), PV generation ($P^{pv}_{v,t}$), and wind production$\left(P^{wind}_{w,t}\right)$. The heating energy demand ($P^{end-user,heat}_{t}$) of the mixed neighbourhood is provided by from CHPs ($\sum_{m} P^{CHP,heat}_{m,v,w,t}$) and HPs ($\sum_{n} P^{HP,heat}_{n,v,w,t}$) as described in Eq. (18). Finally, cooling energy consumption ($P^{end-user,cool}_{t}$) is supplied by only HPs ($\sum_{n} P^{HP,cool}_{n,v,w,t}$) as stated in Eq. (19).

4. Test and Results

In order to minimize the daily operational cost of the MES along with the consideration of PV and wind energy stochasticity, the MES concept is propounded by using MILP. The devised MES management model is tested in GAMS v.24.1.3 environment with CPLEX v.12 solver [26]. It is important to indicate that power flow equations, loss functions, reactive power flow and losses are beyond the scope of our study. Also, the efficiency of the HPs and CHPs is accepted as same even under different loading conditions. The stochasticity is not considered for the other input data (such as demand) excluding wind and PV units. From the other perspective, the sizing and investment-based economic analyses of RES units are not in the scope of our paper. Input data considered and related results to different cases will be detailed in the following subsections.

4.1. Input Data

In this study, real input data are taken into account for each unit in order to provide more realistic results. A real constant gas buying price and real electricity prices considering a ToU tariff are used as energy prices. The electricity, heating and cooling consumptions of a mixed neighbourhood are used for the demand. Electricity, heat conversion efficiencies, rated powers of CHPs and heating, cooling efficiencies, rated powers of HPs are used for the energy integration and conversion. The stochastic wind and solar energy generation is used to for renewable energy generation. Lastly maximum – minimum - initial SOEs, charging efficiencies and maximum charging powers of residential and commercial EVs are used. It should be noted that efficiencies of CHPs and HPs have impacts on the rated power of these units.

The gas price is taken from [27] and varying electricity prices are used according to a ToU tariff indicated in [28], both of which can be seen in Fig. 2. The electricity prices alter throughout a day: 0.039 $/kWh between 12 a.m. - 7 a.m., 0.066 $/kWh between 7 a.m. – 5 p.m. and 0.103 $/kWh between 5 p.m. – 11 p.m. Time-varying prices effect the utilization of CHPs, HPs and the electricity and gas input of the MES so that electricity prices are used to demonstrate the effects. While the electricity prices change hourly, the gas price is fixed to 0.019 $/kWh. It can be clearly seen from Fig. 2 that the gas price is cheaper than the electricity prices throughout the day.

Real electricity, heating and cooling energy consumption data of the mixed neighbourhood is taken from [29]. The demand of the mixed neighbourhood can be seen in Fig. 3. At specific periods mixed neighbourhood draws only electricity or electricity and heating energy or electricity, heating and cooling energy as shown in Fig. 3. The specifications of different types of CHP and HP units taken from [30] and [31] are encapsulated in Table 2 and Table 3, respectively. It should be highlighted that total of ten CHPs and ten HPs which are composed of four different CHPs referred as m1, m2, m3, and m4 and five different HPs presented as n1, n2, n3, n4, and n5 are evaluated throughout the testing of the devised MES concept.

The stochastic wind energy generation based on three different scenarios represented by w1, w2, and w3 is obtained by using the data in [32] and the produced energy patterns are demonstrated in Fig. 4. The probability of the scenarios is assumed as equal. The stochastic PV energy generation [32] along with the time of the day is presented with Fig. 5. Four equiprobable scenarios expressed by v1, v2, v3, and v4 are used for PV generation. Generally, the PV scenarios have generation values between 6 a.m. – 6 p.m. and they can be ordered from the highest to the lowest as v3, v4, v2, and v1. Lastly, the real SOEs, charging efficiencies, maximum charging powers and arrival and departure times of the EVs are given in Table 4 which are taken from [33]. Four EVs (e1, e2, e3, e4) are used as residential and four EVs (e5, e6, e7, e8) as commercial. The purpose of using both commercial and residential EVs is to present the impact of the commercial EVs when they demand charging power in the day and effect of the residential EVs when they demand charging power at night.

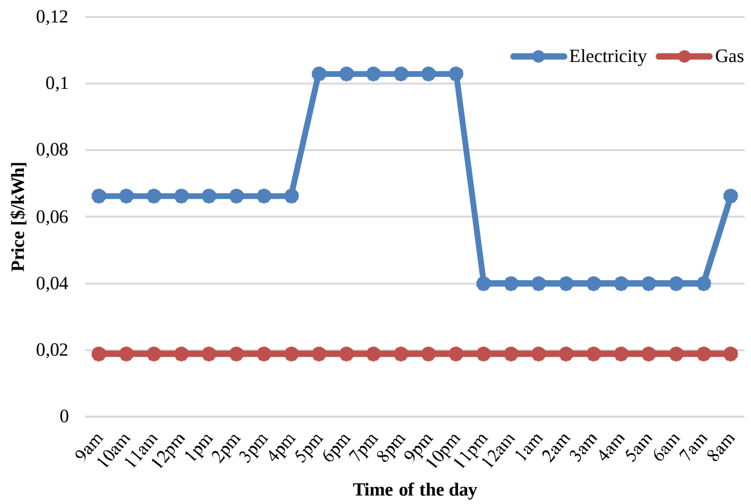

Fig. 2. *Electricity and gas buy prices.*

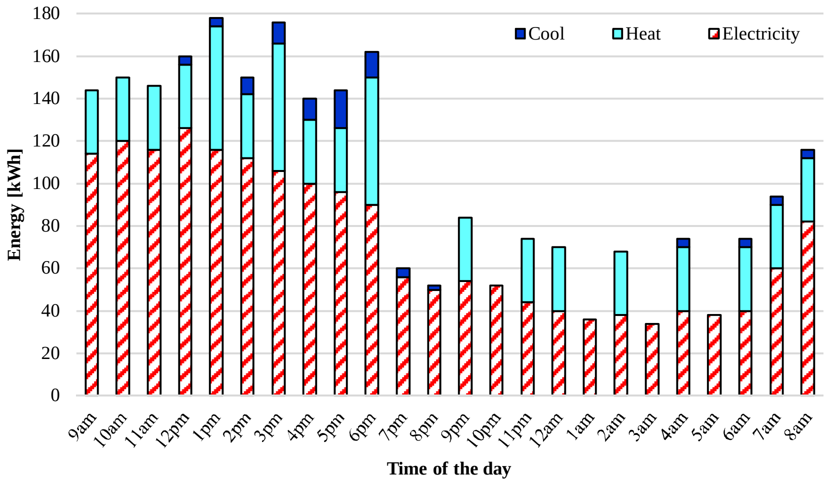

Fig. 3. *Electricity, heating and cooling demand.*

Table 2 CHP units' technical data.

Types of CHP	η^{elec}	η^{heat}	$p^{elec,rated}$	$p^{heat,rated}$
m1	0.270	0.663	6.5	16
m2	0.325	0.628	33	63.7
m3	0.320	0.633	30	59.4
m4	0.325	0.616	48	91

Table 3 HP units' technical data.

Types of HP	COP	EER	$p^{heat,rated}$	$p^{cool,rated}$
n1	4.52	4.51	3.2	2.5
n2	3.94	3.83	4	3.3
n3	3.80	3.43	8.1	7.1
n4	3.82	3.55	6.8	6
n5	3.57	3.16	9	8

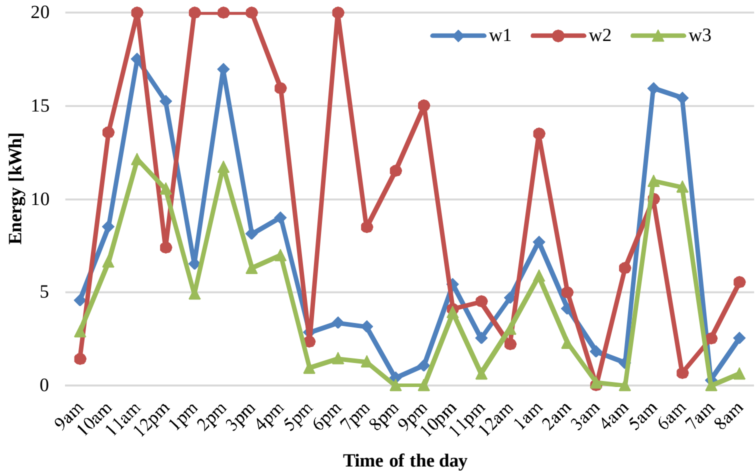

Fig. 4. *Stochastic wind energy generation.*

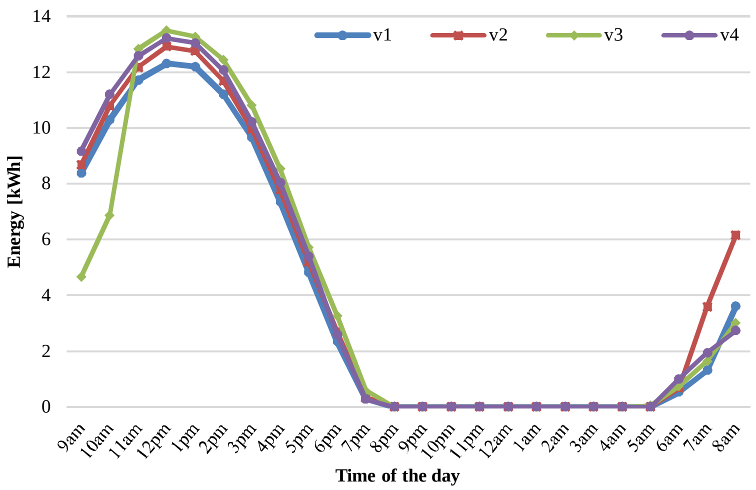

Fig. 5. *Stochastic PV energy generation.*

Table 4 Technical characteristics of evaluated commercial and residential EVs.

Types of EV	$R_{e,t}^{ev,ch}$	$SOE_e^{ev,ini}$	CE_e^{ev}	$SOE_e^{ev,min}$	$SOE_e^{ev,max}$
e1	3.3	6.4	0.95	3.2	16
e2	7.2	9.6	0.95	4.8	24
e3	6.6	8.8	0.95	4.4	22
e4	3.3	6.4	0.95	3.2	16
e5	3.3	6.4	0.95	3.2	16
e6	7.2	9.6	0.95	4.8	24
e7	6.6	8.8	0.95	4.4	22
e8	3.3	6.4	0.95	3.2	16

4.2. Simulation Results

The simulations are carried out for the selected day with a time resolution of one hour and all the figures are given for the first scenarios of both wind and PV (w1 and v1) energy generation for a clearer representation. The demand of the mixed neighbourhood only changes when an EV charging occurs and is fixed for the other time periods. Integration multipliers that can connect CHPs and HPs are all selected as 1 throughout the simulation for the purpose of a complete integration of all units and a comprehensive analysis. This can change the occurrence of different preferences. The electrical energy consumption from the main grid before and after the integration of renewables is showed in Fig. 6. The electricity consumption after the introducing of renewable-based generation units is decreased as expected.

The electricity equilibrium of the MES is displayed in Fig. 7. The net electricity demand varies between 20kW and 110kW. It can be observed from 9 a.m. to 10 p.m. that electricity demand is provided via only CHPs and at 11 p.m., the MES uses grid electricity due to the electricity prices that has the lowest prices during this time interval. MES handles all inputs, constraints etc. and the algorithm knows when the best time is to use electricity or gas considering the objective function. Even though the gas price is always cheaper than the electricity prices, the algorithm uses grid electricity for certain times and this can be observed from Fig. 7. All the efficiencies and rated powers effect this situation. Besides, the consumptions of the mixed neighbourhood are fully provided by the system. Fig. 8 and Fig. 9 show the energy balance of the other representative scenarios. There are some evident differences in the injected energy from grid; EV power consumption; CHP power production and also electrical demand when comparing to the each other. The main reason is that PV and wind production are changing and have great impacts on the system operation that should be investigated. It is beneficial for making realistic analysis through comprehensive models in terms of handling uncertainties caused by RES units.

Fig. 10 shows the equation of the produced heating and cooling energy and the heating and cooling energy consumptions. CHPs are used for heating demand, at 1 p.m., 3 p.m. and 6 p.m. In this interval, HPs cannot afford the consumption and CHPs are used because the heating and cooling consumptions at that times higher than the other times.

Fig. 11 shows the residential and commercial EVs charging needs and the total electricity production of smart MES architecture. It is evidently clear that residential EVs are charged after 10 p.m. The arrival times as well as low electricity prices are the main reasons of this condition. However, commercial EVs have different characteristics i.e., their charging patterns depend strongly on working hours. Therefore, it is possible to charge intermittently until 7 a.m. for covering end-users needs. As a result, this graph has capability to show that EVs have different profiles and can be charged any time during the day that should be investigated.

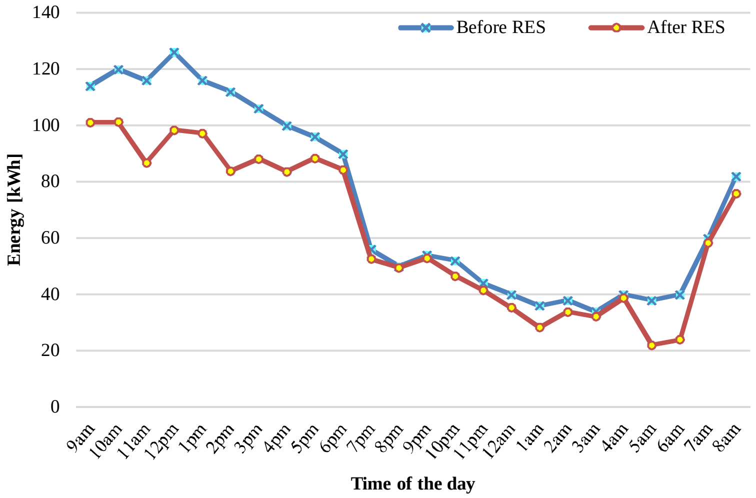

Fig. 6. *Electricity consumption before and after the integration of renewables.*

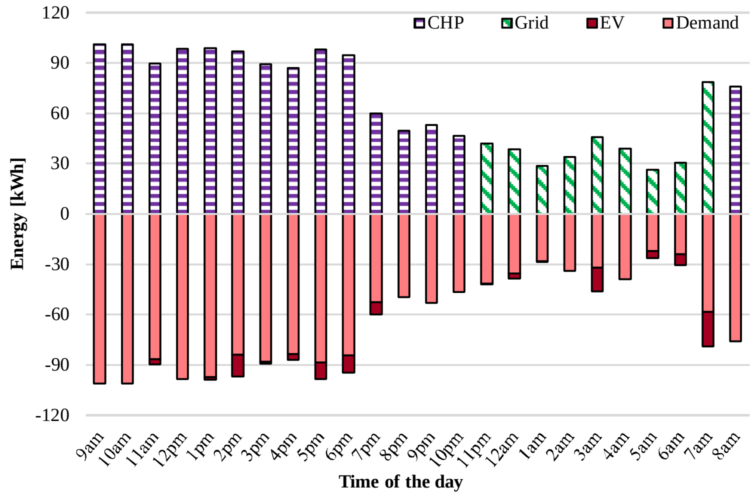

Fig. 7. *Electricity balance of the MES in Scenario 1 for both PV and wind.*

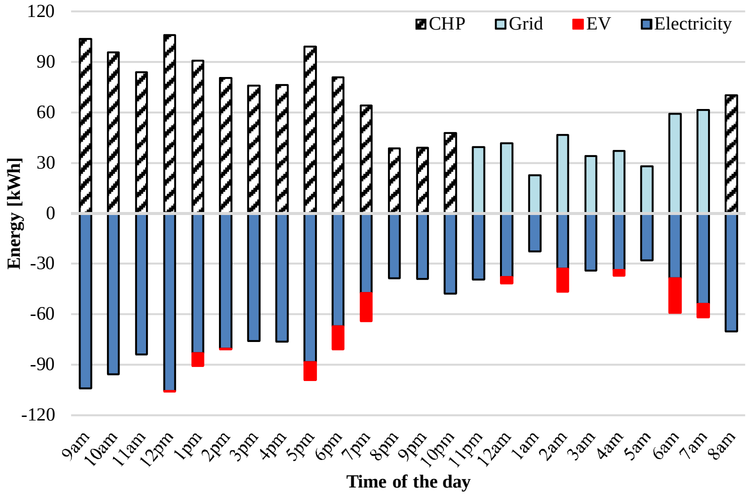

Fig. 8. *Electricity balance of the MES in Scenario 2 for both PV and wind.*

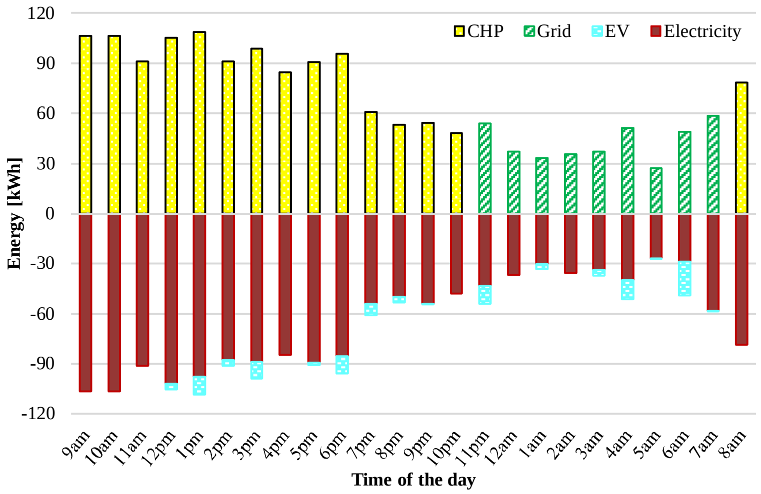

Fig. 9. *Electricity balance of the MES in Scenario 3 for both PV and wind.*

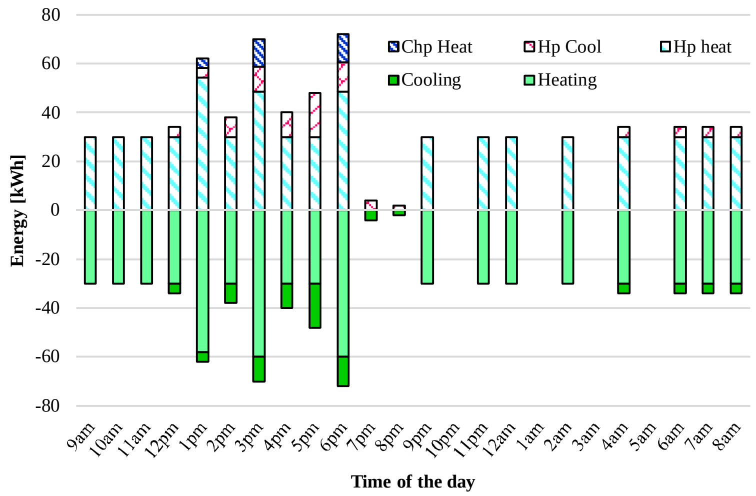

Fig. 10. *Heating and cooling balance of the MES in Scenario 1 for both PV and wind.*

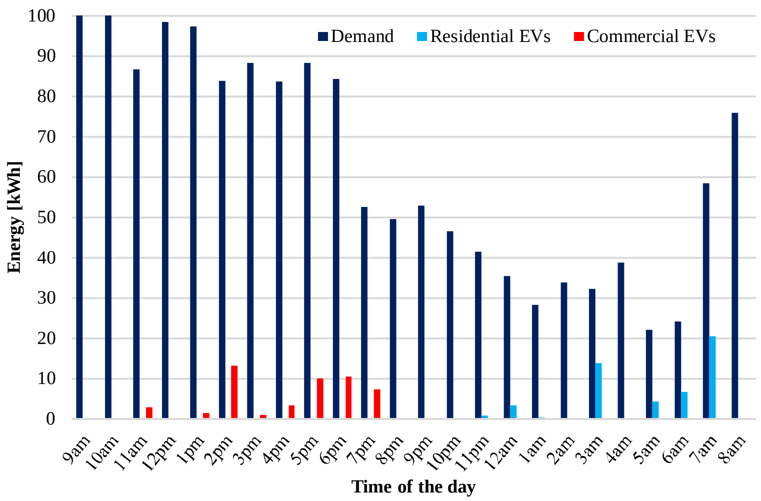

Fig. 11. *Charging powers of EVs with the total consumed electrical energy.*

A total of six different cases is simulated in this paper including the proposed model and the costs of the four cases and the electrical and gas inputs of the three cases are compared to prove the effectiveness of the devised MES. Case-1 has no renewables and EVs integrated to it. Case-2 has only PV energy generation and Case-3 has PV and wind energy generation. Case-4 is the proposed model in this paper and has both PV, wind energy generation and EVs integrated to it. In Case-5 and Case-6, the system is the same as Case-4 except that the gas price is increased 50% and 200%, respectively. Therefore, Case-5 and Case-6 are conducted to analyse the sensitivity of the decision making process to fuel prices.

Table 5 presents the total costs for four cases and as explained Case-1 has no renewable and EVs and therefore has the highest cost with 105.78 $. When PV energy generation is integrated to the system, the cost is reduced to 99.97 $ and with PV and wind the cost becomes 91.55 $. Therefore, Case-3 has the lowest cost. EV integration increases the total electricity demand and obviously it has higher cost (96.46 $) compared to Case-3 but lower cost than the other two cases. The cost results are reasonable and therefore the effectiveness of the MES is proved.

Table 5 Comparison of the Evaluated Cases

Case Descriptions	Total Cost [$]	Cost Change [%]
Case1 (Base Case)	105.78	-
Case2 (PV production)	99.97	5.49
Case3 (PV and wind productions)	91.55	13.45
Case4 (PV, wind productions, and EV consumptions)	96.46	8.81
Case5 (Same as Case4; gas price increased by 50%)	116	-9.66
Case6 (Same as Case4; gas price increased by 200%)	123.2	-16.46

Lastly, in Figs. 12-13, the electricity and gas inputs of the MES are presented for Case-4, Case-5 and Case-6. It can be seen that when gas price is increased, gas inputs of the MES are reduced while electricity inputs of the MES are increased. In Case-5, the reduction is not so much but in Case-6, a considerable reduction can be clearly seen.

The algorithm decides that using electricity is cheaper for these cases and reduces the usage of the gas. Besides, with the last results, the flexibility of the MES is validated once again.

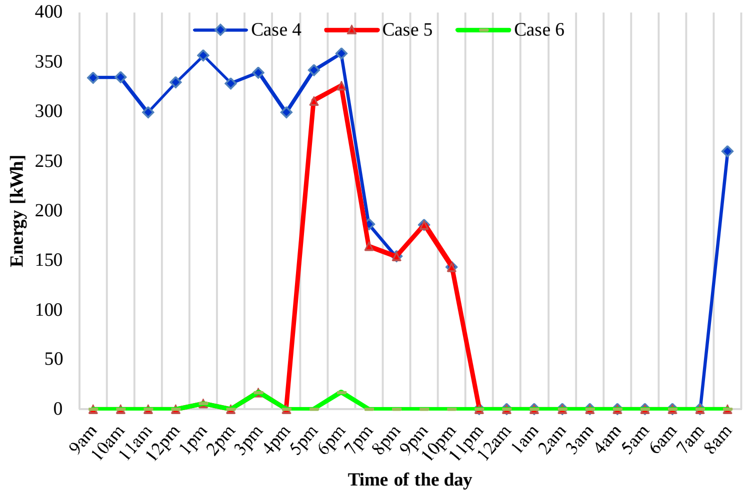

Fig. 12. *Gas inputs of the MES for three cases.*

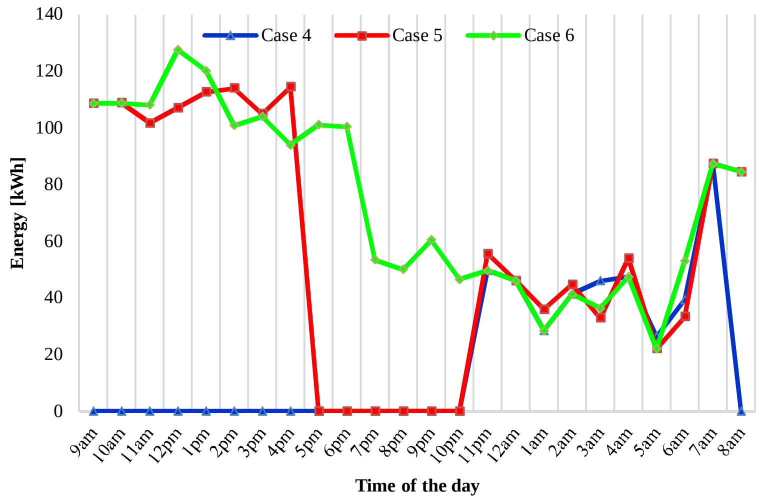

Fig. 13. *Electricity inputs of the MES for three cases.*

5. Conclusion and Discussion

In this study, a smart MES architecture which is actually the state-of-the-art combination of integrating gas, electricity, and heat network was presented for improving optimal operational strategies. Renewable-based MES structure was comprehensively examined through integrating CHPs and HPs on the supply side. System components and operational constraints were modelled via MILP-based mathematical formulation with the target of minimizing total gas and electrical energy costs in daily operation. Moreover, penetrating environmentally friendly EVs has been considered in the residential and commercial end-users side for improving operational strategies and increasing flexibility of the traditional energy system. A scenario-based stochastic approach was developed in this sophisticated energy architecture in order to deal with the uncertain nature of RESs. The power curve outputs of wind and PV farms were calculated by utilizing real radiation, temperature, and wind data in the power supply side. Furthermore, actual ToU tariffs for electricity prices along with the real gas prices were evaluated. Various case studies were carried out considering diverse scenarios to validate the effectiveness of the proposed concept. As a result, it is found that the operational costs get the highest value in the Base Case study which has no RES sources and EVs. On the other hand, the cost was reduced by nearly 5.49% with PV integration while 13.45% reduction was achieved considering both PV and wind generation. From a different perspective, penetrating different types of EVs paved the way for increasing flexibility and even if they are accepted as additional loads, the cost was decreased about 8.81% according to the Base Case.

As a future work, the presented methodology can be extended with taking the advantage of the energy reduction capabilities of flexible loads by demand side management strategies. Also, different types of energy conversion system assets can be considered. Moreover, the multi-objective system modelling can be adopted existing proposed architecture for analysing the performance of this optimization algorithm from different aspects.

6. Acknowledgment

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