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Pave the way for sustainable smart homes: A reliable hybrid AC/DC electricity infrastructure

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ABSTRACT

The development of emerging smart grid technologies has led to more and more penetration of renewable energy resources and electric energy storage in the residential sectors. Besides, owing to the significant evolution of power electronic devices, there is a rapid growth in penetration of DC loads and generations, such as PV and electric vehicles (EVs), into the buildings and homes as a building block of the future smart cities. This is despite the fact that the electricity infrastructure of the conventional buildings is designed based on AC electricity and as a result, there would be a lot of losses due to the frequent power conversion from AC to DC and vice versa. Besides, according to a significant amount of energy consumption in the residential sector, buildings have a prominent role to confront environmental problems and obtain sustainability. In such circumstances, and considering the energy outlook, rethinking the electrification structure of the built environment is necessary. This work is an effort in this regard and looks for a sustainable energy infrastructure for the cyber–physical homes of the future. Three disparate electrification architectures are analyzed. The proposed framework, which is formulated as a mixed-integer linear programming (MILP) problem, not only considers costs associated with investment and operation but also evaluates the reliability of each structure by considering the different ratios of DC loads. Moreover, the optimal size of renewable energy resources and the effect of EV demand response, and different prices of PV and battery are precisely investigated. The efficacy of the proposed approach is evaluated via numerical simulation.

1. Introduction

In recent years, due to the development of the emerging smart grid technologies and increasing penetration of renewable energy sources (RESs) and electric energy storage systems on the demand-side, smart sustainable cities and homes are a concept that has come to the fore [1]. On the other side, since the expansion of the distribution systems poses technical and economic issues, using distributed energy resources (DERs) will be a beneficial solution in order to deliver power with low active power losses and load curtailment to the end-user. These resources are an important option for power generation also they guarantee the future energy systems with flexible and reliable sources [2,3].

Moreover, negligible operational and decreasing investment costs put renewable energy technology in a cost competition against fossil fuel resources. With this in mind, the RESs will play a significant role in future electricity production, and reconsideration is needed in the electrification structures and electricity consumption models since the residential section has a major share in energy consumption. All things considered, one can say in the future homes, which are mostly smart homes, the ubiquitous influence of renewable energy resources, especially solar resources, will be significantly seen more than the past.

Smart grid is not a single technology; indeed it is a combination of various fields of engineering, management, and communication. Based on the National Institute of standard and technology opinion, several key functions of smart grids that are essential for deploying technologies and services of smart grids are as follows: (1) Consumer energy efficiency and Demand response. (2) Wide-area situational awareness, (3) DERs, (4) Energy storage systems, (5) Electric transportation,

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Indices

i	Index of power outage states.
t	Index of optimization time intervals [h].

Parameters

A	Area of PV system [m^2].
C_B	Capital cost of battery [\$].
C_C	Capital cost of converter [\$].
C_{conv}	Capital cost of bidirectional converter [\$].
C_{curt}	Cost of load curtailment [\$].
C_{PV}	Capital cost of PV panel [\$].
$C_{Sell}(t)$	Cost of electricity sold to the grid in period t [\$].
$C_{ToU}(t)$	Time of use ratio in period t [\$].
Cap_{EV}	Capacity of EV's battery [kW].
Cap_{PV}^{Max}	Maximum capacity of PV [kW].
$I_{sun}(t)$	Solar irradiance in period t [kW/m^2].
$ICap_B$	Initial capacity of battery [kW].
$ICap_{EV}$	Initial capacity of EV's battery [kW].
$Load_T(t)$	Total load in period t [kW].
$Load_{TS}(t)$	Total supplied load in the first plan in period t [kW].
P_{Bch}^{Max}	Maximum allowed power charge of battery [kW].
P_{Bdch}^{Max}	Maximum allowed power discharge of battery [kW].
P_{EV}^{drive}	Required power to drive EV [kW].
P_{EVch}^{Max}	Maximum allowed power charge of EV [kW].
P_{EVdch}^{Max}	Maximum allowed power discharge of EV [kW].
P_G^{Max}	Maximum power exchanged between grid and home [kW].
SOC^{Min}	Minimum level of state of charge [kWh].
SOC_B^{Min}	Minimum level of state of charge for battery [kWh].
T_d	Driving time period of vehicle.
T_{in}	The time period when vehicle is in parking outside the home.
T_s	The time period when vehicle stays at home.
β	Ratio of DC loads to total loads.
α_{ch}	Charging coefficient factor.
α_{dch}	Discharging coefficient factor.
$\eta_{AC.DC}$	AC to DC Efficiency of bidirectional converter.
$\eta_{DC.AC}$	DC to AC Efficiency of bidirectional converter.
$\eta_{DC.DC}$	Efficiency of DC to DC converter.
η_{conv}	Efficiency of battery and EV's converters.
η_{PV}	Efficiency of PV panel.

Continuous Variables

Cap_B	Capacity of battery [kW].
Cap_{PV}	Capacity of PV system [kW].
Cap_{conv}	Capacity of bidirectional converter [kW].
$Cost$	Total cost of energy consumption [\$].
$Load^C(t)$	Load curtailment in period t [kW].
$Load_{AC}^C(t)$	AC load curtailment in period t [kW].
$Load_B^C$	Total load curtailment due to battery outage [kW].
$Load_{conv}^C$	Total load curtailment due to converter outage [kW].
$Load_{DC}^C(t)$	DC load curtailment in period t [kW].
$Load_G^C$	Load curtailment due to grid outage [kW].
$Load_i^C$	Load curtailment in state i [kW].
$Load_i^C(t)$	Load curtailment in state i and period t [kW].
$Load_{PV}^C$	Total load curtailment due to PV outage [kW].
$Load_T^C(t)$	Total load curtailment in period t [kW].
$P(i)$	Occurrence probability of state i.
$P_{AC.DC}(t)$	Transferred AC to DC power in period t [kW].
$P_B^{ch}(t)$	Power charge of battery in period t [kW].
$P_B^{dch}(t)$	Power discharge of battery in period t [kW].
P_{con}^B	Capacity of converter needed to connect battery to home [kW].
P_{con}^{EV}	Capacity of converter needed to connect EV to home [kW].
$P_{DC.AC}(t)$	Transferred DC to AC power in period t [kW].
$P_{EV}^{ch}(t)$	Power charge of EV in period t [kW].
$P_{EV}^{dch}(t)$	Power discharge of EV in period t [kW].
$P_G^{in}(t)$	Power received from grid in period t [kW].
$P_G^{out}(t)$	Power sold to grid in period t [kW].
$P_{PV}(t)$	Power generated by the PV in period t [kW].
$SOC_B(t)$	State of charge of battery in period t [kWh].

Binary Variables

$X_{AC.DC}(t)$	1 if power is transferred from AC to DC in period t and 0 otherwise [kW].
$X_{DC.AC}(t)$	1 if power is transferred from DC to AC in period t and 0 otherwise [kW].
$X_B^{ch}(t)$	1 if battery is charging in period t and 0 otherwise [kW].
$X_B^{dch}(t)$	1 if battery is discharging in period t and 0 otherwise [kW].
$X_{EV}^{ch}(t)$	1 if EV's battery is charging in period t and 0 otherwise [kW].
$X_{EV}^{dch}(t)$	1 if EV's battery is discharging in period t and 0 otherwise [kW].
$X_{in}(t)$	1 if power is transferred from grid to home in period t and 0 otherwise [kW].
$X_{out}(t)$	1 if power is transferred from home to grid in period t and 0 otherwise [kW].

Abbreviations

DER	Distributed energy resource.
DR	Demand Response.
FOR	Forced outage rate.
HEMS	Home energy management system.
HWES	Hybrid wind and solar energy system.
LOLE	Loss of load expectation.
MILP	Mixed integer linear programming.
MINLP	Mixed integer nonlinear programming.
EV	Electric Vehicle.
PV	Photovoltaic
RES	Renewable energy source.

(6) Network communications, (7) Advanced metering infrastructure (AMI), (8) Distribution grid management, (9) Cyber-security. AMI is one of the most key elements of SG which is responsible for collecting all the information and data from consumers and load centers and sending the received data to the utility in order to analyze and store it. Also, AMI is responsible for applying control commands to manage

SOC	State of charge.
ToU	Time of use.

Demand Side [4,5]. Indeed, in the future smart grid, all these functions will be implemented in the whole of the grid from generation part to consumption. Therefore, we focused on Consumer energy efficiency and energy management in this study.

Besides, a DC microgrid is known as a replacement for the conventional AC grid in the future smart grid. The DC microgrid integrates with RESs relatively easier, also this microgrid has a significant impact on the realization of some goals in the electric power industry because of the lack of non-zero-crossing current and reactive power [6]. On the other hand, the presence of DC loads, which are supposed to be energized with new DC resources, has notably grown, especially in residential houses. In addition, power electronic technology development has increased the use of DC buses, because of their numerous advantages in comparison with AC buses such as improving reliability and increasing energy saving at the building level [7,8].

Hence, due to the presence of DC resources and loads in future smart homes, studying on the hybrid AC/DC technology is essential for residential building. Thus, one can say it is time to make fundamental changes in the architecture of smart homes and their electrification structure. In other words, the amount of DC resources used for the power supply of household equipment has been increased, which results in decreasing energy losses due to the frequent power conversion from AC to DC and vice versa, and in the long run yields in energy saving. As a consequence, future homes will be absolutely in the form of hybrid AC/DC smart homes.

Although the presence of these resources and loads in the future homes may cause some challenges, it brings many benefits, such as the optimal operation of energy resources and improving reliability. In the smart grid area, a tremendous effort continues in different aspects of generation, distribution, and consumption because they have a critical impact on sustainability [9]. However, it is obvious, there are many issues on the demand side that remain without appropriate solutions. One of the important problems of hybrid smart homes is the management and operation of existing resources aimed at decreasing energy consumption cost. In this respect, several studies have been conducted.

1.1. *Literature review*

The authors in [8] investigated the potential of DC houses with onsite PV for saving energy in comparison with conventional AC houses. They analyzed the effects of energy storage and climate in both pure DC and AC residential microgrid. A conceptual methodology has been proposed in [10] for hybrid AC/DC DSP problem in order to compare the investment and operational costs of the AC/DC microgrid with the conventional AC ones. In [11] Gong et al. evaluated the energy management of smart hybrid AC/DC residential microgrid by considering CHP loads and charging/discharging of EVs. In addition, they proposed a secured architecture for optimal operation of this microgrid. Fu et al. in [12] proposed a new coordinated energy management manner for hybrid AC/DC microgrid by considering multiple players of the market. In [13], a mixed-integer nonlinear programming (MINLP) multiobjective optimization model has been developed for optimal energy management in a smart home by considering a meaningful balance between energy saving and comfortable lifestyle. An intelligent energy management system was proposed in [14] to reduce the cost of energy by scheduling the smart appliances in a conventional smart building without considering DER.

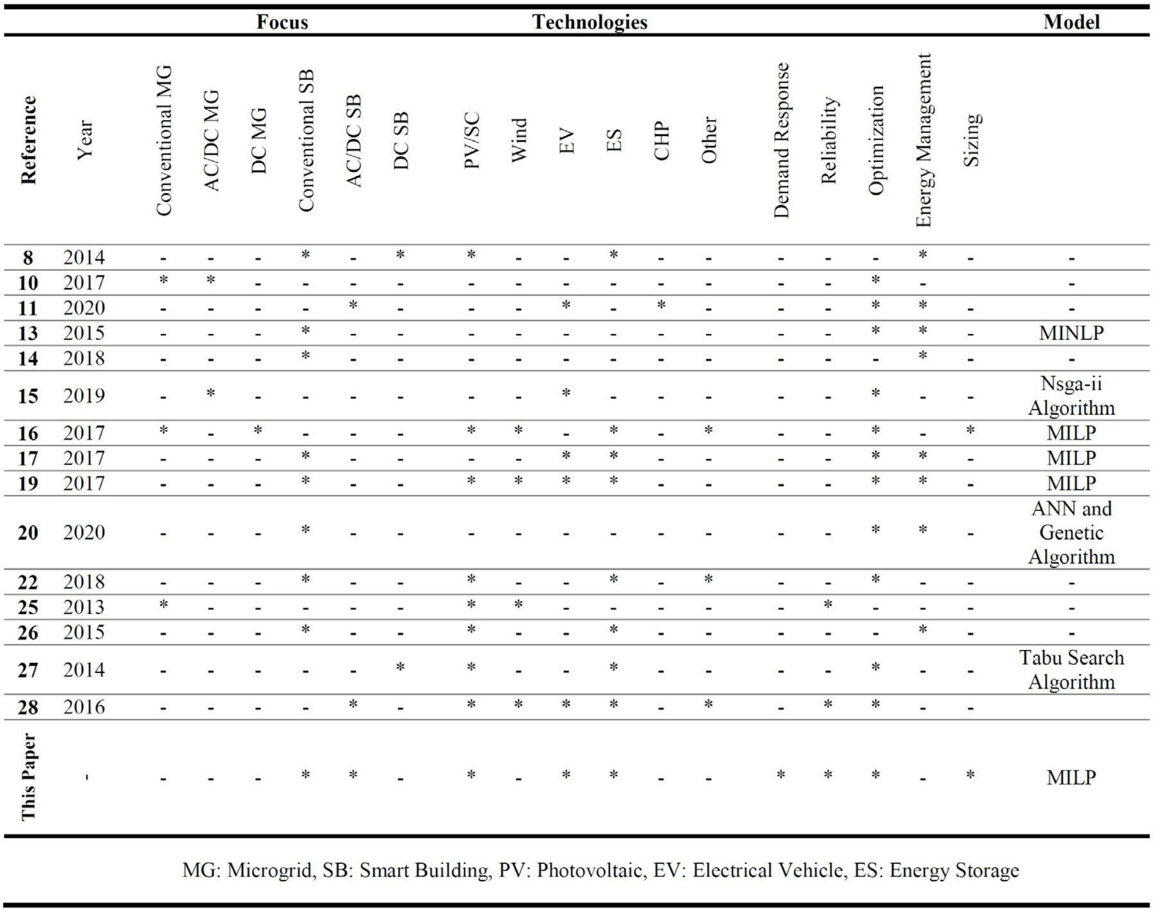
A multiobjective optimization model has been proposed for a hybrid AC/DC microgrid by considering life-cycle cost, self-balancing rate, and losses of the converter also, the effects of different modes of EVs charging have been investigated in [15]. Lotfi et al. presented a mixed-integer linear programming (MILP) model for microgrid planning model to determine the optimal size, generation mix of distributed energy resources, and type of (DC and AC) micro-grid in [16]. A smart energy management framework was proposed to minimize electricity cost and peak load in the residential sector in [17]. Zhou et al. reviewed the concept and structure of smart home energy management system (HEMS), new loads and appliances of smart home and renewable energy resources. Moreover, different types of home appliance scheduling strategies were studied in [18]. An MILP model is proposed in [19] to optimize the energy production and consumption systems in a smart home with effective deployment of renewable energy resources, energy storage systems, and plug-in hybrid electric vehicles. Ilbeigi et al. proposed a reliable model to optimize cost and the amount of energy consumption in a conventional building in [20].

Rodriguez-Diaz et al. in [21] listed main factors that demonstrate the utilization of the DC distribution system in the future is inevitable; furthermore, a new energy model has been presented for intelligent homes. finally, technical and social challenges of using DC system have been discussed. The authors in [22] assess an autonomous microgrid in a residential network for finding optimal structure by considering the different capacity of PV, diesel generator, and batteries. This paper just considers one electrification structure with accounting total load as AC load and finds optimal structure in it. The multiobjective optimization method proposed by Shadmand et al. [23] has used an economic-technical approach for size, cost and availability optimization of the system. The main goal of this study is to express a generic model for quantitative evaluation of availability and cost of renewable energy hybrid systems in a DC smart microgrid. In [24], a hierarchical coordination strategy has been presented to operate an islanded community microgrid economically. The authors in [25] investigated the benefits of hybrid renewable energy integration in a smart site. This study illustrates the utilization of hybrid wind and solar energy system (HWES) noticeably decreases reliance on the main grid; Furthermore, improves power quality and reliability. The new energy management system introduced by Zhao et al. [26], considers a smart home with various load profiles, photovoltaic system and battery. Also, the effects of various load profiles are studied in this paper.

In [27], a re-planning method is proposed for DC smart homes including photovoltaic system, solar collector, battery and heat pump system, using the Tabu Search algorithm. In [28], the author has explored the possibility of integrated the DC power with AC power from the main grid and distributed in the building environment through a hybrid AC/DC system in an efficient and resilient structure. Karabiber et al. in [29] investigated a hybrid DC/AC integration to establish microgrids by using local DGs, distributed domestic renewable sources and traditional local power delivery system. they presented a continuous mixing strategy to integrate local DG into the conventional grid in order that they may support each other constantly. Authors in [30] suggested a methodology for sizing the renewable energy system with different energy storage system scenarios under a techno-economic feasibility study in a microgrid.

1.2. *Research gap and contributions*

As it can be seen, tremendous efforts have been devoted to study on hybrid AC/DC microgrids in terms of control strategy, optimization and etc. There are a few studies in residential sectors but they often investigated just one structure as hybrid AC/DC or pure DC ones in a limited point of view such as cost optimization or energy management. Basically, in this paper, we look at smart homes' issues from a new point of view, and this is a completely novel comparison. None of the previous works compare different structures in terms of investment and operational cost, reliability, sizing, and demand response by considering the different ratios of DC load.



		Focus						Technologies											Model
Reference	Year	Conventional MG	AC/DC MG	DC MG	Conventional SB	AC/DC SB	DC SB	PV/SC	Wind	EV	ES	CHP	Other	Demand Response	Reliability	Optimization	Energy Management	Sizing	
8	2014	-	-	-	*	-	*	*	-	-	*	-	-	-	-	-	*	-	-
10	2017	*	*	-	-	-	-	-	-	-	-	-	-	-	-	*	-		-
11	2020	-	-	-	-	*	-	-	-	*	-	*	-	-	-	*	*	-	-
13	2015	-	-	-	*	-	-	-	-	-	-	-	-	-	-	*	*	-	MINLP
14	2018	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	*	-	-
15	2019	-	*	-	-	-	-	-	-	*	-	-	-	-	-	*	-	-	Nsga-ii Algorithm
16	2017	*	-	*	-	-	-	*	*	-	*	-	*	-	-	*	-	*	MILP
17	2017	-	-	-	*	-	-	-	-	*	*	-	-	-	-	*	*	-	MILP
19	2017	-	-	-	*	-	-	*	*	*	*	-	-	-	-	*	*	-	MILP
20	2020	-	-	-	*	-	-	-	-	-	-	-	-	-	-	*	*	-	ANN and Genetic Algorithm
22	2018	-	-	-	*	-	-	*	-	-	*	-	*	-	-	*	-	-	-
25	2013	*	-	-	-	-	-	*	*	-	-	-	-	-	*	-	-	-	-
26	2015	-	-	-	*	-	-	*	-	-	*	-	-	-	-	-	*	-	-
27	2014	-	-	-	-	-	*	*	-	-	*	-	-	-	-	*	-	-	Tabu Search Algorithm
28	2016	-	-	-	-	*	-	*	*	*	*	-	*	-	*	*	-	-	
This Paper	-	-	-	-	*	*	-	*	-	*	*	-	-	*	*	*	-	*	MILP

MG: Microgrid, SB: Smart Building, PV: Photovoltaic, EV: Electrical Vehicle, ES: Energy Storage

Fig. 1. A comparison taxonomy of the published works with this study.

As aforementioned, the future building will include DC loads and the renewable energy resources which provide DC power in order to prevent losses due to the frequent power conversion from AC to DC and vice versa, the old electrification structure must be replaced with hybrid AC/DC ones. Hence, the development of this study and structures for residential, commercial, and office buildings from the perspective of saving and optimizing energy consumption, and reliability can be useful also, by reducing the total cost of energy consumption, one of the goals of the sustainable smart cities concept will be achieved. Smart Cities may be defined as an ecosystem of ecosystems with essential communications infrastructure to improve life quality and economy. Smart Cities have both challenges and opportunities to achieve sustainability, conservation of resources, and development of technology and economy which are the main goals of smart cities [31].

In this paper, a novel MILP framework is proposed to draw a comparison between various energy supply structures of the future smart homes in terms of reliability improvement, energy optimization, and optimal sizing of resources by considering the growing ratio of DC load. In this regard, three different structures of smart homes, including AC and DC loads, photovoltaic systems, EVs which have bidirectional connections with home, and electric energy storage systems, are studied. Accordingly, the main contributions of this paper are:

1. To introduce and explain potential structures of the smart homes of the future;
2. To propose a novel mathematical framework which simultaneously finds the optimal configuration in terms of operational and investment cost;
3. To assess and compare the reliability of each configuration considering the different occurrence probability of the state of converters;
4. To find the optimal sizes of PV, ESS and bidirectional converters;
5. To determine the optimal type of home, either conventional AC or hybrid AC/DC according to the ratio of AC and DC load;
6. To analysis the EV demand response.

1.3. Organization of the paper

The rest of this paper is outlined as follows: In Section 2, the supposed structure of future smart homes is described. The proposed MILP framework for the problem is expressed in Section 3. Section 4 presents numerical studies and simulation results. Finally, the paper is concluded in Section 5.

2. Proposed structures for hybrid AC/DC smart homes

In this section, three different presented structures for hybrid AC/DC smart home are explained and the proposed algorithm explained.

(A) First plan: The smart home in the first plan is illustrated in Fig. 1, which includes an AC Bus connected to AC and DC loads, EV, energy storage system, and photovoltaic, in which all resources and loads are connected to the AC Bus. Thus, several converters are installed for converting AC to DC power and vice versa.

(B) Second plan: Fig. 2 shows the second plan for the smart home, which includes one AC Bus and one DC Bus. The same loads and resources of the first scheme exist in this scheme. These two buses are connected with a bidirectional converter, to convert the exchanged power, just when it is needed. For instance, the AC loads are fed with resources connected to the DC bus, when the home is disconnected from

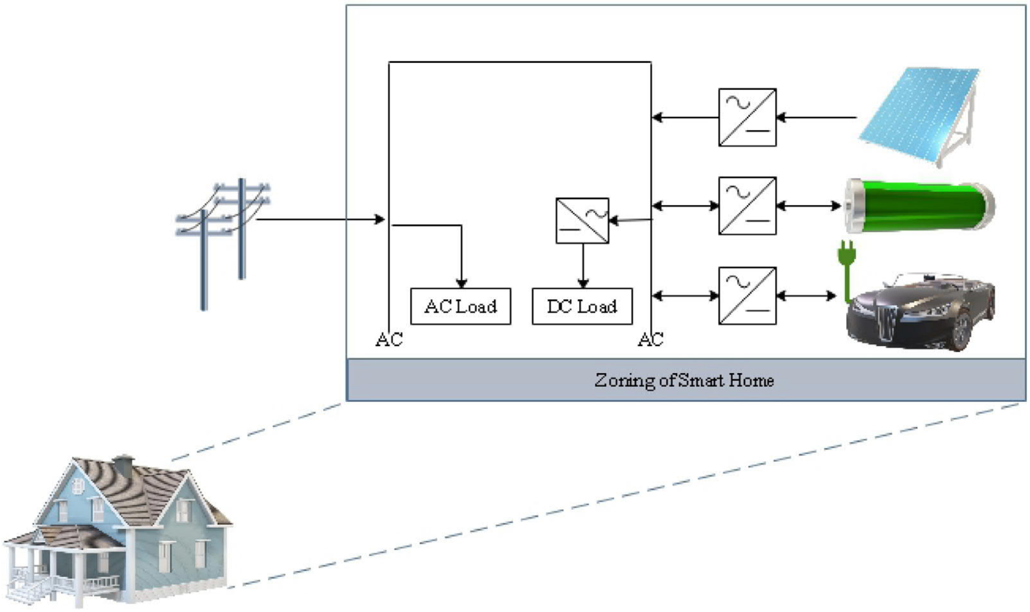


Fig. 2. Hybrid smart home structure according to the first plan.

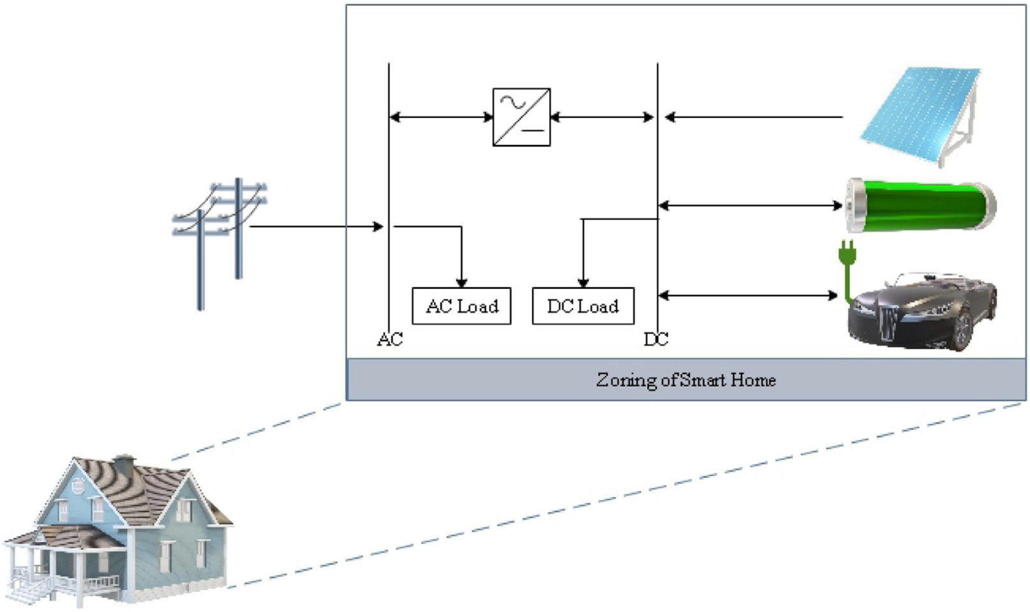


Fig. 3. Hybrid smart home structure according to the second plan.

the grid. When the DC resources are not able to supply loads connected to the DC bus, the grid will compensate power shortage at the DC bus.

(B) Third plan: Finally, the smart home of the third plan is shown in Fig. 3, which includes two buses like the second plan and has all the resources and loads of the two previous structures, with the difference that the buses are completely separate in this plan. In other words, AC loads are supplied only from the grid and DC loads are only fed from the DC bus (see Fig. 4).

3. Problem formulation

In this section, mathematical formulations are provided for all three structures of hybrid smart homes. The objective function, which is minimizing the cost of total energy consumption, including operating and investment costs in the entire scheduling horizon (one year), is defined as follows:

$$\begin{aligned} Cost = \sum_{t=1}^{8760} \Big\{ & \left[C_{ToU}(t) \times P_G^{in}(t)\right] \\ & - \left[C_{sell}(t) \times \left(P_G^{out}(t) + P_{EV}^{dch}(t) \times \eta_{DC.AC} \times \alpha_{dch}\right)\right] \\ & + \left[Load^C(t) \times C_{curt}\right] + \left[C_{PV} \times Cap_{PV}\right] + \left[C_B \times Cap_B\right] \\ & + \left[C_C \times (P_{con}^{EV} + P_{con}^{B})\right] + \left[C_{conv} \times Cap_{conv}\right] \end{aligned} \tag{1}$$

The first term in (1) is the cost of purchasing energy from the grid. The second term represents revenue related to the sale of excess energy to the grid. It is the sum of surplus energy transferred from the home to the grid and the discharging energy of the EVs' batteries in the outdoor parking. The third term shows the cost that load curtailment imposed on the system. This term is added to evaluate the reliability

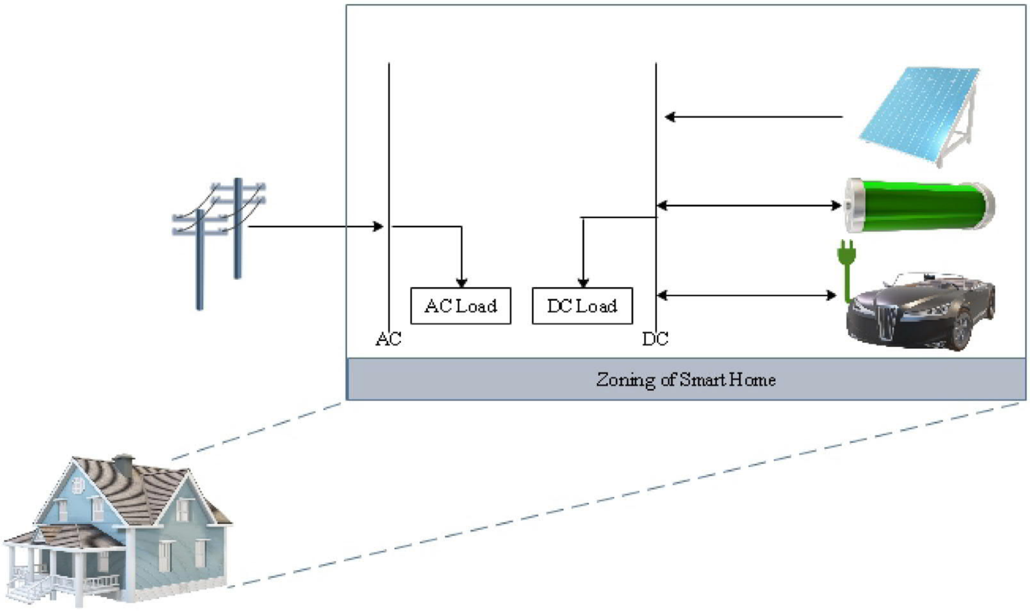


Fig. 4. Hybrid smart home structure according to the third plan.

Algorithm 1: Finding best architecture for hybrid AC/DC smart home

```
Data: Amount of consumption load, solar radiation, characteristic
      of energy storage system, EV, converter and PV, ToU ratio
Result: Finding optimal and reliable structure for future smart
        home
initialization;
Propose various structures for hybrid AC/DC smart homes;
Extract mathematical framework for various structures;
for all structure do
    for $\beta$ =0:0.1:1 do
        Find optimal sizing for resource;
        Find minimum cost of energy consumption;
        if Value of OF is minimized then
            fix size of resource in above amounts;
            calculate LOLE;
            $LOLE_t$=0;
            for all resource do
                if the resource is grid then
                    Calculate load curtailment for one-hour grid
                     interruption across whole 24 hours;
                else
                    Calculate load curtailment for resource outage in
                     one day;
                end
                Calculate LOLE;
                $LOLE_t$ = LOLE;
            end
        else
            go to the beginning of the loop;
        end
    end
end
```

of each plan. In other words, an excessive cost is assigned to this option to eliminate load shedding in the normal condition which all resources are attended. However, in conditions where the system faces with power loss for any reason, it will cut off the load according to the required amount. The fourth and fifth terms are capital cost of installing photovoltaic and battery storage systems, respectively, in which the value of capacities are considered as variables to determine the optimal sizes. The sixth term is the cost of connecting EV's converter to the home. Finally, the last term represents the capital cost of AC/DC bidirectional converter installed in the second plan for connecting the AC and DC buses. Here, the capacity of the converter is considered as a variable for determining its optimal size.

The constraints associated with each of these three plans are stated in the following.

3.1. Power balance constraints

3.1.1. The first plan of smart home

In order to minimize investment and operation cost and find optimal sizes and load curtailment, the power balance constraints must be considered. The power balance in this plan is defined in (2). According to this constraint, the sum of power generated should be equal to the sum of power consumed. Since DC sources are connected to AC Bus, the converter losses power must be considered, as they are applied in (2).

$$\eta_{DC.AC}\left[P_{PV}(t)+\left(P_{EV}^{dch}(t)+P_{B}^{dch}(t)\right)\times\alpha_{dch}\right]+P_{G}^{in}(t)+Load^{C}(t)$$
$$=Load_{TS}(t)+P_{G}^{out}(t)+P_{EV}^{ch}(t)+P_{B}^{ch}(t), \qquad (2)$$

where the first term in (2) is DC power generated that due to injection into AC bus, efficiency of converter has been imposed, power generated by grid and curtailed load have been considered as power generated. The sum of consumption load, power sold to grid and power charge of EV and battery have been taken into account as power consumed. Also, $Load_{TS}(t)$ is:

$$Load_{TS}(t)=(1-\beta)\times Load_{T}(t)+\beta\times\frac{Load_{T}(t)}{\eta_{AC.DC}}. \qquad (3)$$

The DC loads are measured when they are connected to the DC bus. So they must be considered with converter losses when they are supplied with the AC bus.

3.1.2. The second plan of smart home

As mentioned, this plan has AC and DC bus; therefore, two power balance constraints are taken into account for two buses. Furthermore, due to the connection between two buses by the bidirectional converter, the power is exchanged between the two buses, which must be considered in the constraint of power balance.

- Power balance constraint in AC bus

The sum of AC power generated should be equal to the sum of AC power consumed.

$$\eta_{DC.AC}\left[P_{PV}(t)+\left(P_{EV}^{dch}(t)+P_{B}^{dch}(t)\right)\times\alpha_{dch}\right]+P_{G}^{in}(t)+Load_{AC}^{C}(t)$$
$$=(1-\beta)\times Load_{T}(t)+P_{G}^{out}(t)+P_{AC.DC}(t), \tag{4}$$

- Power balance constraint in DC bus

$$\eta_{AC.DC}\times P_{AC.DC}(t)+P_{PV}(t)+P_{EV}^{dch}(t)+P_{B}^{dch}(t)+Load_{DC}^{C}(t)$$
$$=\beta\times Load_{T}(t)+P_{EV}^{ch}(t)+P_{B}^{ch}(t)+P_{DC.AC}(t). \tag{5}$$

3.1.3. The third plan of smart home

Similar to the second plan, in the third plan of smart home, two constraints of power balance in both AC and DC buses are listed below; however, in this plan AC and DC bus do not have any connection with each other.

- Power balance constraint in AC bus

$$P_{G}^{in}(t)+Load_{AC}^{C}(t)=(1-\beta)\times Load_{T}(t), \tag{6}$$

- Power balance constraint in DC bus

$$P_{PV}(t)+P_{EV}^{dch}(t)+P_{B}^{dch}(t)+Load_{DC}^{C}(t)=\beta\times Load_{T}(t)+P_{EV}^{ch}(t)+P_{B}^{ch}(t). \tag{7}$$

3.2. Bidirectional converter constraints

In the second plan of smart home, two zones are connected by the bidirectional converter which allows power exchange between these two sides. The amount of power exchanged between two buses is depended on the capacity of the converter; in addition, the bidirectional transfer of power is impossible simultaneously. This constraint is applied by using binary variables.

$$P_{AC.DC}(t)\le X_{AC.DC}(t)\times Cap_{conv}, \tag{8}$$

$$P_{DC.AC}(t)\le X_{DC.AC}(t)\times Cap_{conv}, \tag{9}$$

$$X_{AC.DC}(t)+X_{DC.AC}(t)\le 1. \tag{10}$$

3.3. The constraints of power exchanged between grid and home

In all plans, it is possible to exchange power between smart home and grid, this power has been limited and shown in (11) and (12), where P_{G}^{Max} is maximum power exchanged between grid and home allowed also, the power is transmitted in one direction at each moment.

$$0\le P_{G}^{in}(t)\le X_{in}(t)\times P_{G}^{Max}, \tag{11}$$

$$0\le P_{G}^{out}(t)\le X_{out}(t)\times P_{G}^{Max}, \tag{12}$$

$$X_{in}(t)+X_{out}(t)\le 1. \tag{13}$$

3.4. Solar system constraints

The capacity of the PV is a variable, this is written as inequality equation as (14). This is to avoid increasing causeless of the PV capacity. The PV power is dependent on area of PV system, solar irradiance and efficiency of PV panel (15) [32].

$$Cap_{PV}\le Cap_{PV}^{Max}, \tag{14}$$

$$P_{PV}(t)\le A\times\eta_{PV}\times I_{sun}(t). \tag{15}$$

It is to be noted that since the capacity of the photovoltaic system in this study is not constant (as it is a problem variable), and also as each panel with a given area produces a certain amount of power, therefore the amount of total power in (15) is proportional to its area. Thus, as the power generation of each solar panel with the area of 1 m^2 is approximately 150 W, Eq. (15) is recast as (16).

$$P_{PV}(t)\le\frac{Cap_{PV}}{0.15}\times\eta_{PV}\times I_{sun}(t). \tag{16}$$

3.5. EV constraints

- The limit of allowed charge/discharge of EV:

EV is as an important DC load in this study, according to its battery and charge and discharge cycle, EV imposes some constraint on the problem. It is assumed that the EV does not charges when it is out of home as (17). Moreover, three different states of discharge are considered, including:discharge at home, discharge during driving time and discharge in parking outside the home (18).

$$\begin{cases}0\le P_{EV}^{ch}(t)\le X_{EV}^{ch}(t)\times P_{EVch}^{Max}, & t\in T_s\\ P_{EV}^{ch}(t)=0, & t\notin T_s\end{cases}, \tag{17}$$

$$\begin{cases}0\le P_{EV}^{dch}(t)\le X_{EV}^{dch}(t)\times P_{EVdch}^{Max}, & t\in T_s\\ P_{EV}^{dch}(t)=P_{EV}^{drive}, & t\in T_d\\ P_{EV}^{dch}(t)\le P_{EVdch}^{Max}, & t\in T_{in}\end{cases}, \tag{18}$$

Eq. (19), which specify the operation mode with two binary variables, is represented to avoid the simultaneous occurrence of charging and discharging the battery of EV when it is at the home.

$$X_{EV}^{ch}(t)+X_{EV}^{dch}(t)\le 1. \tag{19}$$

3.6. Energy storage system constraints

One of the more important equipment in the hybrid AC/DC smart home is Energy Storage System. In this study the optimal capacity of ESS must be determined; thus, the constraints of ESS have been considered. The ESS constraints include constraint to prevent charge and discharge at the same time, constraint of SOC and energy sorted in battery.

- Charging/discharging of battery:

$$0\le P_{B}^{ch}(t)\le X_{B}^{ch}(t)\times P_{Bch}^{Max}, \tag{20}$$

$$0\le P_{B}^{dch}(t)\le X_{B}^{dch}(t)\times P_{Bdch}^{Max}, \tag{21}$$

$$X_{B}^{ch}(t)+X_{B}^{dch}(t)\le 1. \tag{22}$$

Each battery has a certain ratio of charge and discharge. In other words, there is a specific amount of charging and discharging levels in each stage. This amount depends on the battery capacity. As the charging and discharging ratio is considered proportional to the battery capacity, (20) and (21) are rewritten as (23) and (24).

$$0\le P_{B}^{ch}(t)\le 0.2\times Cap_{B}\times X_{B}^{ch}(t), \tag{23}$$

$$0\le P_{B}^{dch}(t)\le 0.2\times Cap_{B}\times X_{B}^{dch}(t), \tag{24}$$

- Electrical energy stored in battery in $t>1$:

The ESS can perform as either generator or load, as it is obvious in the model and power balance constraints; thus, determination of The amount of Electrical energy stored at any moment in the battery is necessary. It is exhibited in (25) [19]. The effect of charging coefficient factor and efficiency of battery converter are applied on the amount of electricity needed to charge.

$$Cap_{B}\times SOC_{B}(t)=Cap_{B}\times SOC_{B}(t-1)+\left[P_{B}^{ch}(t)\times\alpha_{ch}\times\eta_{conv}-P_{B}^{dch}(t)\right]\times dt, \tag{25}$$

- Initial state of the battery:

$$Cap_B \times SOC_B(1) = ICap_B + \left[P_B^{ch}(1) \times \alpha_{ch} \times \eta_{conv} - P_B^{dch}(1)\right] \times dt, \qquad (26)$$

- State of Charge:

The constraint of the state of charge (SOC) at each hour is presented in (27). In this paper, we choose two random typical days in summer and winter to do numerical Studies then it is expanded to the whole year; thus, the state Of Charge should be equal at the beginning and end of the day in order to provide the same situation in the next days for this study (28).

$$SOC_B^{Min} \le SOC_B(t) \le 1, \qquad (27)$$

$$SOC_B(t_1) = SOC_B(t_{24}), \qquad (28)$$

- Maximum battery charge limit:

The battery is able to store a certain amount of energy at each time which cannot be more than the capacity of the battery, it has been applied in (29) where the first term is the amount of stored power from the previous time and the second term is the charge power at the present.

$$Cap_B \times SOC_B(t-1) + \left[P_B^{ch}(t) \times \alpha_{ch} \times \eta_{conv}\right] \times dt \le Cap_B. \qquad (29)$$

Eqs. (25)–(29) are true for both of storage system and battery of EV. Considering that which plan is analyzed and the battery is connected to either AC or DC bus, the related efficiency coefficient is used in (25), (26) and (29).

3.7. Load curtailment constraint

In order to evaluate reliability of each plan, the load curtailment is calculated which caused by the outage of any resources in (33). Finally, with applying the occurrence probability of every state, The LOLE is computed by (34). It is obvious that amount of curtailed AC and/or DC load at each time is lower than amount of total AC and/or DC load at that time.

$$Load_T^C(t) = Load_{AC}^C(t) + Load_{DC}^C(t), \qquad (30)$$

$$Load_{AC}^C(t) \le (1-\beta) \times Load_T(t), \qquad (31)$$

$$Load_{DC}^C(t) \le \beta \times Load_T(t), \qquad (32)$$

- Reliability Evaluation:

$$Load_i^C = \sum_{t=1}^{8760} Load_i^C(t), \qquad (33)$$

$$LOLE = \sum_{i=1, j \ne i}^{n} Load_i^C \times P(i) \times [1 - P(j)]. \qquad (34)$$

4. Numerical studies

As described in the previous sections, three conceivable structures are discussed for future smart homes from the perspective of energy consumption optimization and energy supply reliability in this paper. The test home involves photovoltaic cell, energy storage system and EV. First, the optimal capacity of solar system, electric energy storage system and bidirectional converter (in the second plan) need to be calculated according to the different structures and various rate of AC and DC load. The results obtained for the case study have been tested on a computer with Windows 8.1 Pro 64-b operating system, processor Intel(R) Core (TM) i5-4200U CPU @ 2.30 GHz and 6-GB RAM. Also, during this paper the following items are studied.

- Sensitivity analysis on the outage probabilities of converter;
- Sensitivity analysis on the ratio of AC and DC loads;
- Sensitivity analysis on the price of PV and battery;
- Analysis of demand response of the EV.

Table 1
Required data.

$P_G^{Max} = 5$ [kW]	$\eta_{PV} = 18.6\%$
$\eta_{DC.AC} = \eta_{AC.DC} = 0.85$	$\eta_{DC.DC} = 1$
$Cap_{EV} = 12$ [kW]	$ICap_{EV} = 8$ [kW]
$P_{EVch}^{Max} = 2$ [kW]	$P_{EVdch}^{Max} = 2$ [kW]
$P_{EV}^{drive} = 1.5$ [kW]	$SOC^{Min} = 0.2$ [kWh]
$T_d = t_8, t_9, t_{14}, t_{15}$	$t_{10} \le T_{in} \le t_{13}$
$t_1 \le T_S \le t_7 \& t_{16} \le T_S \le t_{24}$	$\alpha_{ch} = \alpha_{dch} = 0.95$
$C_{Sell} = 0.15$ [\$]	$SOC_B^{Min} = 0.2$ [kWh]

The load consumption profiles are shown in Figs. 5. the solar radiations are obtained in two typical summer and winter days from Tehran, Iran, using the Homer software [33] and are illustrated in Fig. 6. some required data are illustrated in Table 1. The time of use (ToU) ratio for three periods including low, middle and peak load in two parts of the year, i.e. the first and second half of the year, are as follows:

- In the low load period of the first half of the year, from hour 24 to 8, and in the second half of the year, from hour 21 to 5, ToU ratio is $0.065/kW;
- In the middle load period of the first half of the year, from hour 8 to 20, and in the second half of the year, from hour 5 to 17, ToU ratio is $0.095/kW;
- In the peak load period of the first half of the year, from hour 20 to 24, and in the second half of the year from hour 17 to 21, ToU ratio is $0.132/kW

The presented model is solved in GAMS [34] software environment using CPLEX solver [35]. Simulation results of the energy consumption optimization in one year and the optimal size of resources according to different rate of DC and AC load are displayed in Table 2. In this paper we tried to find an optimal and reliable structure with taking into account the effect of changing the ratio of dc load β. This ratio is changed by a step of 0.1 when other parameters are fixed.

4.1. Results and discussion

As can be seen, the cost of energy consumption in the first plan for β =0 is much lower than other plans by increasing the ratio of DC load this difference is much smaller. Because in the second plan, the bidirectional converter imposes an extra cost to the system, as the cost of bidirectional converters is approximately two to three times of common AC/DC converter' cost. For the low ratio of the DC load, the power generated by the PV system should transfer to the AC side; therefore, the more capacity of the bidirectional converter is needed. Meanwhile, the energy storage system is not necessary; thus, there is no more extra energy for selling to the main grid. As a result, the energy consumption cost of the second plan is more than the first plan up to $\beta = 0.6$.

By increasing the DC load the capacity of the bidirectional converter gradually declines, also from $\beta = 0.6$ onwards the optimal structure of the second plan has the determinate capacity of the battery which can store extra energy then discharge it either for supplying residential load or for selling to the grid. On one hand, as the solar system, battery, and EV are connected to the bus with DC/DC converter, the cost of DC/DC converter is low in comparison with AC/DC converter. On the other hand, the efficiency of these converters is more than the others and the amount of loss is negligible in comparison with AC/DC converters, due to the energy conversion process. Hence, the cost of energy consumption decreases until the optimal cost of the second plan

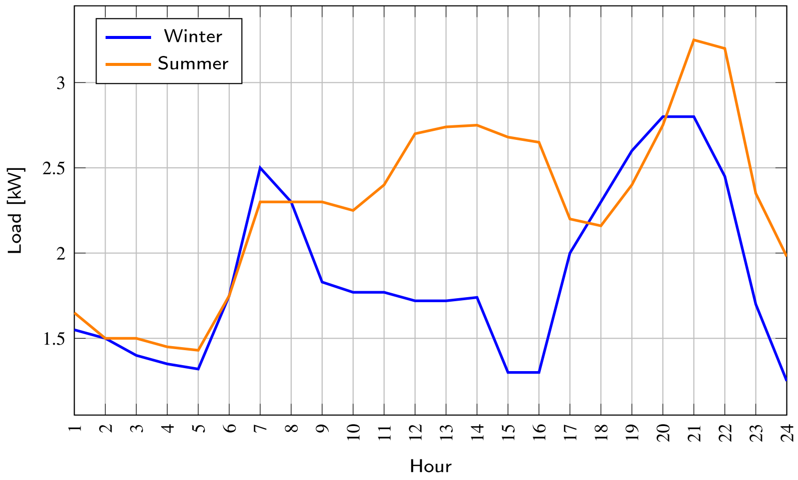


Fig. 5. Amount of load during two typical days.

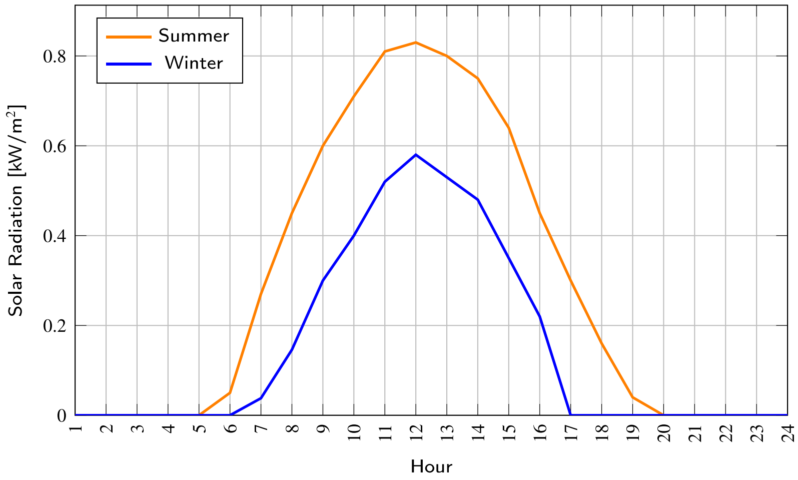


Fig. 6. Solar radiation during a typical winter and summer day.

is less than two other schemes from $\beta = 0.7$ onwards, as it is obvious. As a matter of explanation, the higher the DC load, the more economically viable the second scheme.

In the first plan of smart home, there is no need to the energy storage system to supply all loads, including AC and DC loads, due to permanent existence without intermediaries of the grid, and utilizing it in the smart home in this state is merely imposing an extra cost. Indeed, energy storage systems are utilized to compensate uncertainty in power generation by renewable resources. In this plan, when renewable energy resources are not available, the required power can be easily produced by the grid. Although in the second plan, the grid is permanently available, power is transferred through the bidirectional converter for supplying the loads connected to the DC bus.

This will yield to power losses and extra costs because these converters usually have an efficiency of less than 100%. Also, as it can be seen in Figs. 7 and 8, due to the presence of storage system and sufficient solar system capacity, the amount of sold power to the grid in the second plan is more than other structures of a smart home. In the third plan of smart home, according to the fact that AC and DC sections are completely detached, the energy is continually received from the grid only according to the amount of load demand. As there are not any connections between the AC and DC sections and thus there is no possibility to save energy in the AC side, the energy consumption cost in this structure is much more than two other structures.

Moreover, the capacity of the photovoltaic system is much less than the second plan, as the ratio of DC load increases, the PV capacity increases, for the PV just provides power for the DC load. In order to confront with uncertainties associated with photovoltaic system's power production in this structure, for as much as the battery has a specific charge and discharge ratio, so a limited amount of power can be stored and saved in the battery, in each moment. Therefore the installed battery's capacity is much more than the other two structures for providing the required DC power.

The power exchanged between home and grid for two typical days in cold and hot seasons with $\beta = 0.9$ in all the three plans of hybrid smart homes are displayed in Figs. 7 and 8. The transferred power from the grid to home is specified by positive numbers and the transferred power in the opposite direction, i.e., the selling power from home to the grid, is shown by negative numbers in the diagram. In the third plan, in which the AC and DC buses are distinctly apart, energy is received from the grid only according to the amount of load demand at each moment. According to the fact that there are only AC loads connected to the AC bus and there are not any resources or storage systems, basically, it is not possible to sell power to the grid.

As it is explicit in Figs. 7 and 8, in the second plan, in which the AC and DC buses are connected together with a converter, the receiving power from the grid in peak times when the energy price is high, is much less than the first plan of a common hybrid smart home. Besides, in the second scheme, selling energy to the grid is

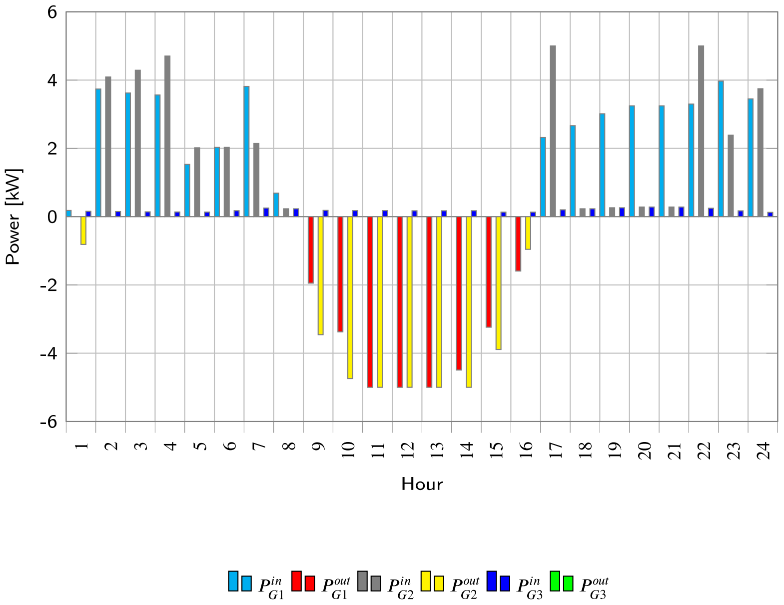


Fig. 7. Power exchanged with grid in the three plans of hybrid smart home in winter ($\beta = 0.9$).

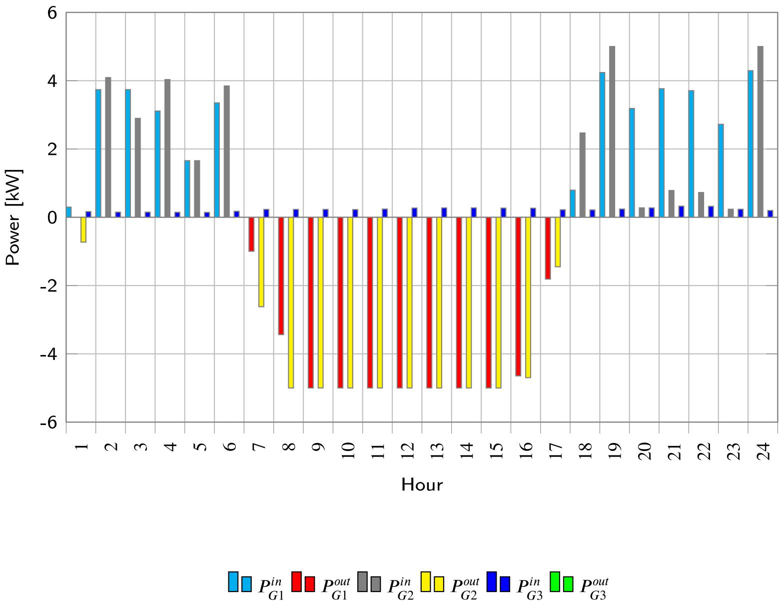


Fig. 8. Power exchanged with grid in the three plans of hybrid smart home in summer ($\beta = 0.9$).

more than the first scheme. As in the second plan, the DC resources are responsible to supply DC loads and the AC resources supply AC loads, the connection of these two groups of loads and resources is possible by the bidirectional converter only when it is required. In this case, the energy is received from the grid in the off-peak hours of consumption, and the surplus energy received from the grid and the photovoltaic system is stored in the battery and therefore, some amount of energy is procured through discharging of the battery in the peak hours, which energy purchasing cost from the grid is high and the photovoltaic system is not available.

The power exchanged between two AC and DC buses in the second plan is shown in Figs. 9 and 10. As it is obvious from these diagrams, the amount of transferred power from the DC to AC side is higher, especially in hours which the solar power is available. Hence, the amount of sold power to the grid in the second plan is more than the first one.

Figs. 11 and 12 illustrate power charge and discharge of battery. According to simulation results, since the home in the first plan is a conventional smart home which the grid is available constantly, no battery usage required. In the third plan that AC and DC zone are separated, the storage system (battery) and battery of EV supply load when the photovoltaic system does not produce power. Therefore, the battery charges when the PV is available and it discharges at other times. In the second plan, dependence on the battery is less than the third plan because the grid is consistently accessible.

As it is obvious, implementation of the third plan is not possible under these circumstances for, it requires a high level capacity of the battery also the energy consumption of this plan is extremely high. This scheme may be an appropriate structure for utilizing in the DC microgrid that there are connections for exchanging power between different buildings.

Table 2
Optimization results for all three designs.

		First plan	Second plan	Third plan
$\beta = 0$	Cost [$]	286.623	625.993	2169.74
	Cap_{PV} [kW]	12.352	12.352	1.571
	Cap_{B} [kW]	0	0	7.649
	Cap_{conv} [kW]	–	9.106	–
$\beta = 0.1$	Cost [$]	313.612	604.770	2231.456
	Cap_{PV} [kW]	12.409	12.344	2.611
	Cap_{B} [kW]	0	0	11.03
	Cap_{conv} [kW]	–	8.784	–
$\beta = 0.2$	Cost [$]	340.601	585.740	2496.601
	Cap_{PV} [kW]	12.466	12.296	5.55
	Cap_{B} [kW]	0	0	15.582
	Cap_{conv} [kW]	–	8.461	–
$\beta = 0.3$	Cost [$]	367.328	568.793	2379.422
	Cap_{PV} [kW]	12.523	13.167	4.788
	Cap_{B} [kW]	0	0	17.75
	Cap_{conv} [kW]	–	8.139	–
$\beta = 0.4$	Cost [$]	393.898	552.803	2444.359
	Cap_{PV} [kW]	12.580	13.116	5.738
	Cap_{B} [kW]	0	0	21.213
	Cap_{conv} [kW]	–	7.816	–
$\beta = 0.5$	Cost [$]	420.469	537.555	2512.339
	Cap_{PV} [kW]	12.637	13.064	6.769
	Cap_{B} [kW]	0	0	24.553
	Cap_{conv} [kW]	–	7.494	–
$\beta = 0.6$	Cost [$]	447.039	509.036	2681.112
	Cap_{PV} [kW]	12.694	13.614	8.904
	Cap_{B} [kW]	0	6.118	27.722
	Cap_{conv} [kW]	–	7.172	–
$\beta = 0.7$	Cost [$]	473.609	470.991	2655.708
	Cap_{PV} [kW]	12.751	13.094	8.849
	Cap_{B} [kW]	0	5.740	31.325
	Cap_{conv} [kW]	–	6.849	–
$\beta = 0.8$	Cost [$]	500.179	461.581	2732.827
	Cap_{PV} [kW]	12.808	12.91	9.890
	Cap_{B} [kW]	0	2.669	34.760
	Cap_{conv} [kW]	–	6.527	–
$\beta = 0.9$	Cost [$]	526.750	445.800	2841.470
	Cap_{PV} [kW]	12.865	13.598	11.366
	Cap_{B} [kW]	0	3.344	37.908
	Cap_{conv} [kW]	–	6.205	–
$\beta = 1$	Cost [$]	553.320	434.774	2900.528
	Cap_{PV} [kW]	12.922	14.514	11.971
	Cap_{B} [kW]	0	8.532	41.951
	Cap_{conv} [kW]	–	5.882	–

According to Figs. 13 and 14 which display power produced by the photovoltaic system, in addition to the solar irradiation and the area of the PV system, the PV power is dependent on the situation of the other resources and amount of load.

After determining the amount of required capacity of the photovoltaic system, battery, and bidirectional converter for presenting optimal structure in each plan, the reliability of the energy supply in each plan with various ratio of AC and DC load is evaluated. To evaluate and compare the reliability of all the plans, the amount of load curtailment in the entire period of schedule is calculated by the equations presented in Section 3 for exiting of each power resources. As simultaneous exiting of all three mentioned components is implausible, one of the resources is considered to be unavailable in each stage and the amount of load curtailment for that case is calculated in whole one year.

Furthermore, it should be pointed out that failure in the photovoltaic system and battery will not be repaired quickly, the unavailability period of these components is assumed to be one day. On the other hand, as power outages are usually short-time rated, the grid's unavailability interval is considered equal to one hour, such that one-hour grid interruption across whole 24 h is applied to both of cold and hot typical days and after that the amount of load curtailment is calculated. Finally, considering the possibility of occurrence in each case, the loss of load expectation (LOLE) is calculable in the whole scheduling period using (32). It is noteworthy that load supply has a higher priority than charging battery storage and EV's battery.

Table 3
Load curtailments due to components outage [kW/yr].

		First plan	Second plan	Third plan
$\beta = 0$	$Load^{C}_{G}$	2183.22	2220.84	17884.8
	$Load^{C}_{PV}$	0	0	0
	$Load^{C}_{B}$	–	0	0
	$Load^{C}_{conv}$	–	0	–
$\beta = 0.1$	$Load^{C}_{G}$	2291.04	2072.52	16096.32
	$Load^{C}_{PV}$	0	0	1730.88
	$Load^{C}_{B}$	–	0	382.14
	$Load^{C}_{conv}$	–	75.24	–
$\beta = 0.2$	$Load^{C}_{G}$	2418.66	1949.76	14307.84
	$Load^{C}_{PV}$	0	0	3460.14
	$Load^{C}_{B}$	–	0	815.58
	$Load^{C}_{conv}$	–	907.2	–
$\beta = 0.3$	$Load^{C}_{G}$	2548.62	1806.12	12519.36
	$Load^{C}_{PV}$	0	0	5192.64
	$Load^{C}_{B}$	–	0	1798.92
	$Load^{C}_{conv}$	–	1060.38	–
$\beta = 0.4$	$Load^{C}_{G}$	2680.74	1706.76	10730.88
	$Load^{C}_{PV}$	0	0	6815.52
	$Load^{C}_{B}$	–	0	2622.6
	$Load^{C}_{conv}$	–	1786.68	–
$\beta = 0.5$	$Load^{C}_{G}$	2821.68	1618.74	8942.4
	$Load^{C}_{PV}$	0	0	8654.4
	$Load^{C}_{B}$	–	0	3435.48
	$Load^{C}_{conv}$	–	2696.76	–
$\beta = 0.6$	$Load^{C}_{G}$	2968.38	119.34	7153.92
	$Load^{C}_{PV}$	0	0	10385.028
	$Load^{C}_{B}$	–	0	4030.74
	$Load^{C}_{conv}$	–	1947.96	–
$\beta = 0.7$	$Load^{C}_{G}$	3117.06	124.02	5365.44
	$Load^{C}_{PV}$	0	0	12116.16
	$Load^{C}_{B}$	–	0	5096.7
	$Load^{C}_{conv}$	–	2998.08	–
$\beta = 0.8$	$Load^{C}_{G}$	3271.68	579.6	3576.96
	$Load^{C}_{PV}$	0	0	13847.04
	$Load^{C}_{B}$	–	0	5927.76
	$Load^{C}_{conv}$	–	4850.28	–
$\beta = 0.9$	$Load^{C}_{G}$	3431.16	401.76	1788.48
	$Load^{C}_{PV}$	0	0	15534.18
	$Load^{C}_{B}$	–	0	6688.8
	$Load^{C}_{conv}$	–	5582.34	–
$\beta = 1$	$Load^{C}_{G}$	5903.1	0	0
	$Load^{C}_{PV}$	0	0	17308.8
	$Load^{C}_{B}$	–	0	7630.92
	$Load^{C}_{conv}$	–	5064.84	–

Total load curtailment caused by a failure in each component of the smart home is illustrated in Table 3, which is calculated for two days and generalized for the entire year by considering different ratio of DC load.

The outage probabilities of the grid, solar system, and battery are 0.002, 0.01, and zero, respectively. Since there were no available real data for a bidirectional converter that connects two distinct sections

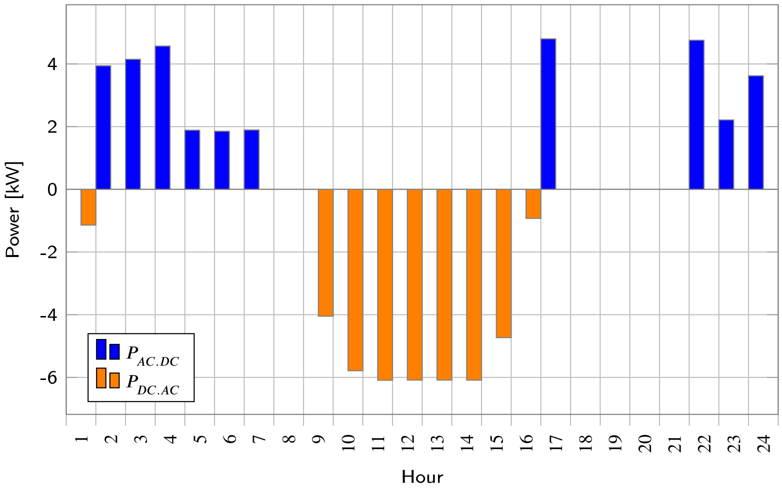


Fig. 9. Power exchanged between AC and DC buses in winter ($\beta = 0.9$).

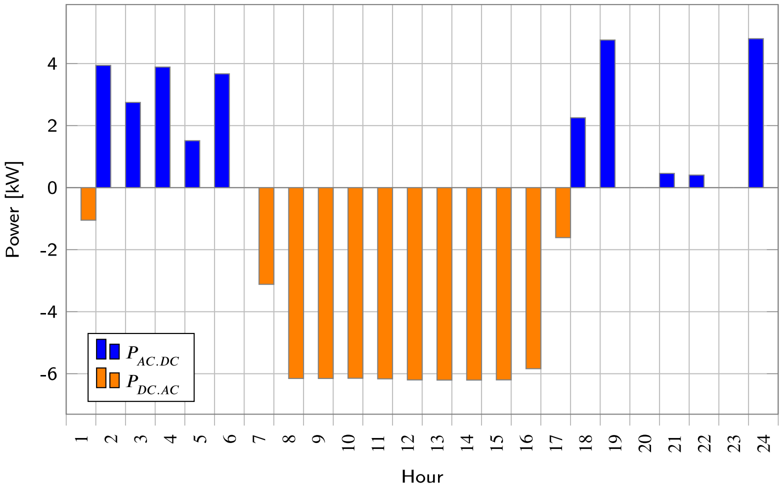


Fig. 10. Power exchanged between AC and DC buses in summer ($\beta = 0.9$).

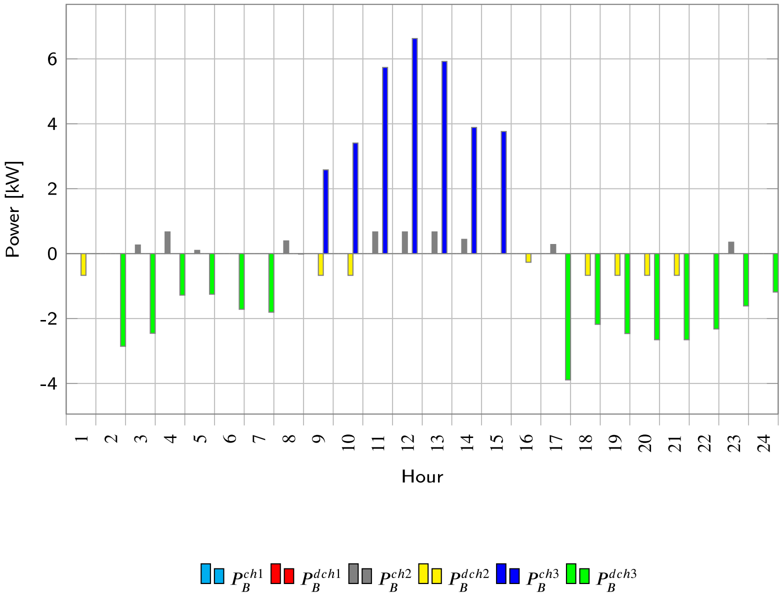


Fig. 11. Power charge and discharge of battery in winter ($\beta = 0.9$).

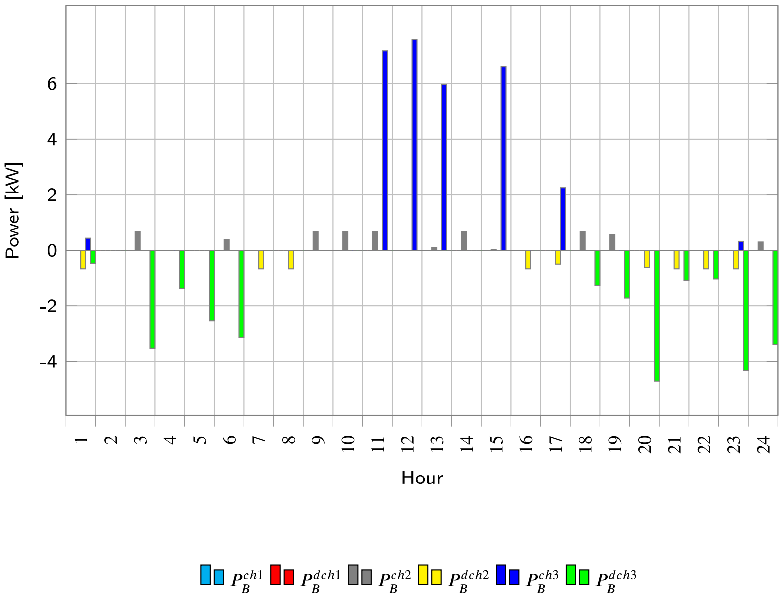


Fig. 12. Power charge and discharge of battery in summer ($\beta = 0.9$).

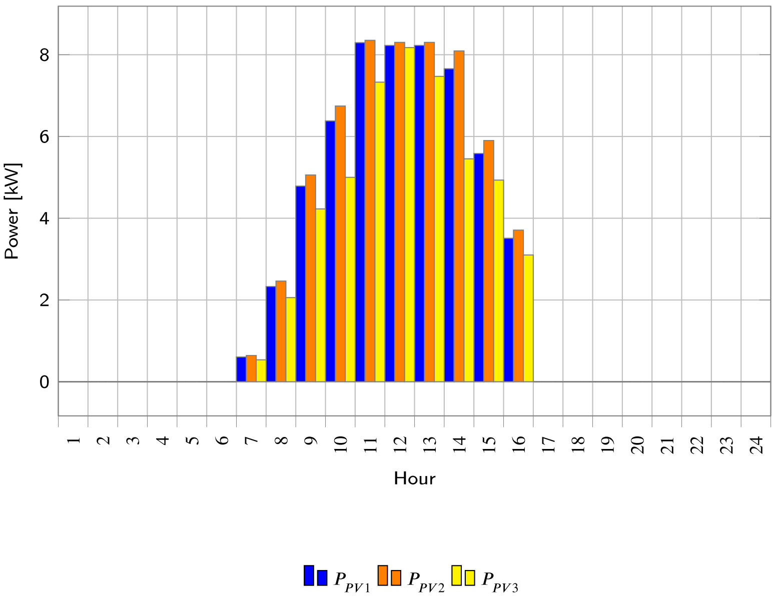


Fig. 13. Power generated by the PV in winter ($\beta = 0.9$).

of AC and DC in a smart home, the reliability is not determined here. So, different amounts of 0.001, 0.002 and 0.01 are considered for sensitivity analyzing on reliability effect of this component on the required power supply in this study.

The LOLE in each plan is given in Table 4. According to this table, it is determined that the reliability of the power supply in the third plan is much lower in comparison with two other plans. In the first and third plan, reliability decreases with increasing DC load. As can be seen, the LOLE of the second plan for β = 0.6, 0.7 is significantly lower due to the presence of more capacity of the battery. In fact, the energy storage system improves reliability. Also, the reliability of the second plan completely depends on forced outage rate (FOR) of the bidirectional converter. In the cases that FOR of the converter is 0.001, reliability is better than the first one. However, while FOR of the bidirectional is 0.01, LOLE in the second plan is more than the first. So the reliability of the first plan is better in this case. When FOR of the converter is 0.002, reliability depends on the capacity of the battery, The higher the battery capacity, the higher the reliability. But, according to recent developments in power electronics, the manufacturing of highly reliable converters is not farfetched. Thus one can say that with highly reliable bidirectional converters, the second plan will be more reliable than the others.

4.2. Sensitivity analysis on the price of PV and battery

This article proposed the model which is beneficial and practical for future smart home because according to the price of PV and battery in the current situation, zoning of smart home is not effective in terms of cost of total energy consumption. Table 5 includes the result of optimization based on the current price of PV and battery as it is evident that the total cost of the second plan is higher than the first plan. However, in the past decades, the price of solar and battery have dropped by an incredible amount especially solar photovoltaic module prices have dropped by 89 percent since 2010 [35] and this pattern

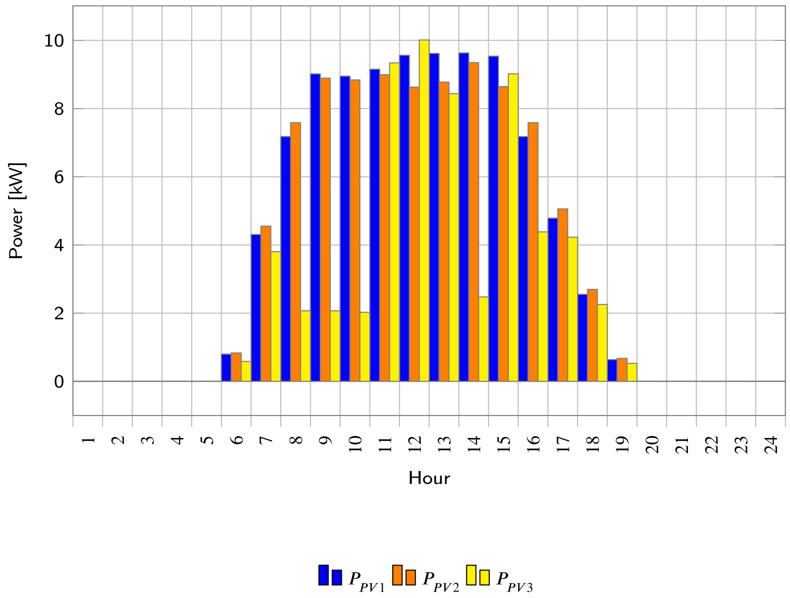


Fig. 14. Power generated by the PV in summer ($\beta = 0.9$).

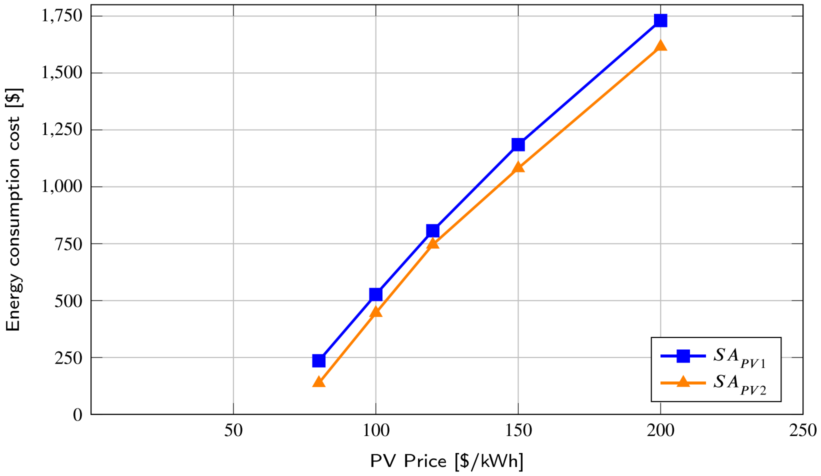


Fig. 15. Sensitivity analyzing on PV cost ($\beta = 0.9$).

will continue in the future. Hence, we considered different amounts of PV and battery costs in the future for sensitivity analysis on the price effect of this component on the total energy consumption.

Figs. 15 and 16 illustrate the result of sensitivity analysis. According to simulation results, by reducing the cost of PV, the total cost declines. It is necessary to mention that in the higher price of PV, the difference between costs of two plan are more noticeable than the lower price of PV, as in the second design when the PV with a lower price is available, more capacity of photovoltaic systems will be installed; thus, battery storage devices will be needed to store and then sell the extra power. It imposes extra money that leads to reduce the difference between the costs of two plans. But, the cost of the second plan is still lower than the first one. Furthermore, according to Fig. 16 when the battery price is high, the battery is not installed because it makes no economic sense; therefore, battery price changes do not affect the cost of the first plan dramatically. On the contrary, when the price of the battery will decrease the battery installation is economical; thus, the energy consumption price of the first plan will decline somewhat. However, the second design is influenced by these changes significantly. As a result, the photovoltaic system price changes constantly lead to changes in the cost of energy consumption but changing the battery price influences the total cost noticeably when its price is very low.

4.3. Analysis of demand response of the EV

In this study we investigated the impact of demand response of EV; for this purpose, two different strategies were proposed. First, the EV adopt a DR strategy; in fact, EV charge and discharge orderly. The discharge power injects into the home for whether supplying the residential load or selling to the grid, these result presented in the previous section. The second one, the EV considered as a conventional DC load. The optimization and reliability results for the first and second plan are shown in Tables 6 and 7. Changing the energy consumption cost with the different ratio of DC load is like Table 2 but, without EV demand response total cost of energy consumption increases also, in the high ratio of DC load the amount of battery capacity increases significantly.

According to Table 7, In the first plan which is a conventional home without EV demand response reliability drops sharply but, in the second scheme, reliability depends on the ratio of DC load. For the low ratio of DC load, battery installation makes no economic sense; therefore,

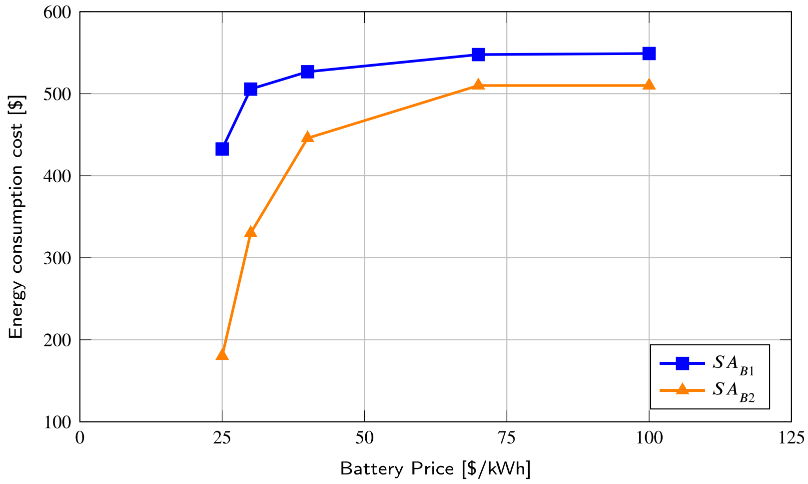


Fig. 16. Sensitivity analyzing on battery cost ($\beta = 0.9$).

Table 4
LOLE in the three plans.

		First plan	Second plan	Third plan
$\beta = 0$	$LOLE$	4.322	–	35.4119
	$FOR = 0.01$	–	4.3533	–
	$FOR = 0.002$	–	4.3885	–
	$FOR = 0.001$	–	4.3928	–
$\beta = 0.1$	$LOLE$	4.5362	–	49.1449
	$FOR = 0.01$	–	4.7177	–
	$FOR = 0.002$	–	4.1551	–
	$FOR = 0.001$	–	4.0848	–
$\beta = 0.2$	$LOLE$	4.7889	–	62.8617
	$FOR = 0.01$	–	12.7852	–
	$FOR = 0.002$	–	5.6455	–
	$FOR = 0.001$	–	4.7529	–
$\beta = 0.3$	$LOLE$	5.0463	–	76.6108
	$FOR = 0.01$	–	14.017	–
	$FOR = 0.002$	–	5.6643	–
	$FOR = 0.001$	–	4.6202	–
$\beta = 0.4$	$LOLE$	5.3079	–	89.266
	$FOR = 0.01$	–	20.9983	–
	$FOR = 0.002$	–	6.9032	–
	$FOR = 0.001$	–	5.1413	–
$\beta = 0.5$	$LOLE$	5.5869	–	104.0769
	$FOR = 0.01$	–	29.8176	–
	$FOR = 0.002$	–	8.5276	–
	$FOR = 0.001$	–	5.3663	–
$\beta = 0.6$	$LOLE$	5.8774	–	117.8098
	$FOR = 0.01$	–	19.4802	–
	$FOR = 0.002$	–	4.0851	–
	$FOR = 0.001$	–	2.1607	–
$\beta = 0.7$	$LOLE$	6.2718	–	131.5412
	$FOR = 0.01$	–	29.8647	–
	$FOR = 0.002$	–	6.1694	–
	$FOR = 0.001$	–	3.2075	–
$\beta = 0.8$	$LOLE$	6.6779	–	145.2758
	$FOR = 0.01$	–	49.057	–
	$FOR = 0.002$	–	10.7297	–
	$FOR = 0.001$	–	5.7386	–
$\beta = 0.9$	$LOLE$	6.9937	–	158.5723
	$FOR = 0.01$	–	55.9422	–
	$FOR = 0.002$	–	11.8248	–
	$FOR = 0.001$	–	6.0101	–
$\beta = 1$	$LOLE$	11.6881	–	172.7418
	$FOR = 0.01$	–	50.041	–
	$FOR = 0.002$	–	10.0083	–
	$FOR = 0.001$	–	5.0042	–

Table 5
Optimization results in the present situation ($\beta = 0.9$).

	First plan	Second plan	Third plan
$Cost$[\$]	2234.152	2869.562	11589.142
Cap_{PV} [kW]	0	2.696	10.93
Cap_{B} [kW]	0	0	35.195
Cap_{conv} [kW]	–	2.500	–

Table 6
Optimization results without EV demand response.

		First plan	Second plan
$\beta = 0.3$	Cost [\$]	439.352	697.416
	Cap_{PV} [kW]	12.523	13.167
	Cap_{B} [kW]	0	0
	Cap_{conv} [kW]	–	8.139
$\beta = 0.4$	Cost [\$]	465.922	692.823
	Cap_{PV} [kW]	12.580	13.116
	Cap_{B} [kW]	0	0
	Cap_{conv} [kW]	–	7.816
$\beta = 0.8$	Cost [\$]	572.203	615.455
	Cap_{PV} [kW]	12.808	15.836
	Cap_{B} [kW]	0	13.720
	Cap_{conv} [kW]	–	6.527
$\beta = 0.9$	Cost [\$]	598.773	572.017
	Cap_{PV} [kW]	12.865	15.926
	Cap_{B} [kW]	0	13.345
	Cap_{conv} [kW]	–	6.205

reliability noticeably decreases. In contrast, when $\beta = 0.8$, 0.9 and without EV demand response, the use of more capacity of the battery is economically justified; thus, reliability notably improves.

5. Conclusion and future work

In this paper, features of the future smart homes with various architectures are analyzed from the required power supply of load point of view. Comparing and analyzing the future homes, in which discussion of hybrid AC/DC grids was remarkable, is addressed. Accordingly, a suitable model for the hybrid AC/DC smart homes is proposed. The analysis has been performed for various cases of existing these grids in future homes, with a focus on energy consumption optimization and reliability improvement.

To sum up, the following conclusions are obtained from this study which are explained in the following paragraphs:

Table 7
LOLE without EV demand response.

		First plan	Second plan
$\beta = 0.3$	$LOLE$	33.580	–
	$FOR = 0.01$	–	44.430
	$FOR = 0.002$	–	23.884
	$FOR = 0.001$	–	21.316
$\beta = 0.4$	$LOLE$	33.641	–
	$FOR = 0.01$	–	53.799
	$FOR = 0.002$	–	25.745
	$FOR = 0.001$	–	22.239
$\beta = 0.8$	$LOLE$	33.883	–
	$FOR = 0.01$	–	32.111
	$FOR = 0.002$	–	6.997
	$FOR = 0.001$	–	3.857
$\beta = 0.9$	$LOLE$	33.944	–
	$FOR = 0.01$	–	42.296
	$FOR = 0.002$	–	9.095
	$FOR = 0.001$	–	4.945

- The optimal structure of the electricity network of a smart home which encompassed different ratio of DC load and sizing of resources is formulated in a novel mathematical framework;
- A solution proposed to cope with the issues caused by the increasing penetration of the DC resources and loads (e.g. increased loss of energy) at home level;
- The potential electricity infrastructure of the smart homes from the reliability perspective is analyzed and the optimal structures proposed;
- Sensitivity analysis performed based on the PV and battery prices;
- The effect of demand response provision by EVs is investigated.

According to the carried out study, the energy consumption cost for an entire year depending on the ratio of DC load. The cost of the second plan decreases with increasing the ratio of DC load, unlike the first scheme. In the future buildings with DC load and renewable energy, if the second plan is performed with the possibility to sell energy to the grid, the cost of this structure will be more improved. Deciding about the reliability of the second plan completely depends on the reliability of the converter employed. Based on the proposed analysis, it is deduced that the lower FOR of bidirectional converter used in the second plan yields in much better reliability of this plan. On the other hand, based on the simulation results, the battery has a significant impact on reliability. This model is able to determine the threshold ratio of DC load which make the second plan of the smart home more appropriate from both energy consumption optimization and reliability improvement points of view.

By performing sensitivity analysis on the PV and battery prices, we figured out that reducing the price of PV impact on the cost of energy directly, although in the lower price of PV the difference between the two plans is not too much because of increasing the capacity of PV and battery, in the long run, it increases profits. On the other hand, battery price impact on the total cost when its price is very low. Also, it can be seen the second plan is more affected by changing prices.

According to this study, without EV demand response the energy consumption cost increase, also in the high ratio of DC load, a more capacity battery is needed. In the first plan without EV demand response, reliability declined dramatically. On the other hand, the reliability of the second one depends on the DC load ratio. when the DC load is at the lower level, there is no need for the high level of battery; therefore, the reliability is reduced.

There were limitations in doing this work, the most important of which was the lack of complete and accurate information on household energy consumption and real data about FOR of bidirectional converter in the residential sectors. For the future research on top of this work, development and assessment of the proposed hybrid electrification concept to the level of large institutional buildings which are heavily loaded with DC devices and also to the level of a smart city can be studied.

Declaration of competing interest

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.

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