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# Adaptive Residential Energy Hubs Scheduling Considering Renewable Sources

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***Abstract*— *One of the crucial challenges within the optimal operation of smart cities is coordinated management of multiple energy carriers in the residential buildings owing to disparate and often conflicting objectives. In response to this challenge, this paper proposes a novel conceptual cost-emission-based scheme for optimal energy-gas use in a smart home in the context of residential energy hubs considering a meaningful trade-off between cost saving and environmental protection. Various energy conversion resources containing energy and heat storage systems, rooftop photovoltaic modules, and also combined heat and power units along with responsible electrical and thermal loads are taken into account in the proposed model. Furthermore, an efficient stochastic scenario-based method is executed to tackle the intense uncertainty associated with photovoltaic production. The proposed model reduces domestic energy consumption and utility costs by incorporating a weighted summation mixed objective function under various system constraints and user preferences, while at the same time optimal task scheduling and comfort for the resident that it can guarantee a good lifestyle. The presented scheme is carried out on a realistic case study equipped with energy hubs and as expected, introduces its applicability and effectiveness in the optimal energy management of the proposed residential energy hub problem. The simulation results confirm that energy procurement costs can be saved by up to 46.16% and emission costs by 34.07% while maintaining the desired level of comfort for the head of the household.*

***Keywords*—** Residential energy hubs, Energy management, Renewable energy, Smart grid.

## NOMENCLATURE

**Functions**

| | |
|---|---|
| $C$ | Objective function (cent) |
| $C_ce$ | Cost of carbon emission (cent) |
| $C_e$ | Power purchase costs (cent) |
| $C_eq$ | Installation cost of the equipment |
| $C_g$ | Natural gas purchase costs (cent) |

**Variables**

| | |
|---|---|
| $E_{es}^t$ | Battery SOC at $t$ (kWh) |
| $E_{es}^{24}$ | Battery SOC at hour 24 (kWh) |
| $G_{Net}^t$ | purchased natural gas at $t$ (kW) |
| $H_c^t$ | Controllable heat load at $t$ (kW) |
| $H_L^t$ | Heat loads at $t$ (kW) |
| $H_{CHP}^t$ | Heat generated by CHP at $t$ (kW) |
| $H_{GB}^t$ | Boiler output at $t$ (kW) |
| $H_{hs,ch}^t$ | Charged heat of thermal storage device at $t$ (kW) |
| $H_{hs,dch}^t$ | Discharged heat of thermal storage device at $t$ (kW) |
| $l_{(es,ch)}^t, l_{(es,dch)}^t$ | Binary values preventing battery from charging/discharging simultaneously |
| $P_c^t$ | Controllable electric load at $t$ (kW) |
| $P_{(es,ch)}^t$ | Charged power of energy storage at $t$ (kW) |
| $P_{(es,dch)}^t$ | Discharged power of energy storage at $t$ (kW) |
| $P_{CHP}^t$ | Power generated by CHP in $t$ (kW) |
| $P_{Net}^t$ | Power imported from grid at $t$ (kW) |

**Parameters**

| | |
|---|---|
| $\alpha_t$ | Natural gas partition coefficient between CHP and boiler |
| $\eta_{(e,L)}$ | Efficiency of electric loads |
| $\eta_{(h,L)}$ | Efficiency of thermal loads |
| $\eta_{CHP,e}$ | Power generation efficiency of CHP |
| $\eta_{CHP,h}$ | Heat generation efficiency of CHP |
| $\eta_{es,ch}$ | Charge efficiency of energy storage |
| $\eta_{es,dch}$ | Discharge efficiency of energy storage |
| $\eta_{GB}$ | Efficiency of boiler |
| $\mu$ | Mean value of sunlight |
| $\pi_{ce}$ | Carbon emission price (cent/kW) |
| $\pi_e^t$ | price of purchased power (cent/kW) |
| $\pi_g^t$ | price of purchased natural gas (cent/kW) |
| $\sigma$ | Standard deviation |
| $C_{CHP}^{max}$ | Maximum capacity of CHP (kW) |
| $DSM^t$ | Participation of rates at t in the proposed DSM |
| $E_es^0$ | Initial value of energy storage SOC (kWh) |
| $E_es^{max}$ | Maximum SOC of energy storages (kWh) |
| $E_es^{min}$ | Minimum SOC of energy storages (kWh) |
| $E_{(c,e)}$ | Energy consumption of controllable electrical load in 24 hours (kWh) |
| $E_{(c,h)}$ | Energy consumption of controllable heat load in 24 hours (kWh) |
| $FF$ | Fill factor |
| $H_{max}^t$ | Maximum energy consumption by controllable thermal loads at t (kW) |
| $H_{min}^t$ | Minimum energy consumption by controllable thermal loads at t (kW) |
| $lDSM^t$ | Load curtailed by DSM program at period $t$ |
| $Load_0^t$ | Load before DSM operation at t (kW) |
| $P_{es,ch}^{max}$ | Maximum charging power of energy storages (kW) |
| $P_{max}^t$ | Maximum usable power by controllable electric loads at t (kW) |

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| | |
|---|---|
| $P^t_{min}$ | Minimum usable power by controllable electric loads at t (kW) |
| $V_{MPP}$ | Voltage at maximum power point (V) |
| $V_{oc}$ | Open-circuit voltage (V) |
| $H^t_{uc}$ | Uncontrollable the heat load at t (kW) |
| $P_(es, dch)^{max}$ | Maximum discharging power of energy storages (kW) |

**Sets and indices**

| | |
|---|---|
| $c$ | Index of controllable loads |
| $ce$ | Index of carbon emission |
| $ch$ | Index of charging |
| $dch$ | Index of discharging |
| $e$ | Index of power |
| $es$ | Index of energy storage |
| $g$ | Index of natural gas |
| $GB$ | Index of gas boiler |
| $h$ | Index of heat |
| $l$ | Index of load |
| $Net$ | Index of network |
| $t$ | Index of hour |
| $uc$ | Index of uncontrollable loads |

## 1. Introduction

Renewable and sustainable energy has become increasingly important in recent decades as a result of their lower operating costs and ability to mitigate emissions [1]. Regarding the problem of global warming and the significant increase in the need for energy around the world, energy management, and environmental protection have attracted great attention at the international level. With the aim of increasing energy supply efficiency and minimizing the generation and emission costs, smart residential buildings should be operated independently of the network. In order to decrease the amount of energy purchased from the upstream network, part of the demands of homes should be supplied through distributed energy resources (DER) such as photovoltaic (PV) modules [2], electricity and heating storage devices [3], and combined heat and power (CHP) units [4].

Nowadays, electricity and natural gas are two popular energy carriers that satisfy major societal needs. Independent use of natural gas and electricity not only reduces energy supply efficiency but also causes excessive consumption of them. This subject will have negative economic and environmental outcomes on the system. Therefore, the simultaneous energy management of multiple energy carriers (MEC) can prevent problems caused by the excessive consumption of energy as well as air pollution problems. Furthermore, the significant increase in the price of fossil fuels accompanied by environmental regulations to counter climate change and global warming (i.e., Kyoto Protocol) creates motivations to integrate renewable clean energy sources in the future smart homes [5]. Recently, a new concept has been introduced called "Energy hub" for simultaneous operation of distinct energy carriers [6]. Energy hub is a multi-input and multi-output energy system aimed at minimizing the energy procurement costs considering a set of technical constraints. In fact, it creates an interface between the energy producer and the energy consumers by providing the potential for optimal operation of MEC [7].

In the optimal operation of MEC, the household sector is very important because it is one of the most important energy consumers in smart cities that consumes a large number of energy carriers. With the introduction of smart residential buildings [8], energy management has been increasingly considered in the household sector. On the other hand, increasing the penetration of advanced measurement infrastructure (AMI) in smart cities has made it possible to measure instantaneous energy consumption. Aside from altering energy demand patterns and lowering charging costs, high-power-consumption home equipment can be moved from peak to off-peak hours. Smart homes are also equipped with new technologies such as renewable resources, storage systems and CHP units that can make the home independent of the utility grid.

According to what was said, the operation of smart homes in the form of energy hubs has great economic and environmental benefits for both network and customers. As a result, it's critical to create a cost-emissions-based model for optimum energy hub scheduling in smart residential buildings that take the residents' comfort into account. Thus, the study presented in this paper incorporates a holistic mechanism for reducing electricity procurement costs as well as emissions pollution in the residential energy hub (REH). To harness the pernicious effects of the uncertainty pertaining to PV generation, the stochastic scenario-based method is incorporated into the model. The proposed model is formulated as a mixed integer linear programming (MILP) problem and solved using the CPLEX solver under GAMS environment.

The topic of energy efficiency has grown a lot because of its importance. The activity of energy carriers in the context of energy hubs has been the subject of extensive study. Some of these researches are reducing the operation costs [9, 10], reducing carbon emissions [11, 12], and increasing the profits owing to energy selling to the market [13]. Among the technologies used in energy hubs and smart homes, there are renewable sources, which help the energy hub to become independent of the power purchase from the grid. They bring about an improvement in overall energy efficiency and also reduce air pollution in the environment [14]. In some studies, the output of renewable sources has been modeled deterministically [15], and in some other studies, their outputs have been considered subject to uncertainty [16]. Plug-in hybrid electric vehicles (PHEV) [17, 18] are other technologies that have been given special attention. They minimize emissions while still supplying electricity to the energy hub at peak hours. Energy storage [19, 20] is the most effective instrument in energy management. It plays an important role in controlling energy consumption by shifting production from off-peak hours to peak hours. Another important device used in the energy hub is CHP [21] which generates power and heat from natural gas and can provide part of the thermal and electric loads of the energy hub.

Various studies have been conducted on the operation of energy hubs, some of which are shown. Ref. [22] examines the economic and technical feasibility of P2G design in energy hub systems under future market conditions. In this modeling, the proposed planning method is divided into several sub-horizon times and the optimal size of system components is determined in each sub-horizon. Also, the P2G system can absorb carbon from CHP chimneys. The proposed model reduces 17.7% carbon emissions and 14.6% operating costs. Ref. [23] provides a framework for long-term energy hub planning in the presence of renewable resource hubs. This energy hub can supply electrical, cooling, and heating loads in the presence of various storage devices. Also, the price-based demand response program has been used in the modeling. This modeling reduces capital and operating costs by 5% and 9%, respectively. Ref. [24] presents a comprehensive model for energy hub design, where the technical, economic, and security criteria of the energy hub are fully considered. In the proposed model, all operational constraints are considered, and seasonal changes in consumers are taken into account. In the proposed model, the results are greatly improved. Ref. [25] presents an adaptive robust optimization approach for multi-layer energy efficiency. In the first stage of this modeling, the multi-layered energy hub concept is fully presented, and in the next stage, adaptive robust optimization is developed for the energy management model in the energy hub. The obtained results show that the proposed model is safer against uncertainties. Ref. [26] has introduced a framework for networked energy hubs which share their resources and cooperate together in order to reduce the cost of operation. These energy hubs use different sources and equipment to increase their flexibility. This modeling uses the Shapley amount to allocate the profit based on the share and performance of the energy hubs. Ref. [27] has presented the island operation of multi-carrier distribution systems which isolates the local network from the main network when occurring a fault. This local network is composed of several energy hubs whose goal is to supply the consumers' needs at the lowest cost. To reach this purpose, the energy hubs optimize the use of the devices and exchange energy with other energy hubs by using Cournot competition. Ref. [28] has proposed an energy hub model which includes different distributed generations and energy storage and investigates the model from planning and operation aspects. The purpose of the modeling is to decrease the cost of operation and carbon emission in the presence of renewable resources. A new energy management framework for multiple energy hubs is proposed in reference [29]. Each energy hub schedules to supply the consumers' needs with the lowest cost and air pollution. First, the energy hubs determine the amount of their own surplus/deficit energy, and then they trade energy with others by participating in energy markets. Ref. [30] presents a participatory management approach for energy hubs. This modeling helps the energy hub to exchange power to achieve more economic and environmental benefits. The obtained results show that in this modeling the operating costs and carbon emissions and the reliability of the system have been improved. Ref. [31] examines the interaction between the energy hub and the natural gas network in the presence of P2G technology, where the energy hub tries to reduce operating costs and the gas network also reduces pipeline congestion. The obtained results show that the proposed model has significantly reduced energy hub costs and gas network congestion. Although many references have investigated the energy hubs management problem from various aspects, nevertheless, there are still several open problems that must be addressed. In summary, none of above works has simultaneously taken both economic and emission issues and various MEC as well as responsible loads into consideration to solve the energy management of REH problem. In addition, one of the crucial challenging issues in smart home management problem is optimal demand scheduling of these homes that can act as hedging tool in order to harness the sharp fluctuations of renewable generation installed in the home and therefore, it leads to improve the efficiency of smart home. On the other hand, the negative effects of the uncertainty of the renewable resources used in smart homes should be evaluated in order to control the risk of the REH. The issues mentioned above were not examined by the previous works, which gave rise to the motivation for the present work.

To the best of our knowledge, none of the previous works have considered the optimal management of MEC in the REH from both economic and emission points of view. Also, the impact of responsible loads in the optimal management of REH is not investigated in prior literature. In order to respond to these shortcomings, the present paper proposes an innovative cost-emission-based approach for an REH to reach the best optimal power and heat dispatch from MEC resources. In view of the discussed context, this paper has made a contribution in the following aspects:

Executing a novel formulation for REH management in the form of a conceptual cost-emission-based model.

1) Using solar panels, electrical and thermal energy storage, and CHP units as new technologies in energy utilization to reduce network energy dependency.
2) Considering responsible electric and thermal loads to optimize the procurement costs of REH
3) Coordinated dispatching of disparate energy carriers considering a meaningful tradeoff between cost saving and a comfortable lifestyle.
4) Restraining the adverse impacts of PV production uncertainty on the obtained profit via exerting a stochastic scenario-based approach.
5) Formulation of the proposed method as stochastic MILP and subsequently minimizing through the implementation of CPLEX solver to reach the global optimality.

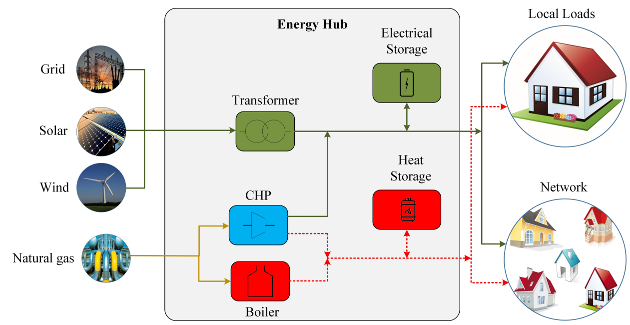

Fig. 1. Overview of energy hub structures

The remainder of this paper is organized as follows: The definition of the energy hub and its general configuration are presented in Section 2. Section 3 depicts the proposed scheme's mathematical simulation and problem formulation. The simulation findings are summarized and analyzed in Section 4. Finally, in Section5, the paper's conclusion is presented.

## 2. Background of energy hub

Energy now plays an undeniable part in the growth and progress of human cultures and life. Especially, electricity energy as irreplaceable energy can easily be converted to other energy based on the requirements of customers. In today's communities, to ensure the proper functioning of energy conversion systems, the existence of an energy conversion center for efficiently changing different energies to each other is felt more and more. The energy conversion center, which creates a suitable platform for optimal integrating and converting of various energy sources to each other, is called the energy hub.

A super node that takes energy carriers as feedback and then provides them with optimized preparation for customers is known as an energy hub. An energy hub can be defined as a residential home, commercial or industrial center, and even a city that includes household, industrial, and commercial consumers. In the other words, the energy hub is an interface between MEC which aims to transmit multiple energy flows effectively [32]. Fig 1 schematically shows the overall structure of a typical energy hub. As can be seen, the energy hub is equipped with various equipment to respond to the various needs of the consumers. The equipment includes electrical and thermal storage, boiler, and CHP which make it possible for the energy hub to convert energy into various forms and store them. An energy hub can also provide part of its energy through renewable resources such as solar panels and wind turbines, which reduce air pollution and costs.

## 3. Problem Formulation

### 3.1. Main propose

The operation structure for the proposed REH has graphically been demonstrated in Fig. 2. Various issues, sometimes conflicting, must be considered for optimal configuration of an energy hub like the reliability of the system, environment protection, procurement costs, comfortable lifestyle of inhabitance, social and economic sustainability as well as permissions and authorization processes [33]. The proposed energy hub for smart residential buildings in smart cities receives two kinds of energy carriers at its input including electricity and natural gas. The energy hub not only uses various generation equipment to meet its demands such as solar panels, and electric and thermal storage units but also has two types of consumers including thermal and electric loads. The heat load is provided by the heat-generated CHP unit, the boiler, and the heat storage used in the REH. The electric loads are fed by electricity purchased from the main grid, electricity created by CHP units, solar panels, and battery energy storage. Optimal

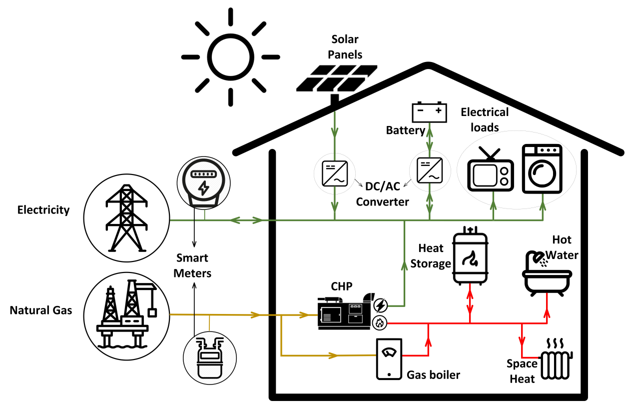


Fig. 2. Proposed residential energy hub

management of REH requires an integrated model that combines renewable resources and responsible demands with innovative technologies for the generation, control, and utilization of energy in different forms in such a way that demand is met at the minimum possible cost.

Given the fact that today one of the most important global worries is environmental pollution, the problem of air pollution should be considered in addition to the economic problems. Furthermore, one of the most beneficial approaches, in order to improve the efficiency of energy hub systems with the aim of reducing operating costs and CO2 emission in residential users, is peak load management by employing responsible loads [34]. Residential users can control their load usage by shifting their load intensity from peak to off-peak times. On the other hand, the energy hub can sell its energy surplus to the main grid or even other energy hubs in order to increase its own profit. The proposed REH is controlled by the technology of the internet of things (IoT). In this way, the sensors calculate the inputs and loads, as well as the output state of the systems, and the information is sent to the central smart controller. The controller also receives information about electricity and gas prices from the electricity and gas markets and optimizes energy consumption based on the proposed energy management algorithms. On the other hand, an operator monitors the performance of the smart controller.

One of the basic goals of smart building research is to increase the comfort of everyday life which can be obtained in two ways. The first method relies on human activity detection and incident automation in local settings, while the second method relies on centralized home management from afar. The following REH management dilemma aims to automate home appliances using human interaction and behavior awareness. Since the house is smart enough to reduce energy usage by monitoring unattended home equipment, this assistive program optimizes energy consumption.

### 3.2. Components modelling of proposed REH

In this section, the utilized equipment and responsible loads of REH are introduced and their mathematical modeling is shown to be used in the optimization process.

*A) Energy storage devices*

The impact of energy storage in the electricity sector is increasing significantly today, given rising energy source prices and significant fluctuations in energy prices in the spot market. On the other hand, these dispatchable resources can dramatically increase the influence of renewable resources by controlling their intense fluctuations of renewable productions, which will lead to an increase in the quality of the systems and lowering energy prices, which in turn will cause to increase the profit of systems [35]. Hence, energy storage units have become one of the most useful and beneficial components of a smart home [36, 37]. Energy storage has been regarded because of its cost-effectiveness and dependability. Since they are paid at hours where the cost of energy carriers is minimal and placing their surplus energy at the hands of customers at periods when the cost of energy carriers is high, the usage of energy storage units in the energy hub contributes significantly to lowering the cost of buying energy carriers. In the proposed model, there are battery energy storage and heat storage whose mathematical equations are given in the following.

*a) Battery energy storage unit:*

The battery installed in the REH charges at off-peak periods when the consumption of the home is low, by surplus power of installed PV modules and/or CHP unit and also discharges its stored power to the home when it is needed [38]. The battery state of charge (SOC) which is the amount of stored energy in the battery is shown in Eq. (1); also, the lower bound and upper limits of battery SOC are expressed in Eq. (2). The power limits for charging and discharging the battery are given by Eq. (4) and Eq. (5), respectively.

$$E_{es}^{t} = E_{es}^{0} + \sum_{h=1}^{t} \left( \eta_{es,ch} P_{es,ch}^{h} - \frac{P_{es,dch}^{h}}{\eta_{es,dch}} \right) \tag{1}$$

$$E_{es}^{min} \le E_{es}^{t} \le E_{es}^{max} \tag{2}$$

$$E_{es}^{24} = E_{es}^{0} \tag{3}$$

$$0 \le P_{es,ch}^{t} \le P_{es,ch}^{max} I_{es,ch}^{t} \tag{4}$$

$$0 \le P_{es,dch}^{t} \le P_{es,dch}^{max} I_{es,dch}^{t} \tag{5}$$

$$0 \le I_{es,ch}^{t} + I_{es,dch}^{t} \le 1 \tag{6}$$

*b) Heat storage unit:*

Regarding the proposed REH problem, both electrical energy and natural gas could be turned into thermal energy in order to feed local heat demand. This inherent energy stability increases grid efficiency, and we can fulfill dispersed thermal loads from stored thermal energy by employing heat energy storage within the proposed REH, which eliminates network congestion that occurs during peak demand [39]. Heat storage allows excess heat energy to be stored and used after hours, days, or months. The mathematic formulations of heat storage are similar to the equations of the battery energy storage (1)-(6), so, we avoid repeating them.

*B) CHP unit*

CHP is a cogeneration technology that absorbs natural gas as input and concurrently produces power and heat at its output. This unit, which is crucial in the relationship between natural gas and electricity, was chosen because of its high quality. CHP units can be categorized into three main groups including only power, only heat, and heat and power; where in this paper the heat and power CHP unit has been used in the smart residential building. CHP has a feasible operating range, demonstrating that the generation of electricity and heat by CHP is interdependent. In other words, a specific amount of heat production produces a specific amount of electricity. The mathematical equations for the CHP unit are as follows [40]. The power and heat generated by the CHP are obtained by Eq. (7) and Eq. (8), respectively, and Eq. (9) shows the limitation of power produced by the CHP. Given that the amount of power and heat generation by the CHP are dependent on each other, restricting power generation makes to be limited heat generation.

$$P_{CHP}^{t} = \eta_{CHP,e} \alpha_t G_{Net}^{t} \tag{7}$$

$$H_{CHP}^{t} = \eta_{CHP,h} \alpha_t G_{Net}^{t} \tag{8}$$

$$\alpha_t G_{Net}^{t} \le C_{CHP}^{max} \tag{9}$$

### C) Solar panels

As a result of air pollution, people are increasingly turning to sustainable and green energy sources. Solar panels are one of these outlets, which have gained popularity in recent years due to their ease of use and installation. Under these circumstances, photovoltaic modules have attracted a great deal of attention around the world by converting the radiant energy generated by the sun into DC power, enabling 100% renewable and emission-free power generation. It's worth noting that *t*he output of solar panels is determined by the amount of sunlight received and the condition of the panels [41]. The mathematical equations for the output power of solar panels are as follows [34].

$$T_{cy} = T_A + s_{ay}\left(\frac{N_{OT} - 20}{0.8}\right) \tag{10}$$

$$I_y = s_{ay}(I_{sc} + K_i(T_c - 25)) \tag{11}$$

$$V_y = V_{oc} - K_v T_{cy} \tag{12}$$

$$P_{sy}(s_{ay}) = N.FF.V_y.I_y \tag{13}$$

$$FF = \frac{V_{MPP} I_{MPP}}{V_{oc} I_{sc}} \tag{14}$$

One of the major challenges in exploiting solar panels is the extreme fluctuations in the production of these sources due to the variability of sunlight throughout the day. The uncertainty in the production of PV modules causes many problems in the exploitation of these resources and energy scheduling problems, which must be carefully assessed and evaluated. In this paper, an efficient scenario-based approach was proposed to study the impact of PV fluctuations on system performance to address the adverse effects of uncertainty. In so doing, the probability density function (PDF) of solar radiation is extracted at *t*he location in which PV modules are installed. In this paper, normal PDF is used for sunlight radiation as below [33].

$$f(s) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(s-\mu)^2}{2\sigma^2}} \tag{15}$$

Finally, the power generated by the solar panel, which is a function of solar irradiance and ambient temperature, can be given by Eq. (16).

$$P_{PV} = \frac{P_{STC}}{S_{STC}} S\left(1 + K_{MPPT}(T_C - T_A)\right) \tag{16}$$

### D) Demand side management system

Recently, much attention has been devoted to demand side management (DSM) systems in smart cities as an effective tool for optimal managing demand to decrease the peak load and therefore reduce the operating costs [42]. Actually, the basic aim of DSM programs is to change the consumption pattern with the purpose of lowering costs and improving the reliability of system use through activities or programs that encourage customers to optimize their energy usage [43]. These programs provide low-cost energy and capacity resources, shifting the need to purchase electricity during peak hours, thereby reducing household procurement costs [44]. Also, it can provide considerable benefits for customers in terms of reduced costs and giving them greater control over the energy they use and produce.

An optimized power-heat-demand scheduling model is introduced in this paper in order to reduce the operation and pollution costs of the proposed REH. To this end, smart home loads are split into two categories: thermal loads and electrical loads. The electric and thermal loads are divided into controllable and uncontrollable groups; to put it another way, a portion of the thermal and electric loads has a certain amount of consumption and running time that is uncontrollable (e.g. critical loads). Controllable loads, on the other hand, have certain unmonitorable consumption, but you can control their usage time to shift from peak hours to off-peak hours (such as process loads). The formulation of thermal and electrical responsible loads to participate in the proposed DSM program is given as follows.

*a) Electrical loads:*

By applying for the proposed TOU-based DSM program, the customers curtail their unnecessary consumption at peak hours when the electricity price is high, or transfer to off-peak hours in order to reduce the procurement costs of the home. Note that *t*he values of curtailment/shiftable loads have a limited capability. Total electric load is the sum of controllable and uncontrollable loads which has been shown in Eq. (17). The lower bound and upper bound of controllable loads have been expressed in Eq. (18). In Eq. (19), it is explained that sum of controllable loads in 24 hours is equal to the amount of daily energy consumption. Finally, Eq. (20) and Eq. (21) indicate DSM program.

$$P_L^t = P_{uc}^t + P_c^t \tag{17}$$

$$P_{min}^t \le P_c^t \le P_{max}^t \tag{18}$$

$$\sum_{t=1}^{24} P_c^t = E_{c,e} \tag{19}$$

$$Load^t = (1 - DSM^t).Load_0^t + lDSM^t \tag{20}$$

$$Load_0^t - Load^t = DSM^t.Load_0^t - lDSM^t \tag{21}$$

*b) Thermal loads:*

In this paper, the proposed DSM program is also used for responsible thermal loads of the home. Total thermal load is the sum of controllable and uncontrollable loads which has been shown in Eq. (22). The lower bound and upper bound of controllable loads have been expressed in Eq. (23). In Eq. (24), it is explained that sum of controllable loads in 24 hours is equal to the amount of the total consumed energy. Finally, Eq. (25) and Eq. (26) indicate DSM program.

$$H_L^t = H_{uc}^t + H_c^t \tag{22}$$

$$H_{min}^t \le H_c^t \le H_{max}^t \tag{23}$$

$$\sum_{t=1}^{24} H_c^t = E_{c,h} \tag{24}$$

$$Load^t = (1 - DSM^t).Load_0^t + lDSM^t \tag{25}$$

$$Load_0^t - Load^t = DSM^t.Load_0^t - lDSM^t \tag{26}$$

### E) Mismatch constraints of power and heat

The most basic constraints of the proposed REH problem are the power and heat balance equations. The equations indicate that *t*otal power and heat production must meet the total power and heat demands. The following are the power and heat balance equations, as seen in Fig. 2:

$$P_{Net}^t + P_{PV}^t + P_{CHP}^t + P_{es,dch}^t = \frac{P_L^t}{\eta_{e,L}} + P_{es,ch}^t \tag{27}$$

$$H_{GB}^t + H_{CHP}^t + H_{hs,dch}^t = \frac{H_L^t}{\eta_{h,L}} + H_{hs,ch}^t \tag{28}$$

$$H_{GB}^t = \eta_{GB}(1 - \alpha_t) G_{Net}^t \tag{29}$$

Eq. (27) and Eq. (28) indicate the balance of power and heat, respectively. Also, the heat generated by the gas boiler is obtained from Eq. (29).

*F) Total objective function*

Different objective functions, depending on customer choice, can be adopted to solve the proposed optimization problem. Thus, the main target of exploitation of proposed REH is to minimize the procurement costs of residential buildings including reduction of purchased electricity and gas from the main network as well as decreasing the emission cost of the system. So, an integrated power-gas-demand model has been introduced to reach the best optimal power dispatch between various resources under the DSM program so that minimize the operating costs of smart homes with the least amount of air pollution. Eq. (30) shows the total objective function of the proposed model, which includes operating costs and is obtained from the sum of Eqs. (31) to (34). These conflicting objectives are turned into one unique objective function via applying the weighted sum method in Eq. (30). Eq. (31) and Eq. (32), are the costs of purchasing electricity and natural gas from the network, respectively. Eq. (33) is the carbon emission cost and Eq. (34) is the fixed cost of DER units. It should be mentioned that in the Eq. (30) $\psi_1, \psi_2, \psi_3$ and $\psi_4$ are the coefficients of weighted sum method that are set to be 1.

$$C=(\psi_1 \times C_e) + (\psi_2 \times C_g)+(\psi_3 \times C_{ce}) + (\psi_4 \times C_{eq}) \quad (30)$$

$$C_e=\sum_{t=1}^{24} \pi_e^t P_{Net}^t \quad (31)$$

$$C_g=\sum_{t=1}^{24} \pi_g^t G_{Net}^t \quad (32)$$

$$C_{ce}=\pi_{ce} \sum_{t=1}^{24} (\beta_e P_{Net}^t+\beta_g G_{Net}^t) \quad (33)$$

$$C_{cq}=\sum_{t=1}^{24} \sum_{d=1}^{DG} (\alpha_d+\gamma_d P_d^t) \quad (34)$$

Subject to: (1)–(9), (17)–(19), (22)–(24) and (27)–(29).

## 4. Numerical Results

In this paper, the sample test system was analyzed as a multi-carrier REH system and investigated the impact of the proposed integrated model on improving home quality and reducing air pollution. The objective function of the proposed model is the weighted sum of the operating costs and carbon emissions to optimize the utilization of the energy hub. Finally, the results of receiving the DSM program are evaluated using the proposed model, which means that expense and pollution should be kept to a minimum. The proposed optimization problem is minimized by CPLEX solver [45] under GAMS environment and the obtained results are presented and discussed in the following.

### 4.1. Data

In this section, the technical data of the system that is used in the optimization process is provided, which includes the costs of energy carriers, consumer and equipment data. Table 1, shows the power and natural gas prices, which are in the TOU tariff, respectively. The values of the natural gas dispatch factor [46] between CHP and gas boiler are expressed in Table 2. Also, information on battery energy storage and heat storage utilized in the REH is given in Table 3. Table 4 shows the amount of energy used, the higher and lower bounds for power usage, and the time spent using the washing machine as a controllable electric load and hot water as a controllable heat load. Table 5 shows the efficiency of the electric and thermal appliances. In addition,

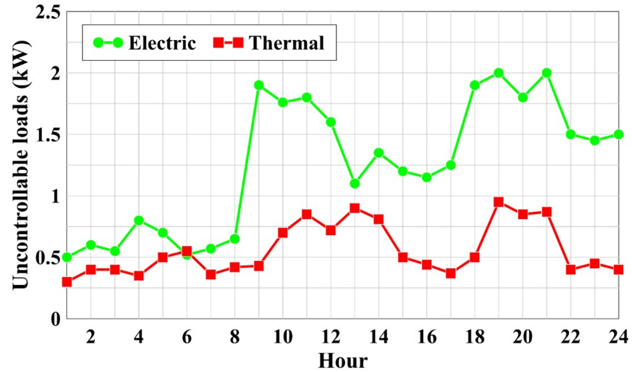


Fig. 3. Profile of uncontrollable loads

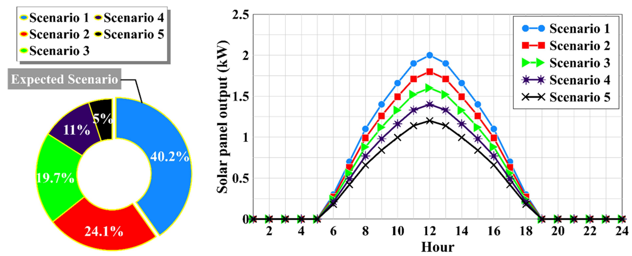


Fig. 4. Solar panel outputs in different scenarios

Fig 3 depicts the uncontrollable thermal and electrical loads at various hours. The thermal and electrical efficiencies of the CHP unit are estimated to be 45% and 30%, respectively, as well as maximum natural gas imported into it is assumed at 3.5 kW. Also, the maximum capacity of PV installed in the REH is 2 kW and its available capacity can vary between 0 to 2 kW. It is worth noting that in order to handle the uncertainty of PV generation, the stochastic scenario-based method has been incorporated into the model. To this end, five scenarios are generated from a PDF of sunlight at *t*he place whose PV modules are installed. The profiles of PV output and the occurring probability of each scenario are shown in Fig. 4 [47]. The generation price of solar panels and also price of charging/discharging power of energy storage at different hours are fixed at 0.1 and 0.2, respectively. The installation costs of CHP, energy storages, and photovoltaic are 10, 7, and 9 cents, respectively.

### 4.2. Case studies

To determine the impact of the proposed integration model on REH's profits, four different case studies were reviewed and the findings were compared the findings. In order to evaluate the effect of multiple resources on the proposed model, desperate cases are developed as below:

1) **Case 1:** Base case (no energy resources are added into the REH)
2) **Case 2:** Only CHP is added to the REH
3) **Case 3:** Battery and thermal energy storage are added to Case 2
4) **Case 4:** PV modules are added to Case 3

### 4.3. Results

This section shows the results of the simulation; then, the performance of each piece of equipment will be analyzed. In Case 1, the operating cost of the REH regardless of energy management of DERs and without considering the various equipment was examined. In other words, in this case, each energy carrier was independently used, and electrical and thermal loads were directly fed from energy carriers purchased from the network regardless of their prices at different times.

Table 1. Energy carrier price in TOU tariff

| | Electricity | | | Natural gas | |
|---|---|---|---|---|---|
| | Off-Peak | Mid-Peak | On-Peak | Off-Peak | On-Peak |
| Time (h) | 1 - 8 | 13 - 17<br>22 - 24 | 9 - 12<br>18 - 21 | 1 - 9<br>15 - 18<br>22 - 24 | 10 – 14<br>19 – 21 |
| Price (cent/kWh) | 7 | 10 | 14 | 2 | 6 |

Table 2. Dispatch coefficient at different times

| Hour | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $\alpha_t$ | 0.8130 | 0.8300 | 0.7760 | 0.7410 | 0.8520 | 0.7170 | 0.7380 | 0.7410 |
| Hour | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| $\alpha_t$ | 0.8010 | 0.8340 | 0.7690 | 1.0000 | 0.8580 | 1.0000 | 1.0000 | 1.0000 |
| Hour | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| $\alpha_t$ | 0.8340 | 0.7450 | 0.7140 | 0.6660 | 0.7410 | 0.7700 | 0.6750 | 0.7050 |

Table 3. Information about energy storages

| | $P_{es,ch}^{max}$ (kW) | $P_{es,ch}^{max}$ (kW) | $E_{es}^{max}$ (kWh) | $E_{es}^{min}$ (kWh) | $E_{es}^{0}$ (kWh) | $\eta_{es,ch}$ | $\eta_{es,dch}$ |
|---|---|---|---|---|---|---|---|
| Battery | 0.7 | 0.9 | 5 | 1 | 2 | 0.88 | 0.88 |
| Thermal storage | 0.5 | 0.5 | 3 | 0.5 | 2 | 0.60 | 0.80 |

Table 4. Information about the controllable loads

| Electric load | | | | Thermal load | | | |
|---|---|---|---|---|---|---|---|
| $P_{max}^{t}$ (kW) | $P_{min}^{t}$ (kW) | $E_{c,e}$ (kWh) | Operating time (Hour) | $H_{max}^{t}$ (kW) | $H_{min}^{t}$ (kW) | $E_{c,h}$ (kWh) | Operating time(Hour) |
| 0.55 | 0.3 | 5.5 | 6 - 17 | 0.4 | 0.25 | 3.5 | 8 – 18 |

Table 5. Efficiency of the electric and thermal appliances

| $\eta_{e,L}$ | $\eta_{h,L}$ |
|---|---|
| 0.8 | 0.8 |

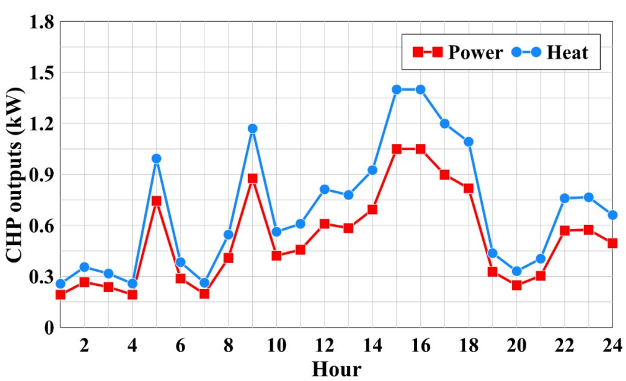


Fig. 5. CHP output in the proposed model

CHP was added to the REH in Case 2. Given to the fact that applying restrictions to reduce the amount of air pollution will increase the use of more expensive network resources, this issue will increase the costs of network operation. But when different production resources such as CHP units and energy storages are added to the system, this not only reduces the network operating costs by applying energy arbitrage (charging in low load hours and discharging in peak load hours), but also it reduces the use of air polluting resources. Since the price of natural gas is often lower than the price of electricity in this article, the CHP unit lowers operational costs by producing power from natural gas. The quantities of power and heat emitted by a CHP unit are depicted in Fig. 5. It can be seen, that when the price of natural gas is low,

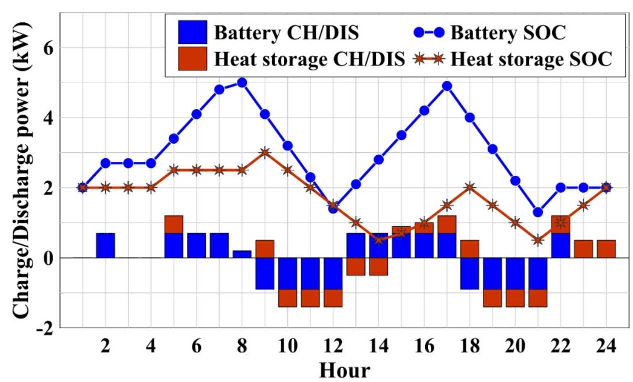


Fig. 6. SOC of energy storages in the proposed model

the CHP increases its production and when the price of natural gas is high, it reduces its production. For example, because the price of natural gas from hour 15 to hour 18 is low, the CHP increases its production. Also, because the price of natural gas from hour 19 to hour 21 is high, the CHP decreases its production. As can be shown, the amount of produced energy and heat is relatively constant at various hours because, as previously said, the amount of generated power by CHP is dependent on its heat generation.

The previous case is supplemented with electrical and thermal energy storage systems in Case 3. Energy storage saves energy when energy prices are low and provides stored energy to customers when energy prices are high. Fig. 6 depicts the battery and heat storage state of charge. For example, the battery was charged from hour 13 to17, when electricity was cheap, and discharged from hour 18 to21, when electricity was expensive. Similarly, when natural gas prices are cheap, the heat storage unit is charged from 15 to18, and when natural gas prices rise, it is discharged from 19 to 21. In Case 4, solar panels were inserted on the roof of home. Solar panels, which are clean energy sources, have a considerable

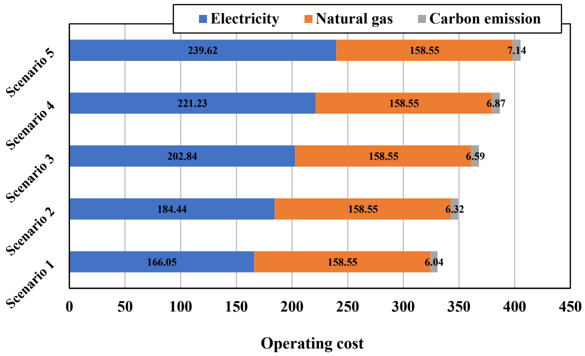


Fig. 7. Impact of solar panel performance on REH operating cost

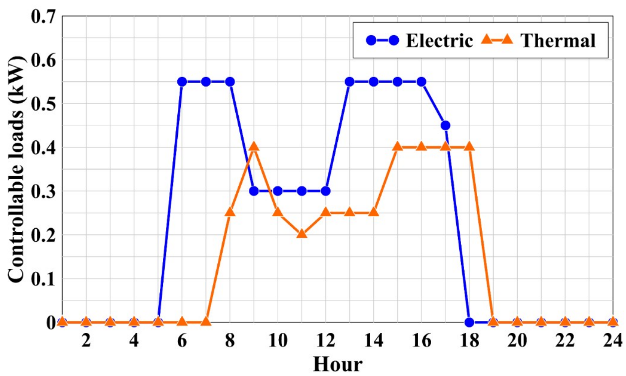


Fig. 8. Profile of controllable loads

effect on reducing air pollution and purchasing electricity from the network. On the other hand, solar panels are uncertain, as has been said, for this reason, five scenarios have been generated from PDF of sun radiation to evaluate the impact of solar panels on the use of the energy hub. Fig. 7 shows the cost of operation in each scenario. As can be seen, in various scenarios, with increasing the solar panel production, carbon emission and purchased energy costs from the main grid are reduced accordingly. The profile of controllable electrical and thermal loads is also seen in Fig. 8. As can be shown, when the price of the energy carriers is high, the consumption is lowest, and when the price of the energy carriers is low, the consumption is highest. For example, because from hour 6 to hour 8 and hour 13 to hour 17 the price of electricity is low, the electric controllable load increases its consumption. Also, because from hour 9 to hour 12 the price of electricity is high, the electric controllable load decreases its consumption. Similar to that, the thermal controllable load increases its consumption from hour 15 to hour 18 because in these hours the price of natural gas is low, and the load reduces its consumption from hour 10 to hour 14 because the price of natural gas is high. Due to changed upstream grid pricing, the load profile has been shifted and the proportion of load has changed in some peak to off-peak stages, as seen in Fig. 8. The proposed DSM policy has the following advantages: it reduces REH system emissions and operating costs, as a result, it improves the economic and environmental performance.

### 4.4. Discussion

After reviewing the results, this section will compare different items. The extent of purchasing power and gas of the REH system by consumers from the upstream networks is illustrated in Fig. 9 for all Cases. In Case 1, energy carriers are exploited separately, and the amount of entry of each energy carrier per hour depends on the number of loads that same hour. In Case 2, by adding the CHP unit to REH, the amount of natural gas input has increased, and the amount of power input has dropped. Because CHP, part

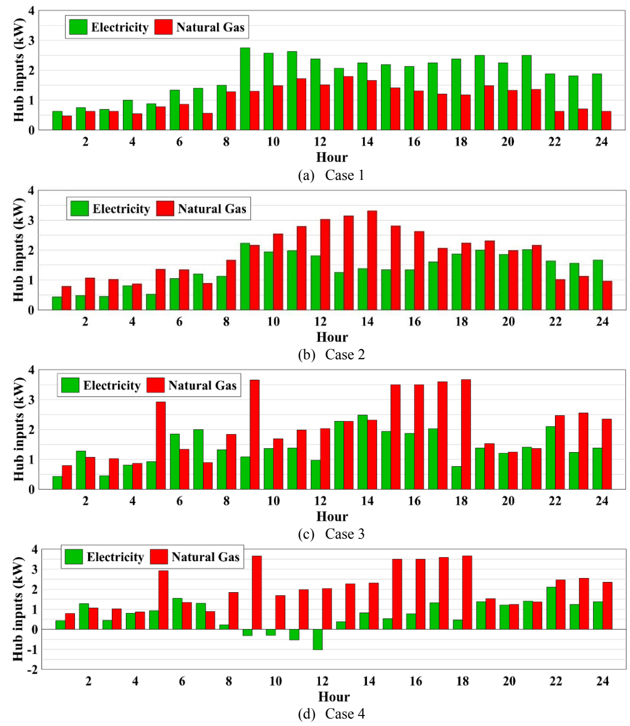


Fig. 9. Energy hub inputs in each Case.

of the power required by the energy hub generates energy from natural gas. In Case 3, with the addition of more energy storage devices, the input of the energy hub is shifted to hours where the price of energy carriers is low. In Case 4, with the installation of solar panels, the power supply to the energy hub is zero at certain hours, but the energy hub will sell the surplus energy to the network at other hours. Table 6 also displays the cumulative performance of the energy hub's optimum use. In the existence of the DSM scheme, imported power and gas from the upstream grid are minimized in the peak period, as seen in Fig. 9. According to Table 6, the buying power and gas from the main grid are lowered due to the use of peak-load control and DER units, and as a result, the pollution and maintenance costs of the REH system are reduced. Also, According to Table 6, the cost of purchasing the energy carriers in Case 1, where the energy hub has no energy management equipment, equals 603.15 (500.9 + 102.25). On the other hand, in Case 4, the energy hub is equipped with different facilities, and the operating cost equals 324.7 (166.05 + 158.56). Now we can calculate the decrement in operating cost as follow:

$$\frac{C_{case\ 1} - C_{case\ 4}}{C_{case\ 1}} = \frac{603.15 - 324.7}{603.15} = 46.16\%$$

Also, we used this equation to calculate the percentage of carbon emission reduction. To obtain the decrement of carbon emission we can write as follow: (Note that $E_{case\ 1}$ means carbon emission cost in Case 1)

$$\frac{E_{case\ 1} - E_{case\ 4}}{E_{case\ 1}} = \frac{9.162 - 6.04}{9.162} = 34.07\%$$

## 5. Conclusion

The optimum use of MEC in the form of REH was studied in this paper under responsible loads in order to reduce REH's economic and pollution costs. REH was described as a smart residential house powered by IoT technology. Simulations were run with different instruments, including the CHP unit, battery energy storage and heat storage systems, and solar panels, all of

Table 6. Values of all objective at different Cases

| Case | Electricity | Natural Gas | Carbon emission | Total |
|---|---|---|---|---|
| Case 1 | 500.9 | 102.25 | 9.162 | 612.31 |
| Case 2 | 375.64 | 175.76 | 8.36 | 569.77 |
| Case 3 | 349.99 | 158.56 | 8.78 | 534.33 |
| Case 4 | 166.05 | 158.56 | 6.04 | 356.65 |

which were linked to the TOU-based DSM scheme. In addition, to model the volatility of solar production, an effective stochastic scenario-based technique was used.

The numerical results of calculations show that implementing the proposed REH management solution reduces residents' smart home billing costs and also greenhouse gas emissions. Furthermore, it was shown that using heat storage units in the REH flattens the natural gas demand profile. Furthermore, integrating solar panels into the REH results in stronger compatibility between solar generation and energy usage, i.e., the controllable demands are shifted as far as possible to sunny hours of the day. Furthermore, by installing storage systems into the REH, natural gas and electricity are bought and retained in the storage when the price of energy carriers is low, and when the price of energy carriers is high, they place their stored energy at *t*he disposal of customers. Hence, by optimal arbitrage of these storage devices, the operating costs of the system are reduced significantly. In addition, the simulation results proved that *t*he solar panel not only decreases the operating costs of REH and dependency on electricity purchases but also causes to reduce the carbon emissions of the system. Therefore, the proposed integrated approach not only ensures optimal task scheduling and thermal comfort zones for REH residents but also allows surplus residential power to be sold to the upstream grid, increasing system revenue. As a result, the procurement costs of REH are reduced by 46.16% and the emission cost is decreased by 34.07% while maintaining the household owner's desired comfortable lifestyle.

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