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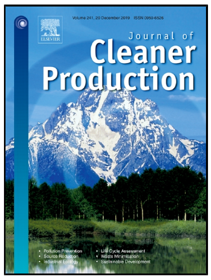

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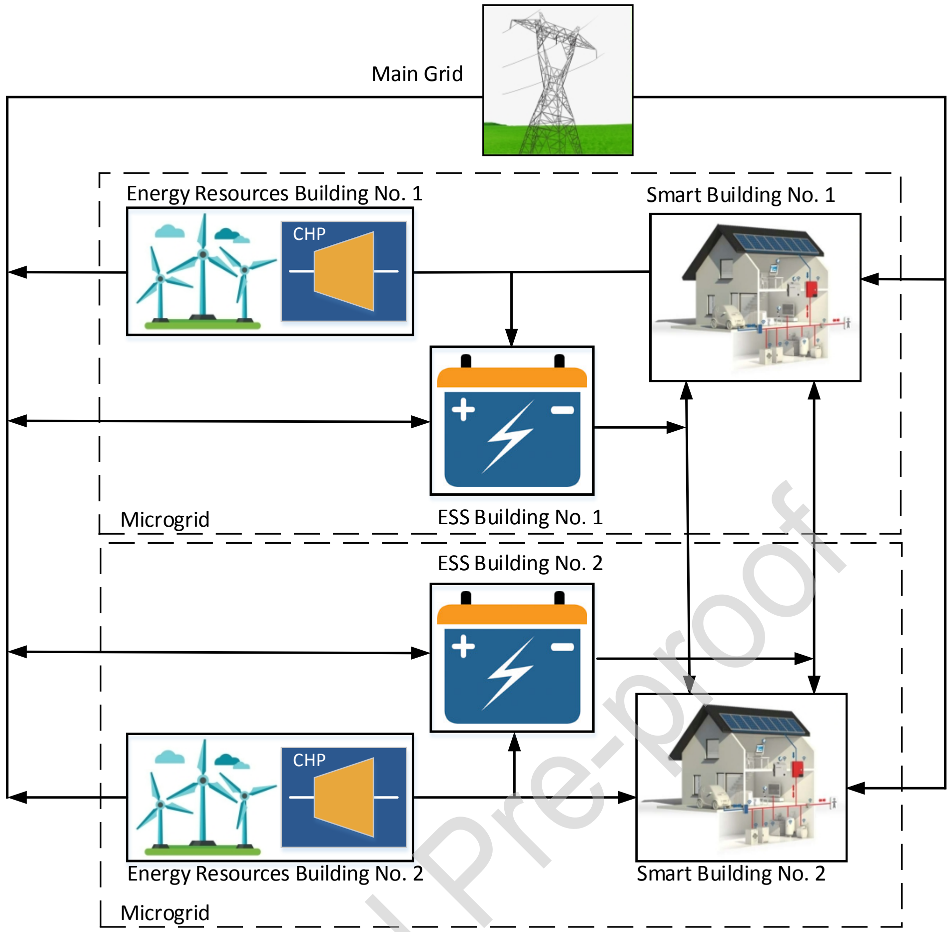
Main Grid
Energy Resources Building No. 1
CHP
Smart Building No. 1
Microgrid
ESS Building No. 1
ESS Building No. 2
CHP
Energy Resources Building No. 2
Smart Building No. 2
Microgrid

Intelligent Energy Management in Off-grid Smart Buildings with Energy Interaction

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Abstract: The energy interaction between smart homes can be a solution for developing renewable energy systems in residential sections and optimal energy consumption in homes. The main objectives of such energy interactions are to increase consumer participation in energy management, boost economic efficiency, increase the user's satisfaction by choosing between electricity sellers and buyers, and reduce the electricity purchased from the grid especially at peak hours. Thus, the innovations of this study includes defining an energy exchange method between smart buildings in an off-grid mode considering renewable energy systems, considering both thermal and electrical equilibrium and studying the lightning loads. it is assumed, here, that smart homes are off-grid, and the critical loads are supplied by the energy transfer between the homes using mixed integer linear programming. A compromise between the cost and time interval for using home appliances is considered to provide consumer's comfort. An objective function is introduced considering programmable and non-programmable loads, thermal and electrical storages and lighting loads aiming to optimize the cost of energy between different smart buildings. Based on the method, which is tested in two different cases not only does the total cost of the smart buildings decrease but also the cost is reduced significantly when lightning loads are managed.

Keywords: Energy management, Smart homes, smart microgrid, Energy storage system, Wind turbine.

Nomenclature

Indices and Sets

SH	Smart home
MG	Microgrid
PV	Photovolatic
SG	Smart Grid
FC	Fuel Cell
EMA	Energy Management Algorithm
RTP	Real Time Pricing
PSO	Particle Swarm Optimization
EMS	Energy Management System
DG	Distributed Generation
ESS	Energy Storage System

1. Introduction

1.1. Literature review

The applications of hybrid energy systems have been studied with the focus on smart homes (SHs) and their optimal management in various studies. In (Yin, et al., 2017), a hybrid DC Microgrid (MG) (based on power supply from photovoltaic (PV) cells) was investigated. This research shows that if the smart grid (SG) is in the off-grid state, the diesel generator with the electrochemical storage can be a better choice as a backup source. On the other hand, diesel generator cannot supply a stable power at the start-up. In (Arabul, et al., 2017), the smart home loads are supplied by fuel cells (FCs), wind and solar energy resources. The method used in this research which is balancing and optimization of energy production and consumption using the Energy Management Algorithm (EMA), has been investigated. This method enhances the efficiency of the whole system improves the penetration of renewable energy sources, and increases the reliability of the system compared to conventional load shifting methods. In (Pilloni, et al., 2018), the energy management method based on renewable energies in MG is presented., The energy sharing between SHs considering renewable energy participation is analysed in (Celik, et al., 2018). (Wu, et al., 2018), adopt a method for energy management in SHs which is discussed considering renewable energy systems. In this method, electric vehicles are implemented as energy storage systems in order to compensate for the uncertainties in renewable energy supplies. In (Melhem, et al., 2017), smart home management with PV, wind turbine and batteries are examined considering the role of electric vehicles.

One of the most important issues in planning and managing SHs is the optimal planning and management of home appliances. In order to manage residential appliances, it is necessary to identify and categorize them in the first step. In (Aminian, et al., 2016), these categories include Uncontrolled loads and controllable loads which can be either interruptible or non-interruptible. For instance, (Wang, et al., 2017), have planned a controllable thermostatic system using a queue theory model in which heating ventilation and air conditioning systems are switched on or off based on the minimum and maximum user temperature settings. In (Teng, et al., 2019), the application of home appliances and their management in smart buildings is studied. The management of smart home appliances is done by an improved cooperative algorithm in (Zhu, et al., 2019). A method is introduced in (Kim, 2017) which recognizes appliances in SHs, proving to be necessary in home energy management systems. In (Zhai, et al., 2019), the flexibility of home appliances and its impact on home energy management is investigated..

Various models have been developed in order to model the interactions between SGs and SHs. In (Wang, et al., 2018), the effects and benefits of automatic load response have been considered in the real time pricing (RTP) framework for residential consumers, taking into account elasticity (load sensitivity to price changes) for household electrical appliances. In (Cleik, et al., 2018), a method is examined to determine the economic distribution of controllable loads of SHs for demand response purposes. The authors have discussed the general formulation of the problem to minimize the total cost. Researchers in (Alquthami, et al., 2018), have investigated SH energy management considering customers' comfort. In (Arun, et al., 2018), an intelligent house energy management algorithm is provided for household electric consumption management. The proposed algorithm has the advantages of controlling the selected home appliances and keeping the entire household's energy consumption below a certain level. In (Wang, et al., 2012), an intelligent control system is designed with novel optimization that can control goals through the interaction between multiple factors and optimization. In (Aminian, et al., 2016), SHs are residential buildings equipped with devices that communicate with each other through communication channels in order to achieve a common set of goals that are in the interest of the end users. The result of this research shows that if SHs can exchange energy with other homes, they can save their costs while trading energy with the network. The concept of SHs interaction in SG is investigated in (Dong, et al., 2018), and SHs participation in the SGs is optimized by a multi-objective function in (Khalid, et al., 2018).

Minimizing energy consumption has recently become a major concern. A number of studies have focused on the importance of heating and cooling systems especially in SGs. In (Peltokorpi, et al., 2019), a new framework has been developed in order to manage the demands in the SHs of the heating and cooling systems. important information such as weather forecasting and energy prices are gathered by the building's EMS, which are then applied to set the energy consumption and room temperature. In (Sun, et al., 2016), the effect of applying demand response method on the combined systems including heating, venting and air-conditioning has been studied. Consequently, a model for the combination of manufacturing and heating/cooling system has been proposed in this study. In (cao, et al., 2019), a new index as thermal welfare has been defined, and thermal storages have been applied in the commercial building in order to provide it. The efficiency of this method has been analysed in the stochastic optimization problem. In (Zhou, et al., 2018), the amount of heating energy saving in a residential building in China has been estimated about 30.9%-66.1%, and two main factors including high indoor temperature and window opening has been introduced for high energy demand. In (Irshad, et al., 2019), the efficient application of photovoltaic system and thermoelectric technology has been reviewed. Based on the studies carried out , the amount of energy saving is about 22% and it is stated that about half of building's thermal load has been reduced by applying PV panel on the wall.

Applying efficient EMS in the buildings decreases the amount of energy consumption, which can be used in different residential loads. It can also have a significant impact on the energy cost minimization. In (Abikarram, et al., 2019), the effect of real time and demand charge pricing in EMS on reducing the energy cost has been analysed. It is claimed that considering demand charges decreases the peak loads. Another study (Zhu, et al., 2018) investigates, the importance of two factors such as price elasticity and income elasticity in the residential sector. According to the results in this research, the electricity demand is price-inelastic and income-inelastic in the short-term; however, it can be price-elastic and income-elastic in the long-term. In (Lu, et al., 2018), a review on the methods of optimal load scheduling has been done, and the methods for solving this problem has been classified in conventional mathematical optimization, heuristic optimization and data-driven methods. The importance of scheduling electric vehicles and renewable energy systems in reducing energy consumption, and, as a result, cost minimization has been studied in (Aliasghari, et al., 2018). In (Wang, et al., 2018), the EMS has been used in the SG, including PV, combined heating cooling system, ESS, and the SG operation cost has decreased considering real time pricing. It is shown that applying suitable EMS is affected by the environmental issues (Annala, et al., 2018). In (Wang, et al., 2018), the amount of reduction in electricity consumption and the total cost has been 7% and 34%, respectively. In this study, it is claimed that the controllable loads have the most effects on price-based demand response.

In (Hassan, et al., 2019), the effect of dynamic price-based demand response on profit maximization has been studied in the SG, including renewable energy, traditional systems, flexible and inflexible loads. Another study has considered the EMS for matching the supply and demand of smart buildings by applying intuitionistic fuzzy sets (Yin, et al., 2018). An EMS optimization problem is solved by particle swarm optimization method and sequential quadratic programming to reach the minimum cost in presence of wind and solar energy in SG (Huang, et al., 2019). In addition to common controllable and uncontrollable loads, other loads can have significant effect on energy consumption. The effect of EMS on lightning loads has been studied in (Loureco, et al., 2019). The effect of setting lightning loads on human's comfort and user's behaviour has been examined, and the efficiency of it on annual energy saving until 29 kWh/m2 has been claimed.

1.2. Contribution

Considering the importance of applying EMS on energy consumption reduction and cost minimization, it is unavoidable to develop comprehensive EMS. The proposed EMS should consider all controllable and uncontrollable loads including heating and cooling systems. Based on the previous studies, considering lightning loads in demand response can significantly decrease the energy consumption, but it is not studied in addition to other loads. In this research, a comprehensive EMS is proposed in order to minimize the cost considering renewable energy systems, electrical and thermal ESS, programmable and non-programmable loads and lightning loads all in the smart building.

In an effort to improve energy efficiency in residential buildings, the interaction between SHs can be considered as a solution. From this perspective, SHs can trade energy with each other; therefore, SHs are assumed to be equipped with an energy management system (EMS), distributed generation resources (DG), and energy storage systems (ESSs).

Each SH has its own MG, which is able to supply part of the electrical loads and provide its own thermal loads. EMS, as a key interface between MG and SH, receives RTP tariffs from the power company by the smart meter installed inside the homes. Planning of flexible loads and utilization of DGs are done in a way to minimize the total cost including the cost of energy consumption and the utilization of energy resources in the SHs in the coming 24 hours. Additionally, it is assumed that EMS of each SH has the ability to communicate with other adjacent homes in order to exchange information on the price and the amount of energy exchanged. In order to account the possibility of energy exchange between SHs, it is assumed that homes can use each other's ESSs.

The main contribution of this study is considering the cleaner production and renewable energy development through energy transfer between SHs. Energy interaction between buildings has always been beneficial in solving energy problems, yet only recently it has assumed more importance based on the following reasons:

1) Development of renewable energy resources (especially PVs and WTs) in smart buildings. These resources are producing more power than the hourly demand of building, which can be transferred to other buildings.
2) Electrical demand growth due to electrification of heating/cooling loads. If the heating/cooling systems in smart buildings are using thermal energy, it can be transferred between smart buildings. As a result, more energy could be saved.
3) Electric vehicles are significantly growing, which increase the demand in electric network. However, electric vehicles can be applied as an electrical energy storage system.
4) The communication infrastructure especially internet of things between smart appliances in SHs is recently developed, which simplifies the energy trading between smart buildings.
5) Development of electrical and thermal energy storage systems in SHs especially smart buildings, which can be helpful specifically at peak hours.

The main objectives of this study are as follows:

1) Managing the energy consumption in SHs considering their thermal and electrical loads in two different programmable and non-programmable categories.
2) Trading energy between smart buildings in the off-grid mode in case of shortages through ESSs.
3) Developing application of renewable energies in SHs through ESSs and energy exchange in order to mitigate their uncertainties.
4) Determining the production of each thermal and electrical unit in order to minimize the total cost.

2. Methodology

In this section, the components of the studied system are examined, and their consumption or production is calculated. After introducing all components in the SHs, the presented method would be discussed in order to clarify the EMA. The purpose of this study is to provide the maximum load of SHs in conditions where they can operate off-grid. In order to achieve this goal, the constraints are first defined to solve the problem, then the objective function is introduced.

A simple schematic diagram of the system is presented in Fig. 1. As it can be seen in this Figure, two different MGs are considered in relation to each other. The set of smart building, energy resources and ESSs are assumed as a MG. These MGs can send information to each other and have energy transfer at the same time. These smart MGs can work in both on-grid and off-grid mode.

If our MGs are working in the on-grid mode, they can buy electricity from and also sell to the main grid. It should be considered that this relation can affect the main grid in different aspects such as rising at demand, peak load and energy loss. However, a reliable off-grid application can avoid these problems. It can be seen in Fig.1 that each MG can work independently and interact with other MGs.

If MGs are working in an off-grid mode, they can send and receive, both information and electricity. Two connections between smart building No.1 and smart building No.2 show the information and energy transfer between them. In each Mg, energy is transferred between different components including smart building, renewable energy system and ESS.

As it is mentioned, the main aim of this study is to supply all loads in each MG in an off-grid mode. Each MG supplies its demand from its renewable energy system and ESS, and can also buy electricity from another MG in case of shortage. The energy management is done in a way that the total cost is minimized considering the system constraints.

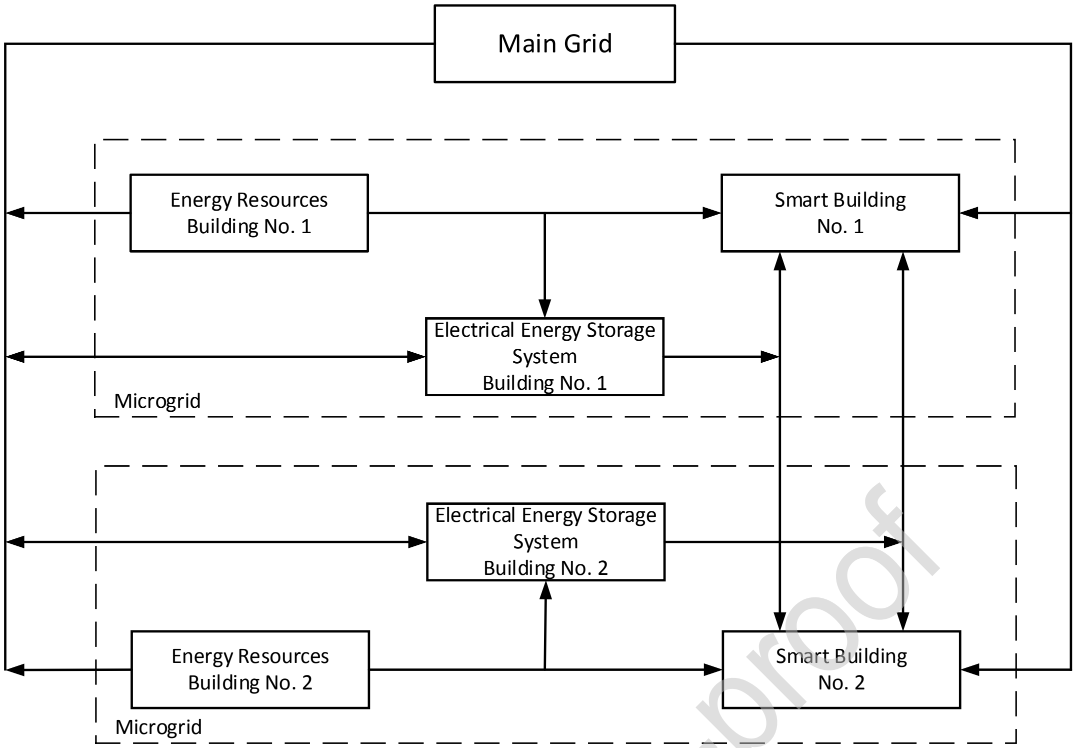

Fig. 1. A schematic of system

Table 1. Nomenclature

$Se_{b,t}$	Amount of energy (kW_eh) which can be stored in bth building at period t
$z_{b,t}$	Power that can be charged in electrical ESS in bth building at period t (kW_e)
$Y_{b,t}$	Amount of power received from electrical ESS of bth building at period t
$ys_{b,t}$	Amount of power (kW_e) discharged from ESS
$yc_{b,i,t}$	Power that ith building receives from ESS of bth building
$T^z_{b,t}/T^y_{b,t}$	Binary parameters which indicate the charge/discharge state
$Se_{b,0}$	Amount of energy charged in electrical ESS (kW_eh)
Se_b^{min}/Se_b^{max}	Minimum/maximum of energy in electrical ESS respectively
$St_{b,t}$	Heat stored in thermal ESS at bth SH in the (t) period
$g_{b,t}/f_{b't}$.	Charging/discharging rate of bth SH's thermal ESS at (t) period
DT_b^{max}/CT_b^{max}	Maximum amount of heat discharge/charge of bth SH's thermal ESS respectively
DT_b^{min} and CT_b^{min}	Minimum limit of charge/discharge of bth SH's thermal ESS respectively
LDR_{light}	Lighting loads' DR

P_{bulb}	lamp power consumption
n_{Home}	Number of building units
PDR	Variable of power reduction in lighting loads.
Vcut-in	Cut-in wind speed of wind turbine
Vcut-out	Cut-out wind speed of wind turbine
Vnom	Nominal wind speed of wind turbine
ρ	Air density
A	Area of wind turbine
ηw	Wind turbine efficiency
wcb,t	Produced power of CHP at t (kW_e)
n_G	Price of natural gas ($/kWh)
α	Electrical efficiency of CHP
$w_{ib,}$	Produced power of wind turbine at t (kw_e)
$x_{b,t}$	Produced power by boiler (kw_{th})
B	Thermal efficiency of boiler
$f_{b,t}$	Discharge rate of thermal ESS (kw_{th})
m_{THS}	Cost of thermal ESS
C_b	Interaction between smart buildings
LDR_{light}	Power of lighting loads

2.1. Electrical energy storage system

In SHs, the periods of charge and discharge of the electrical ESSs are determined in order to manage the consumption of the appliances.

The electric ESS is charged at intervals when the price of electricity is cheap, and discharged when electricity is expensive. It also sells energy to other appliances and, if possible, to networks or other SHs.

The electricity stored in the electrical ESS at t is equal to the amount of electricity in the (t-1) period plus the electricity supplied, minus the electricity discharged in the (t) period.

$$Se_{b,t} = Se_{b,t-1} + z_{b,t}\eta_{ELE}\delta - {}^{Y_{b,t}\delta}/_{\eta_{ELE}} \qquad \forall\, b, 1 \le t \le \tau \tag{1}$$

$$Y_{b,t} = \sum_{\substack{i=1 \\ i \ne b}}^{n} yc_{b,i,t} + ys_{b,t} \qquad \forall\, b, 1 \le t \le \tau \tag{2}$$

where, $Se_{b,t}$ shows the amount of energy (kWeh) which can be stored in bth building at period t, and $z_{b,t}$ is the power that can be charged in electrical ESS in bth building at period t (kWe). $Y_{b,t}$ specifies the amount of power received from electrical ESS of bth building at period t which includes $ys_{b,t}$ and $yc_{b,i,t}$. $ys_{b,t}$ is the amount of power (kWe) discharged from ESS, and $yc_{b,i,t}$ is the power that ith building receives from ESS of bth building.

2.2. Thermal energy storage system

The amount of energy exchanged through ESS decreases when efficiency is considered in charge and discharge process. For example, when $z_{b,t}\delta$ is stored in ESS, the actual amount of charge is equal to $z_{b,t}\eta_{ELE}\delta$, and the remainder is wasted. When the ESS is discharged in order to supply the load $Y_{b,t}\delta$, it needs energy equal to $Y_{b,t}\delta/\eta_{ELE}$. Obviously, charging and discharging is not simultaneously feasible in ESSs. This is expressed mathematically in Eq. 3.

$$T^{z}_{b,t} + T^{y}_{b,t} \leq 1 \quad \forall\, b, 1 \leq t \leq \tau \tag{3}$$

where, $T^{z}_{b,t}$ and $T^{y}_{b,t}$ are the binary parameters which indicate the charge and discharge state. When the ESS of bth SH is charged at (t) period, $T^{z}_{b,t}$ is equal to 0, and when it is discharge, $T^{y}_{b,t}$ is equal to 1.

At the beginning of every day, the ESS has an initial charge, which should return to its original charge by the end of the day. This constraint is also expressed by Eq. 4.

$$Se_{b,0} = Se_{b,t} = ISe_{b} \qquad \forall\, b \tag{4}$$

where, $Se_{b,0}$ is the amount of energy charged in electrical ESS (kWeh).

To improve storage efficiency, and increase its life expectancy, two constraints are considered as follows.

The life of the ESS may be reduced by working at less than one specific charge level. In order to prevent damage to the ESS, the stored energy must always be within the following limits:

$$Se^{min}_{b} \geq Se_{b,t} \leq Se^{max}_{b} \qquad \forall\, b, 1 \leq t \leq \tau \tag{5}$$

where, Se^{min}_{b} and Se^{max}_{b} are the minimum and maximum of energy in electrical ESS respectively. In order to prevent damage to the ESS and reduction in its capacity, the charging and discharge rates must not exceed the minimum and maximum values.

$$DE^{min}_{b} T^{y}_{b,t} \leq Y_{b,t} \leq DE^{max}_{b} T^{y}_{b,t} \qquad \forall\, b, 1 \leq t \leq \tau \tag{6}$$

$$CE^{min}_{b} T^{z}_{b,t} \leq z_{b,t} \leq CE^{max}_{b} T^{z}_{b,t} \qquad \forall\, b, 1 \leq t \leq \tau \tag{7}$$

The heat stored in the thermal storage in the interval t is equal to:

$$St_{b,t} = St_{b,t-1} + g_{b,t}\eta_{THS}\delta - {f_{b,t}\delta}/{\eta_{THS}} \qquad \forall\, b, 1 \le t \le \tau \tag{8}$$

Where, $St_{b,t}$ shows the heat stored in thermal ESS at bth SH in the (t) period. $g_{b,t}$ and $f_{b,t}$ are the charging and discharging rate of bth SH's thermal ESS at (t) period. The stored heat must return to the primary value at end of the day.

$$St_{b,0} = St_{b,t} = ISt_b \qquad \forall\, b \tag{9}$$

Where, ISt_b shows the primary state of the bth SH's thermal ESS.

It is obvious that the thermal ESS cannot be charged and discharged simultaneously, which is expressed for electrical ESS, as well.

The thermal storage output should not exceed its designed capacity.

$$St_{b,t} \geq C_b^{THS} \qquad \forall\, b, 1 \le t \le \tau \tag{10}$$

Where, C_b^{THS} is the maximum capacity of bth SH's thermal ESS.

The rate of heat charging and discharging cannot exceed the thermal ESS charge and discharge limits.

$$DT_b^{min}T_{b,t}^{f} \le f_{b,t} \le DT_b^{max}T_{b,t}^{f} \qquad \forall\, b, 1 \le t \le \tau \tag{11}$$

$$CT_b^{min}T_{b,t}^{g} \le g_{b,t} \le CT_b^{max}T_{b,t}^{g} \qquad \forall\, b, 1 \le t \le \tau \tag{12}$$

Where, DT_b^{max} and CT_b^{max} show the maximum amount of heat discharge and charge of bth SH's thermal ESS. DT_b^{min} and CT_b^{min} are the minimum limit of charge and discharge of bth SH's thermal ESS , respectively.

The output of each component should not exceed its designed capacity.

Generator CHP: $$wc_{b,t} \geq C_b^{CHP} \qquad \forall\, b, 1 \le t \le \tau \tag{13}$$

Thermal ESS (boiler): $$x_{b,t} \geq C_b^{Boiler} \qquad \forall\, b, 1 \le t \le \tau \tag{14}$$

2.3. Residential appliance modeling

Home appliances are divided into non-programmable and programmable categories, which aims to save energy and provide demand response in the system.

2.3.1.non-programmable loads

Non-programmable loads are the loads which there is no control over them. In other words, each time, each day, they are subject to user command, and are used randomly by consumers at specific intervals, hence when modelling them, it is assumed that, firstly, all of these programs are used in our study period. Secondly, each of them, if turned on, continuously operate until the end of their operation, then they turn off.

2.3.2. programmable loads

Programmable load are the loads that can be programmed when switched on and off. In the following, the mathematical formulation of these types of loads is based on the earliest start time, the latest time and the required time to function correctly.

$$\sum_{t \geq S_{h,k}}^{E_{h,k} - D_{h,k}} Ts_{b,h,k,t} = 1 \qquad \forall\, b,h,k \tag{15}$$

$$\sum_{t \geq S_{h,k} + D_{h,k}}^{E_{h,k}} Te_{b,h,k,t} = 1 \qquad \forall\, b,h,k \tag{16}$$

Eq. 15 emphasizes that the start time of each appliance cannot be earlier than the earliest time. If the appliance k in the bth building is switched on at hth home in the interval (t), the binary variable $Ts_{b,h,k,t}$ is 1, or otherwise zero. Eq. 16 indicates that the end time of each device cannot be later than the latest time. The binary variable $Te_{b,h,k,t}$ is equal to 1 if the programmable kth appliance in the bth building is turned off at hth home in the t-range, otherwise it is zero.

If an appliance starts at time t, it must be terminated at time t, plus its operating time $D_{h,k}$.

$$Ts_{b,h,k,t} = Te_{b,h,k,t + D_{h,k}} \qquad \forall\, b,h,k,\, S_{h,k} \leq t \leq \tau - D_{h,k} + 1 \tag{17}$$

All appliances should operate continuously from the start to the end.

$$w_{b,h,k,t} = w_{b,h,k,t-1} + Ts_{b,h,k,t} - Te_{b,h,k,t} \qquad \forall\, b,h,k,\, 1 \leq t \leq \tau \tag{18}$$

where, $w_{b,h,k,t}$ is equal to one when kth appliance in the bth building is switched on at hth home. Total consumption of all programmable and non-programmable loads are calculated as following.

$$PL_{b,t} = \sum_h \sum_k w_{b,h,k,t} C_k + L_{b,t} \qquad \forall\, b,\, 1 \leq t \leq \tau \tag{19}$$

2.3.3. Lighting loads management

The lighting loads management can be expressed by following equations.

$$LDR_{\boldsymbol{light}} = gain * P_{bulb} \tag{20}$$

$$P_{bulb} = bulb * n_{Home} * PDR \tag{21}$$

where, LDR_{light} is the lighting loads' DR, P_{bulb} is the lamp power consumption, gain shows the amount of encouragement considered to participate in DR, n_{Home} specifies the number of building units and PDR is the variable of power reduction in lighting loads.

2.3.4. Wind turbine power production

The output power of wind turbines is calculated by the wind power equation:

$$wi_t = \begin{cases} 0.5\rho A \eta_w min(v_t, V^{nom})^3 & \forall t: V^{cut-in} \leq v_t \leq V^{cut-out} \\ 0 & \forall t: v_t \leq V^{cut-in} \; and \; v_t \geq V^{cut-out} \end{cases} \quad (22)$$

where, $V^{cut\text{-}in}$, $V^{cut\text{-}out}$ and V^{nom} are the cut-in, cut-out and rated wind speed. ρ is the air density, A shows the area of wind turbine, and η_w shows the wind turbine efficiency.

2.3.5. Interaction between smart buildings

The interaction between smart buildings is modelled as Eq. 23:

$$C_b = Y_{b,t} m_{ELE} + \sum_{\substack{i=1 \\ i \neq b}}^{n} (yc_{i,b,t} - yc_{b,i,t}) N_B \quad (23)$$

2.3.6. Objective function

The objective function is as follow.

$$X_b = \sum_t [(wc_{b,t} n_G/\alpha + wi_{b,t} m_{WIND} + x_{b,t} n_G/\beta + f_{b,t} m_{THS} + C_b - LDR_{light})\delta] \;\; \forall b \quad (24)$$

where, $w_{cb,t}$ shows the produced power of CHP at t (kWe), n_G is the price of natural gas ($/kWh), α is the electrical efficiency of CHP, $w_{ib,t}$ shows the produced power of wind turbine at t (kW_e), m_{WIND} specifies the cost of produced power by wind turbine, $x_{b,t}$ determines the produced power by boiler (kW_{th}), β is the thermal efficiency of boiler, $f_{b,t}$ shows discharge rate of thermal ESS (kW_{th}), m_{THS} is the cost of thermal ESS, C_b determines the interaction between smart buildings, and LDR_{light} shows the power of lighting loads.

2.4. Energy management algorithm

In this study, home appliances are classified in two different groups including programmable and non-programmable loads. The working time and amount of demanded power of programmable loads can be determined by the energy management algorithm. However, the start time and power of non-programmable loads are constant and are specified by the consumers. The total consumption of programmable and non-programmable loads are defined by Equation (19). When all loads including the programmable and non-programmable loads are identified in the smart building, the energy management algorithm is applied in the planning time.

In each hour of planning time, energy management algorithm calculates the total demand based on the present thermal and electrical loads at this time. After the calculation, the amount of power for supplying electrical loads by wind turbine and CHP in addition to supplying thermal loads by boiler and CHP would be determined in condition that the total cost is minimized.

If the produced electrical power is more than the electrical loads, the electrical ESS is charged. When the produced electrical power by wind turbine and CHP is less than the electrical loads, the electrical ESS is discharged. As the smart buildings are applied in an off-grid mode, any shortages that cannot be supplied by ESS should be bought from another building. ,. The methodology is demonstrated and clarified in the flowchart:

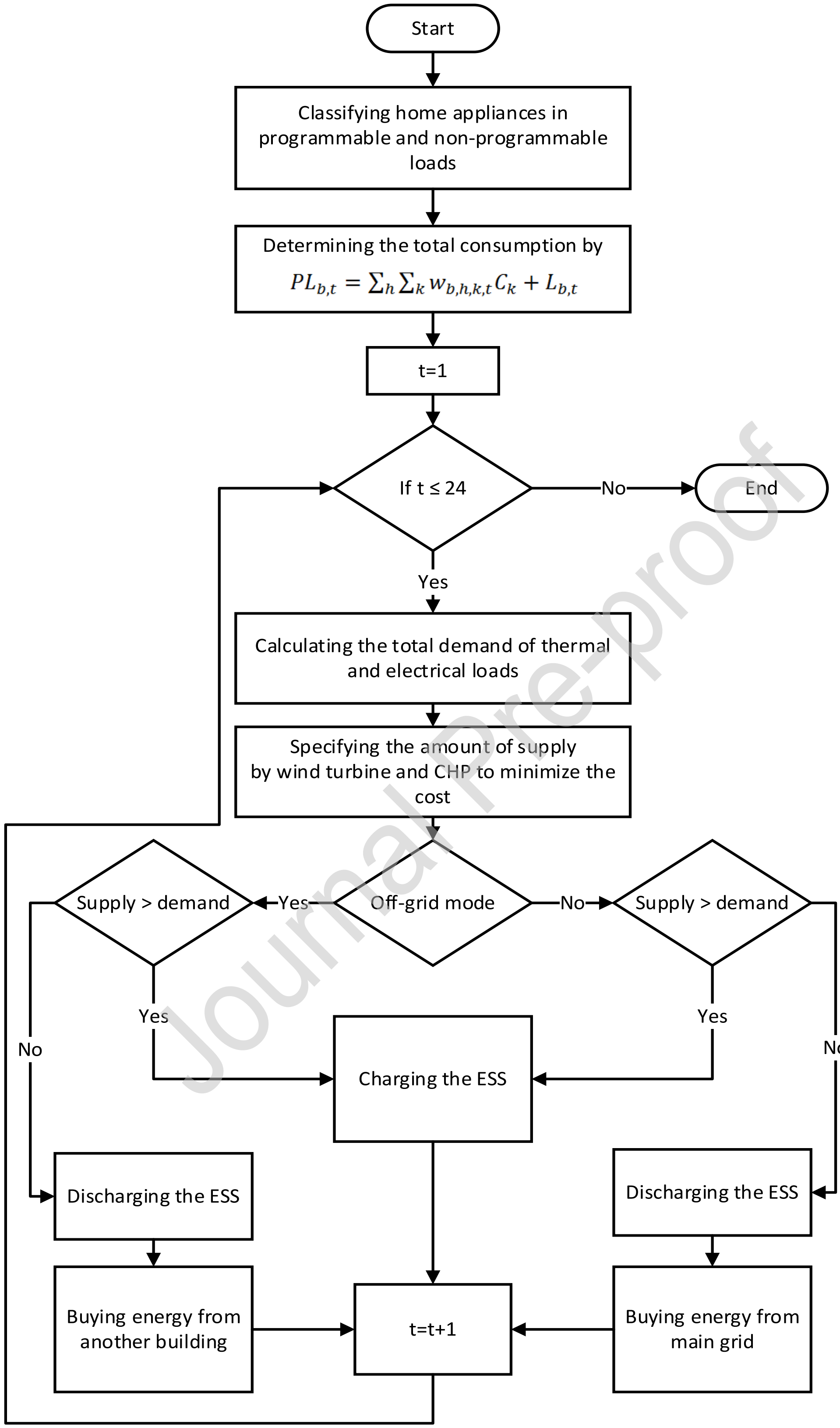

Fig. 2. A flowchart of presented method

The limitations of this method are as follows:

1) In this study, electricity pricing is considered to be constant on the consumer side. It is suggested that by expanding the scope of the research, electricity prices should be considered as competitive and variable in the consumer side.
2) In the proposed model, it is possible to exchange energy only by the ESSs of each building. This interaction can be seen more broadly so that buildings can directly exchange their local production with other buildings without the need for ESSs.

3. Case study

In order to evaluate the proposed model, two, 50 units, intelligent buildings are considered . Each of the smart buildings has the following energy resources:

1) A CHP generator with a capacity of 60 kW_e in each of buildings 1 and 2, with electrical efficiency of 35%, the conversion ratio of heat to electricity is 3.1 and the natural gas price is 2.7 p/kWh.
2) A wind farm is considered for each building 1 and 2, where each wind turbine's capacity is 10 kW_e, and its maintenance cost is 0.5 p/kWh_e.
3) An electrical ESS with a capacity of 60 kW_e in each of the buildings 1 and 2, and at least 20% of its total capacity remains in the ESS for the technical reasons. The charge and discharge efficiency of both ESSs are 95%, the maximum charging and discharge rates are equal to 60 kW_e, and the maintenance cost is 0.5 p/kWh.
4) A boiler with a capacity of 90 kW_{th} for each of the 1 and 2 buildings with an electrical efficiency of 80%.
5) A thermal ESS with a capacity of 20 $kW_{th}h$ in each of buildings 1 and 2, with a charging and discharge efficiency of 95% and a charging and discharge limit of 20 kW_{th}, and a maintenance cost of 0.1 p $kW_{th}h$.
6) The simulation time-step is equal to 30 minutes.

The optimization problems are solved by CPLEX 11.2.1 under the GAMS, and an integer linear programming solver. Before simulations, general assumptions are considered in all scenarios:

1) It is assumed that the network is off-grid.
2) The MG is able to provide all electrical power and heat for each building.
3) Electric vehicles return to the parking lot at the end of the day and have no charge.
4) The sources of energy production in buildings are studied assuming their initial capital is returned.

It is assumed that all wind turbines are installed outside the city and their power is transmitted. The characteristics of household loads are presented in the following Table 1. The electricity price and hourly wind speed are shown in Fig. 3 and Fig. 4 respectively. It is important to notify that the buildings are electrically off-grid, but they are connected to the gas grid in order to supply the CHP units.

Table 2. The characteristics of household loads

	Load	Type	Power (kW)	Power factor	Duration of application (hours)	[the earliest start time, the last stop time]
1	Refrigerator	Non-programmable	0.3	0.8	24	[0,24]
2	Microwave	Non-programmable	1.7	0.93	0.5	[8,10], [10,12], [14,16], [21,23]
3	TV	Non-programmable	0.3	0.8	4	[9,15], [18,24]
4	Incandescent lamp	Non-programmable	0.84	1	6	[18,24]
5	Fluorescent lamp	Non-programmable	0.1	0.9	6	[18,24]
6	vacuum cleaner	Non-programmable	1.2	0.95	0.5	[10,13]
7	Computer	Non-programmable	0.3	0.55	3	[10,15], [19,23]
8	Laptop	Non-programmable	0.1	0.55	2	[10,15], [18,21]
9	Washing machine	programmable	1	0.65	1.5	[9,12]
10	Dish washer	programmable	1	0.99	3	[9,17]
11	Cloth dryer	programmable	3	0.99	1	[12,18]
12	Electric vehicle	programmable	3.5	1	3	[18,8]

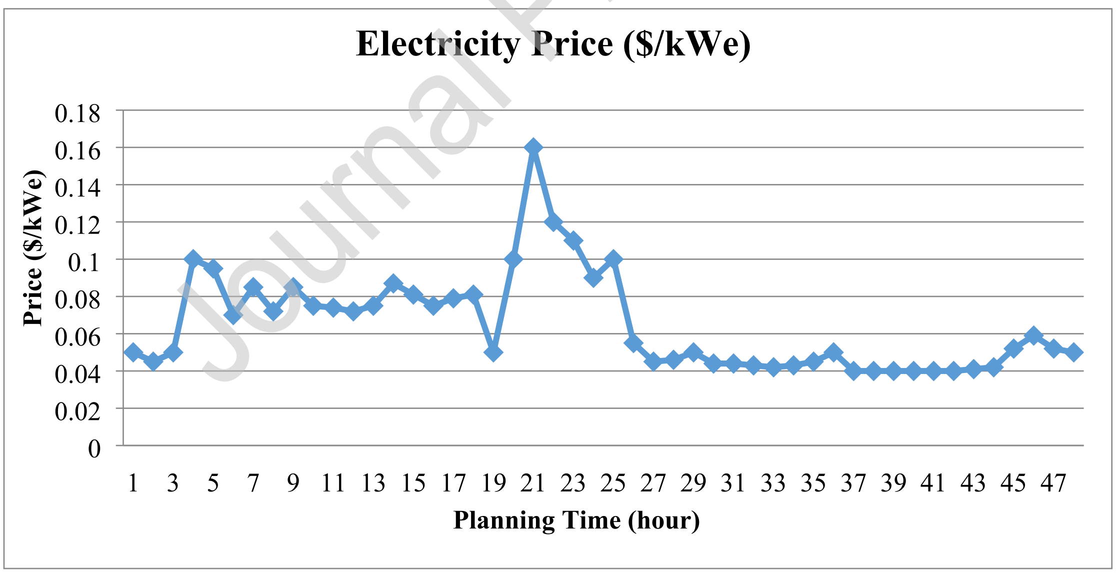

Fig. 3. Electricity Price ($/kWe)

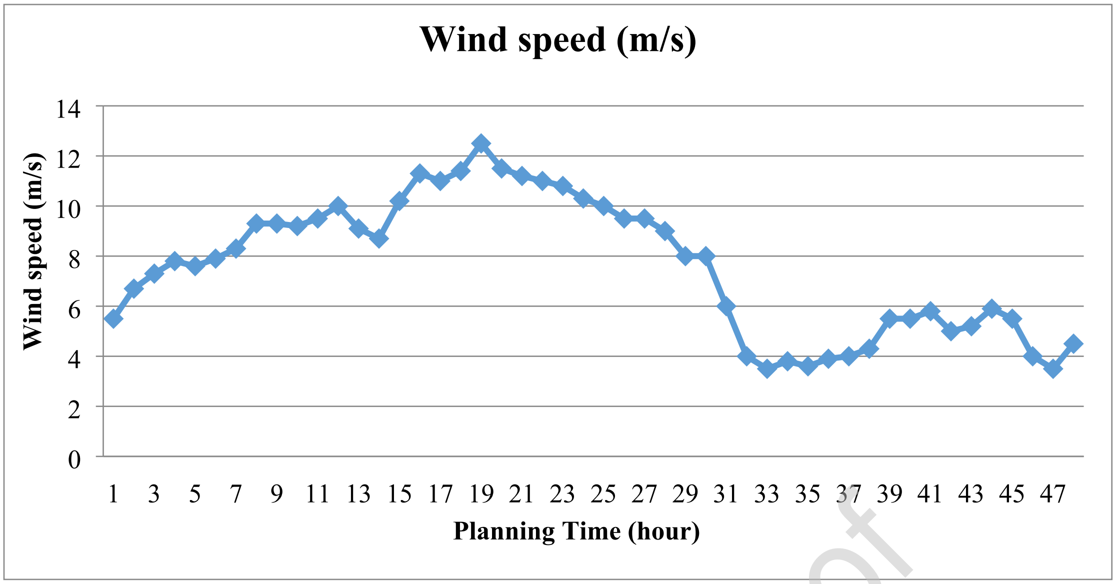

Fig. 4. Wind speed (m/s)

4. Numerical simulation and results

In order to assess the efficiency of the proposed method, the results of the presented method are compared with a similar paper (Aminian, et al., 2016). In (Aminian, et al., 2016), the energy interaction between SHs is defined considering two different 30-units and 90-units smart buildings without demand response. If the presented method is applied for the similar buildings, the total cost is calculated (Table 2).

Table 3. The comparison between total cost of presented method and reference (Aminian, et al., 2016)

	Total cost ((Aminian, et al., 2016))	Total cost (Presented method)	Error
30-units building	121.5 $	124.3 $	2.3%
90-units building	451.5 $	444.8 $	0.6%

The presented EMS is tested in the case study including two different smart buildings. The characteristics of thermal and electrical loads and SHs are presented in the previous section. Two scenarios are considered to assess the application of the proposed method.

4.1. Scenario 1: Interaction between off-grid smart buildings

In this scenario, the demand of the buildings is supplied only by the MG, and the programmable loads are presented in Table 1. In this scenario, the cost of building 1 and building 2 are 190.1 $ and 189.9 $. The results of this scenario are presented in Fig. 5 and Fig. 6, and the thermal equilibrium is presented in Fig. 7 and Fig. 8.

As it can be seen in Fig. 5 and Fig. 6, the electrical equilibrium is reached when all loads are supplied. The amount of electrical energy which is supplied from wind turbine, electrical ESS and another building is determined in Fig. 5, and Fig. 6.

It is depicted in Fig. 5 that the electrical ESS is charged in the 1st hour of the planning time while the demanded electrical energy is supplied by the wind turbine and CHP in the smart building 1. As it can be seen in Fig. 5, the high demand at the 5th hour concludes that the wind turbine, CHP, electrical ESS and energy purchased from smart building 2, altogether, supply the electrical energy .

The electrical equilibrium of smart building 2 is shown in Fig. 6. For instance, at the first hour of planning time of smart building 2, the electrical power is supplied by CHP and wind turbine. However, at the 5th hour of planning time, CHP, the wind turbine and electrical ESS participate in the energy supply, and energy surplus is sold to smart building 1.

It can be concluded that the amount of supplied energy from the wind turbine, CHP, electrical ESS and another building is determined by the energy management algorithm in conditions which the total cost is minimized, and all loads are supplied.

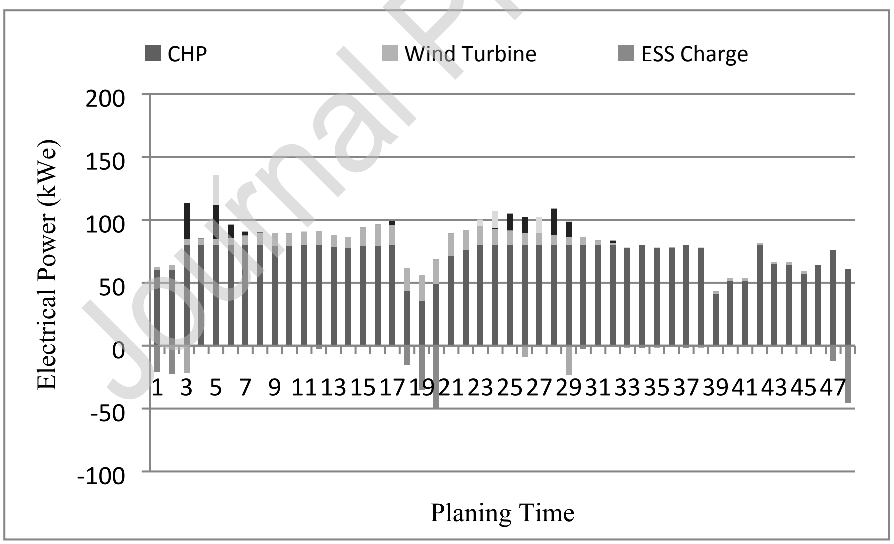

Fig. 5. Electrical equilibrium in smart building 1

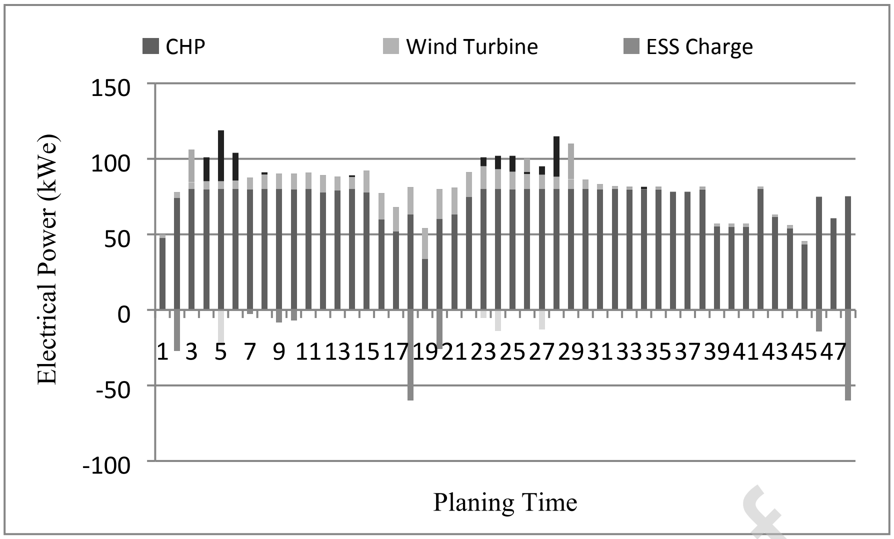

Fig. 6. Electrical equilibrium in smart building 2

The thermal equilibrium in smart buildings is shown in Fig. 7, and Fig. 8. Thermal loads in both buildings are supplied by CHP, ESSs and boiler. If the thermal demand is more than the production of thermal energy by the boiler and CHP, the surplus will be stored in the thermal ESS. The stored energy in thermal ESS is applied when the thermal loads are more than the produced thermal power. The amount of power which should be supplied by each source is determined through the energy management algorithm under condition which thermal equilibrium is reached, and all loads are supplied. For instance, it can be seen in Fig. 7 that the CHP and the boiler supply the thermal energy at the 1st hour of planning time in smart building 1. At the 13th hour of planning time, the produced thermal power of CHP and boiler is more than the thermal load, therefore, the thermal ESS is charged. However, the thermal load is more than the produced thermal power at the 19th hour, which leads to thermal ESS discharge.

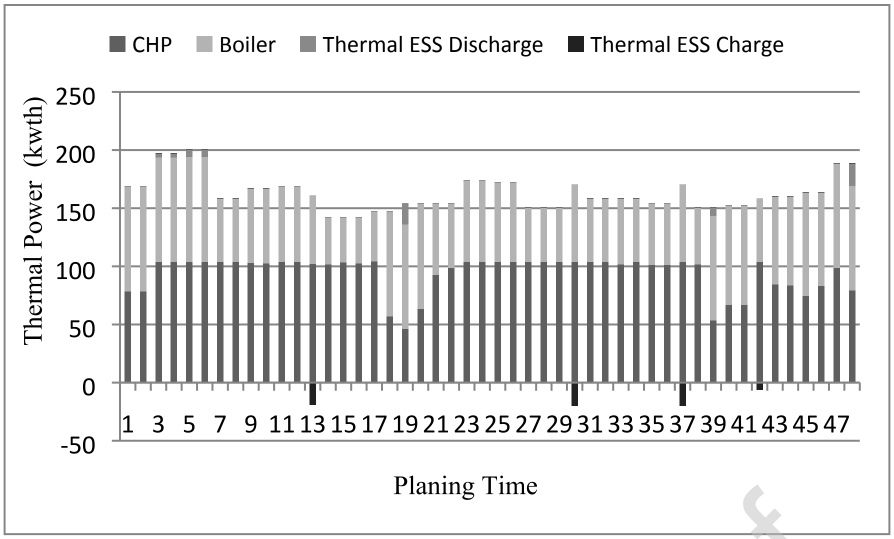

Fig. 7. Thermal equilibrium in smart building 1

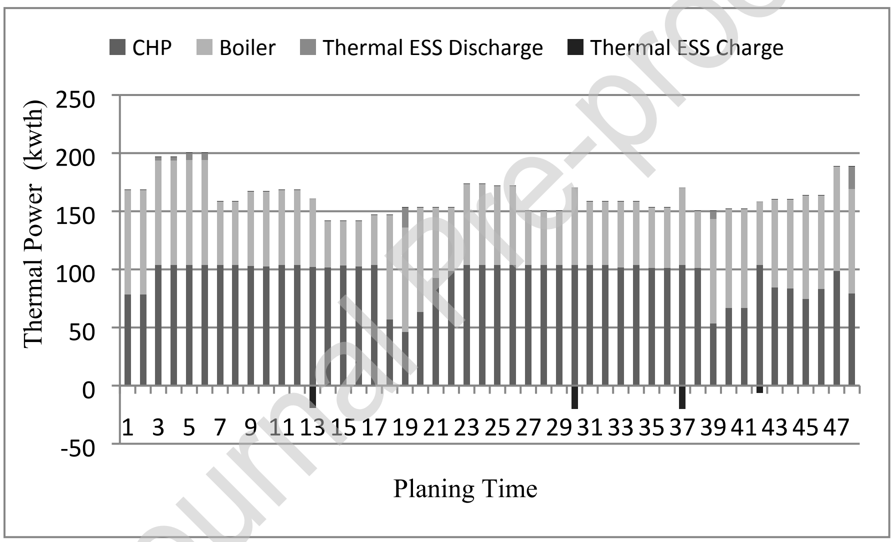

Fig. 8. Thermal equilibrium in smart building 2

By selecting the minimum capacity for the boiler, the thermal ESSs of the buildings participate in the heat equilibrium, and the thermal loads are supplied as well.

4.2. Scenario 2: Interaction between off-grid smart buildings considering lighting loads demand response

In this scenario, DR of the lighting loads is considered in order to save energy. In this case, the cost of building is equal to 179.16 $ and 178.81 $ considering the encouragement of DR programs. The results of electrical and thermal equilibrium are shown in Fig. 9 to Fig. 10. In comparison with scenario 1, the total cost of the buildings decreases since managing the lighting loads reduces the amount of demand, especially throughout the day. The energy management algorithm considers the day light and decreases the lighting loads when the sun light can be used.

The electrical equilibrium in the smart buildings is reached when all demand is supplied, and the surplus power is stored in the electrical ESS. In this scenario, CHP, wind turbine and electrical ESS participate in the load supply.

For example, at the first hour of planning time, the electrical demand is supplied by the wind turbine and CHP, and the electrical ESS is charged by the surplus power (Fig. 9). At the 3rd hour of planning time, the electrical power is supplied by wind turbine, CHP and electrical ESS while some energy is sold to another building considering the financial benefit and electrical equilibrium. A similar trend can be seen in Fig. 10 related to the electrical equilibrium of smart building 2.

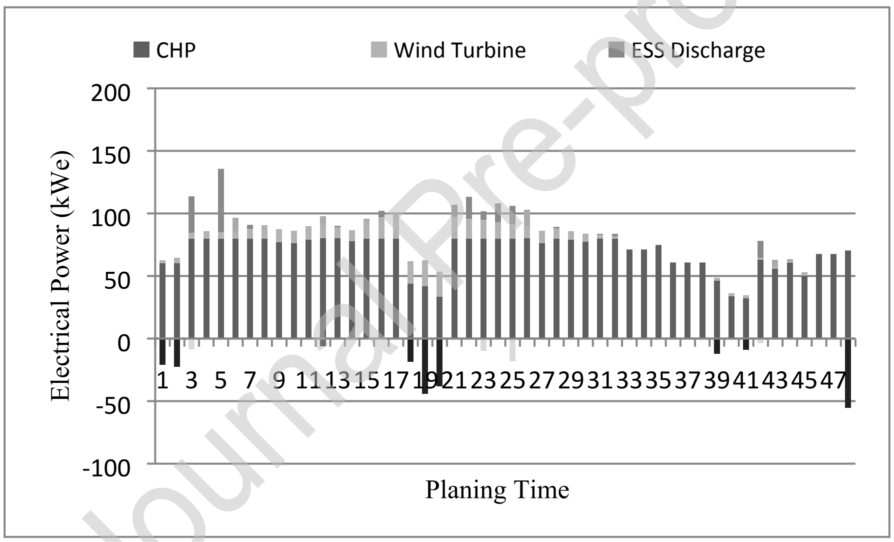

Fig. 9. Electrical equilibrium in smart building 1

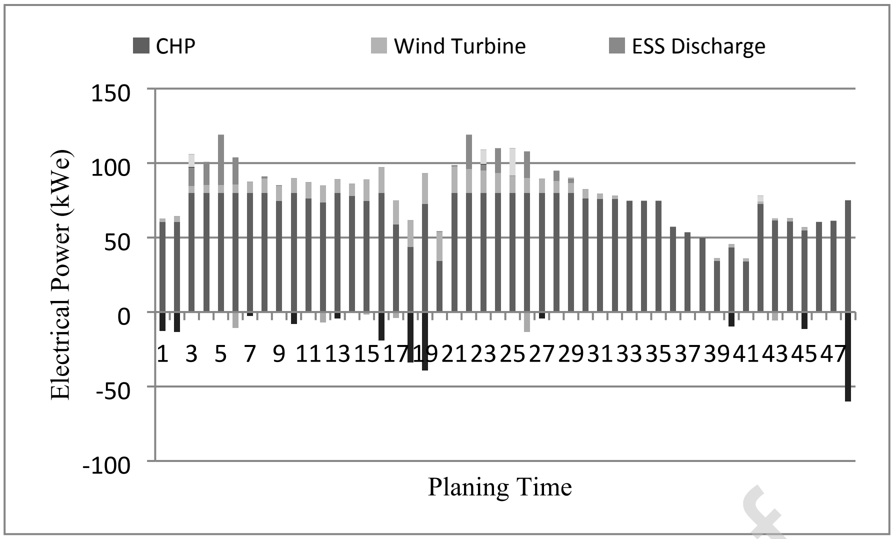

Fig. 10. Electrical equilibrium in smart building 2

The thermal equilibrium in the smart building is illustrated in Fig. 11 and Fig. 12. CHP, boiler, and thermal ESS participate in the supply of thermal loads. If the amount of produced thermal power is higher than the thermal loads, the thermal ESS will be charged. On the contrary, when thermal loads are more than the produced thermal power, thermal ESSs will be discharged.

At the first hour of planning time, the amount of produced thermal power of CHP and boiler is equal to the thermal loads. While in the period between the 3rd to the 6th hour of planning time, thermal ESS is discharged, due to the shortage in the produced thermal power by CHP and boiler (Fig. 11). At 10th and 11th hour of planning time, the amount of thermal power is more than the thermal loads, which leads to thermal ESS charging.

The similar trend in supplying thermal loads in the smart building 2 can be seen in Fig. 12. Thermal demand is equal to the produced power by the boiler and CHP, so thermal ESS does not participate in these hours. However, thermal ESS compensate the shortages in the following period between the 3rd hour to the 6th hour.

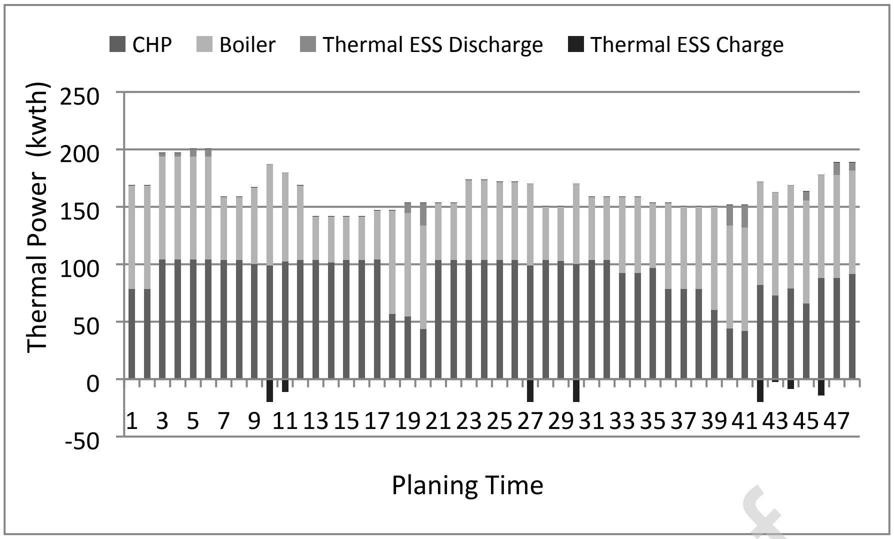

Fig. 11. Thermal equilibrium in smart building 1

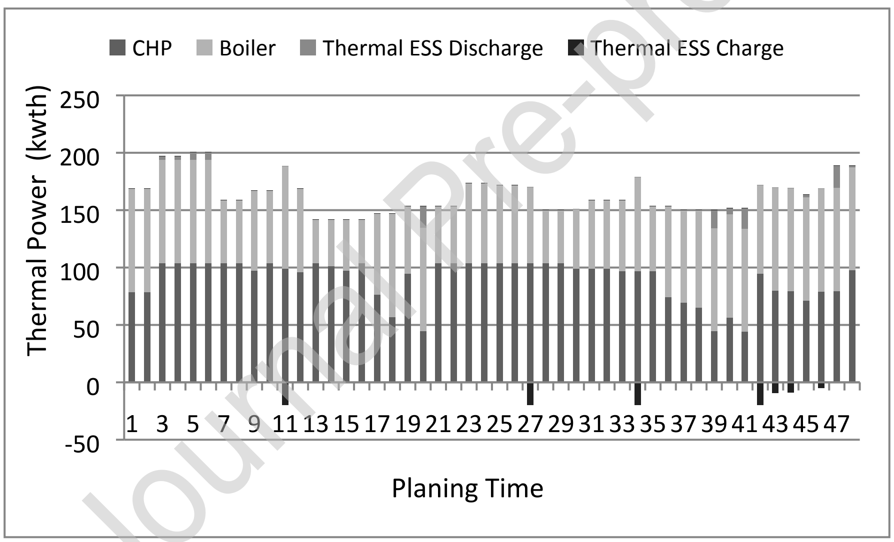

Fig. 12. Thermal equilibrium in smart building 2

4.3. Comparison between two scenarios

After analysing the results of the two scenarios, the importance of applying demand response method and lightning loads can be verified. In the first scenario, the energy interaction between smart buildings is done in an off-grid mode. In the second scenario, the energy is transferred considering lightning loads and their participation in demand response method. The significant decrease can be seen in the total cost, which proves the importance of considering lightning loads in residential energy consumption. The comparison between results is shown in Table 3.

Table 4. The comparison between two scenarios

	Scenario 1	Scenario 2	Reduction (%)
Total cost	190.1 $	179.16 $	5.8
	189.9 $	178.81 $	5.8

5. Conclusion

The goal of this study is to provide the energy transfer between buildings in off-grid conditions. .. Thus, to reach the goal, MILP solution is selected to be used in GAMS software. The smart home appliances are divided into two groups of programmable and non-programmable loads. The amount of power and the start time of the programmable loads are determined by the energy management algorithm. In the simulation section, two scenarios are constructed and studied, which include smart building interaction in an off-grid mode with responsive and non-responsive lighting loads.

The results of the simulations indicate the validity of the idea. Therefore all thermal and electrical loads are supplied with the lowest cost. Then, the interaction between the two 50-unit smart buildings in an off-grid mode is introduced as the proposed model. In the second scenario, In the second scenario, the assumption of the responsive lighting loads reduces the amount of energy consumed at the peak time, thus, decreases consumer's costs by 5.8%. One of the problems in developing this method is the initial investment cost; However, this problem will be solved while the cost of renewable energy system will reduce. The presented method has a significant effect on managing smart homes, and reducing the energy consumption, which leads to lesser fossil fuels use for energy production. As a result, this lays a groundwork for a cleaner and more environmental-friendly production in smart homes, and a sustainable energy development can be achieved by this perspective.

5.1. Novelties

In this study, while building on the previous works, the following concepts can be considered as novelties:

1) Interaction between off-grid SHs (two 50-unit buildings).
2) The thermal energy balance of the buildings: The heat storage facilities can be applied in the buildings in condition that the proper capacity for the boiler is chosen. Selecting the optimal capacity for the boiler also has the advantage of reducing energy consumption.
3) Lighting loads of SHs planning: The demand response is improved by reducing lights at the beginning of the night (from 19 to 22), synchronizing these hours with the peak hours, leads to a better energy balance during these hours.

5.2. Future studies

Based on this method , the following could be considered for future studies:

1) The general policy of this study is, to control consumption, to shift the load between different hours, and to eliminate the peak load at peak hours of consumption. However, it may be possible that the reduced consumption would not necessarily shift over to the following few hours, and therefore, create a new peak at a different hour of the day. The recommendation is to periodically review and edit the electricity tariffs.
2) Consumer pricing of electricity, in this study, is considered constant and it is suggested that by expanding the scope of study, electricity prices on the consumer side should be considered competitive and variable.
3) In the proposed model, it is possible to exchange energy only by the ESSs of each building. This interaction could be seen more broadly, and buildings can directly exchange with each other.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

- The goal of this study is to provide the energy transfer between buildings in conditions that they are off-grid.
- The energy interaction between smart homes can be a solution for optimal energy consumption in homes.
- In this study, the method of MILP solution is used in GAMS software.
- In this study, it is assumed that the smart homes are off-grid, and critical loads are supplied by the energy transfer between smart homes.
- The smart home appliances are studied in two groups of programmable and non-programmable loads.