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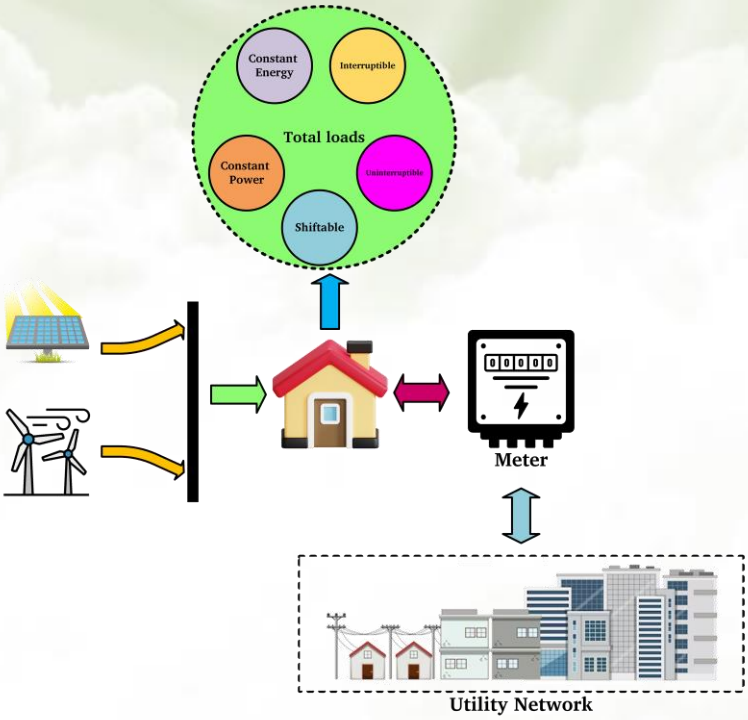
Utilizing Hybrid Sine Cosine Shuffled Frog Leaping Algorithm for Optimal Energy Management in the Residential building with Renewable Energy Resources and Corresponding Uncertainties

Behdad Arandian

Highlight

- Integration of WT and PV systems in residential building is modeled
- Different loading models are incorporated as load control program
- Both connected and island operation of residential building are considered
- Daily energy cost is minimized by using HSFL algorithm.
- Load control handles generation uncertainty of renewable energy resources

Graphical Abstract



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Utilizing Hybrid Sine Cosine Shuffled Frog Leaping Algorithm for Optimal Energy Management in the Residential building with Renewable Energy Resources and Corresponding Uncertainties

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ABSTRACT

In this study, optimal energy management is addressed in the residential building. The residential building is equipped with renewable energies including wind turbines (WT) and photovoltaic (PV) systems. Stochastic programming is used to model the uncertainty of renewable energy resources. To manage these uncertainties and reduce the total daily cost of energy, the load control program is adopted. In this respect, five different types of loads are modeled in the building, including interruptible, uninterruptible, constant-energy, constant-power and movable loads. The above charges are properly adjusted and shipped to minimize energy costs and address the uncertainties of renewable energy by hybrid sine cosine shuffled frog leaping algorithm. The residential building is considered as later active in the network, which transfers energy from network to the building and vice versa. The simulation results show that the proposed model can efficiently harness all the energy possible from WT-PV systems, manage uncertainties, minimize total daily costs and operate as an island. All of these objectives are achieved by optimal load distribution and control within the proposed load control program.

1. Introduction

The integration of energy resources is one of the interesting problems of electrical engineering and several types of energy resources have been modeled and studied for good integration [1]. In real networks, the grid is often equipped with different types of renewable and non-renewable energy, such as wind turbines, photovoltaic systems and hydropower systems as renewable energy sources, as well as micro-turbines, internal combustion engines (ICE), and the fuel cell (FC) as non-renewable energy resources. It is therefore useful to study the correlation and the cogeneration of these resources. This problem has been approached in different ways, for example by combining hydro, WT and PV [2, 3], WT and PV [4], WT and PV-thermal [5], MT, FC and ICE [6], PV-FC [7], and PV-thermal [8]. Studies show that such a correlation exerts a significant influence on the network and that it is necessary to take this element into account in the problem.

The correlation of renewable energy sources can also be studied in the problem of household energy management. This problem manages energy consumption in homes and the building. Domestic energy management has been well taken into account, including various renewable and non-renewable energy resources such as WT [9], PV [10, 11], geothermal biomass [12]. In addition, the management of domestic energy has been approached from different angles, such as reduction of emissions to the environment [6], operation and management of wireless networks [13], control analysis the load [14], the comfortable lifestyle [15] and electrical systems loading [8] and increasing of energy performance [16]. Energy storage systems are also useful technologies that can be used properly in energy management [6, 8].

Load control (demand response) is one of the preferred methods for managing energy exchange in buildings. Load control is a broad term that offers a variety of methods to improve the operation of the system by managing demand rather than generation [17, 18]. Loads and their models are one of the main components of load control. There are different types of loads, such as interruptible loads [19], constant power or power loads [20], and switchable loads [21]. Thus, the load control program, as a demand management method (DSM), optimally adjusts and modifies loads to meet loads, while minimizing total daily energy costs.

This study presents an optimization strategy aimed at minimizing the total daily energy cost in the residential building. Despite the fact that this building is equipped with WT and PV systems as an internal renewable energy source, it is connected to the distribution network. This means that the building can receive its energy from the internal generation system or the distribution network (network) and also sends its surplus energy to the grid. Such an operation can help the building to reduce energy costs because it can sell energy to the upstream network at high-cost periods. It is assumed that the building comprises five types of loads, namely interruptible load, constant power load, constant energy load, uninterrupted load, and load that can be moved. Optimization programming manages energy in the building subject to the correlation of WT and PV energy resources as well as the load control program such as the DSM. The uncertainty of the WT and PV generation systems is managed by proper charge control and the total daily cost of the energy is minimized. So, the contribution of this paper is complete model of various parts in the system with consideration of renewable energy uncertainties. Also new optimization algorithms are improved and applied on the system.

The rest of this study is organized as follows. Section 2 describes the proposed model. Section 3 discusses the mathematical modeling used in this study. Section 4 provides the data required for simulation studies. In Section 5, numerical results are given. Finally, Section 6 presents conclusions and recommendations for future work.

2. The Proposed Method

The schematic structure of the proposed model is shown in Figure 1. In spite of considering WT and PV systems as internal production units, the building is also connected to the distribution network (network).

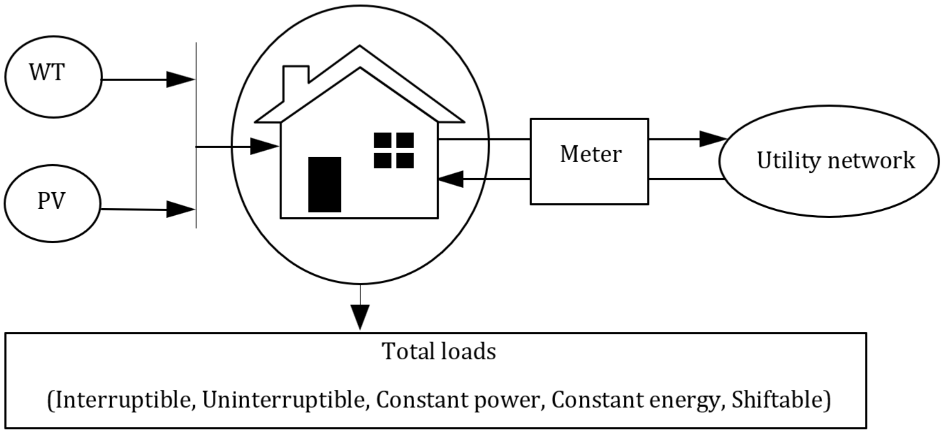


Figure 1. Schematic structure of the proposed model for energy management in building.

There is a counter between the building and the network to record the reception and sending energies. Energy management in the building is carried out by controlling loads and surplus produced energy can be send to the grid and make profits at the right time of the operation horizon. There are five different types of loads in the building and the plan can properly adjust the loads to manage energy and minimize the total daily energy cost in the building.

3. Mathematical Modeling

3.1. Optimization Programming

The energy management tool given in the residential building minimizes the total daily cost of energy in the building, as defined by Equation (1) as an objective function. It calculates the expected value of the cost in all the performance scenarios related to the uncertainty of the WT and PV generation systems. It should be noted that the probability of each scenario is less than one and the sum of all probabilities is equal to one, as indicated by the Equations (2) and (3).

$$TC = \sum_{s=1}^{N} \sum_{t=1}^{24} (P_{UN.st} \times \rho_s \times \alpha_t) \tag{1}$$

$$0 \leq \rho_s \leq 1 \tag{2}$$

$$\sum_{s=1}^{N} \rho_s = 1 \tag{3}$$

The energy exchange between the building and the distribution network is calculated by the Equation (4). The load is a positive variable Equation (5) and is modeled by five different load types, including loads 1 to 5 Equation (6), which are modeled and described in subsections 3.2 to 3.6 The building can send power to the grid or receive power from the grid. If this calculated power is negative, the building sends electrical energy to the grid, otherwise the network sends electrical energy to the building.

As a result, the exchange power between the building and the grid can be positive or negative, as shown in Equation (7). However, the line capacity between the building and the network limits this exchange power, as indicated by the Equation (8).

$$P_{UN.st} = P_{load,t} - P_{PV,st} - P_{WT,st} \tag{4}$$

$$P_{load,t} \geq 0 \tag{5}$$

$$P_{load,t} = P_{load1,t} + P_{load2,t} + P_{load3,t} + P_{load4,t} + P_{load5,t} \tag{6}$$

$$-\infty \leq P_{UN.st} \leq +\infty \tag{7}$$

$$|P_{UN.st}| \leq P_{line.max} \tag{8}$$

3.2. Interruptible Load

One of the load types in this study is interruptible loads. The energy consumed by interruptible loads is not required to be continued. This type of loads can consume energy at different times with several start and stop commands. Such operation can be defined for certain devices such as electric motors. Load 1 is an interruptible load and it is a positive variable, as the Equation (9) shows. A binary variable is defined as Equation (10) and it is fixed as Equation (11). Then, the load profile of the interruptible load is modeled by Equation (12).

$$P_{load1,t} \geq 0 \tag{9}$$

$$B_{load1,t} \in \{0,1\} \tag{10}$$

$$\sum_{t=1}^{24} B_{load1,t} = NL1 \tag{11}$$

$$P_{load1,t} = B_{load1,t} \times P_{load1,rated} \tag{12}$$

3.3. Constant Energy Load

Another load types considered in this study is constant energy loads. This load type uses fixed energy level during the day, regardless of the operating time. Such a procedure can be considered as operation of billable devices. They can be loaded at intermittent intervals with different powers. Charge 2 is a constant energy charge and it is a positive variable, as the Equation (13) shows. The energy of the load is defined in Equation (14) and its power is limited by Equation (15).

$$P_{load2,t} \geq 0 \tag{13}$$

$$\sum_{t=1}^{24} P_{load2,t} \times t = EL2 \tag{14}$$

$$P_{load2,t} \leq P_{load2,rated} \tag{15}$$

3.4. Constant Power Load

Constant power loads follow a constant profile during the hours of the day, such as lighting demand. Load 3 is a constant power load and it is a positive variable, as the Equation (16) shows. The constant charge is defined by Equation (17).

$$P_{load3,t} \geq 0 \tag{16}$$

$$\sum_{t=1}^{24} P_{load3,t} = P_{load3,rated} \tag{17}$$

3.5. Uninterrupted Load

Some loads must have consecutive and uninterrupted operation such as the washing machine. This means that the operation of these devices cannot be interrupted before the end of their work. Load 4 is modeled as a load with a consecutive operation. It is a positive variable like Equation (18). A binary variable is defined as Equation (19) and the uninterrupted operation is modeled by Equation (20). The loading profile for this load is modeled by Equation (21).

$$P_{load4,t} \geq 0 \tag{18}$$

$$B_{load4,t} \in \{0,1\} \tag{19}$$

$$\sum_{t=i}^{i+NL4} B_{load4,t} = NL4 \tag{20}$$

$$P_{load4,t} = B_{load4,t} \times P_{load4,rated} \tag{21}$$

3.6. Shiftable Load

The usage time of certain charges can be changed during the day. This means that the operation of these devices is not limited to specific hours. Load 5 is modeled as a load with varying duty cycle as movable loads. It is a positive variable like Equation (22). A binary variable with a maximum limitation is defined as Equation (23) and the load profile for this load is modeled by Equation (24).

$$P_{load5,t} \geq 0 \tag{22}$$

$$B_{load5,t} \in \{0,1\} \tag{23}$$

$$P_{load4,t} = B_{load5,t} \times P_{load5,rated} \tag{24}$$

4. Data and Setting of Problem

Figure 1 shows the schematic structure of the residential building. A photovoltaic system of 20 kW WT and one of 20 kW are installed for this building [2]. The electric powers produced by the WT and PV systems are illustrated in Figures 2 and 3, respectively [2]. The nominal power of the load 1 since the interrupted load is 20 kW, it must work 8 hours a day. The nominal energy of the load 2 being constant, it is 50 kWh and its nominal power of 5 kW [4]. The nominal power of the load 3 with a constant load power is 25 kW and its load profile is given in Figure 4 [4]. Since the nominal power of the load 4 is a continuous load of 15 kW, it must operate for 6 consecutive hours per day [4]. It is assumed that 90% of the total load is considered a load that can be moved (load 5). The line capacity between the network and the building is 42 kW. The price of electric energy is changed throughout the day and three levels are taken into account, as shown in Figure 5 [20].

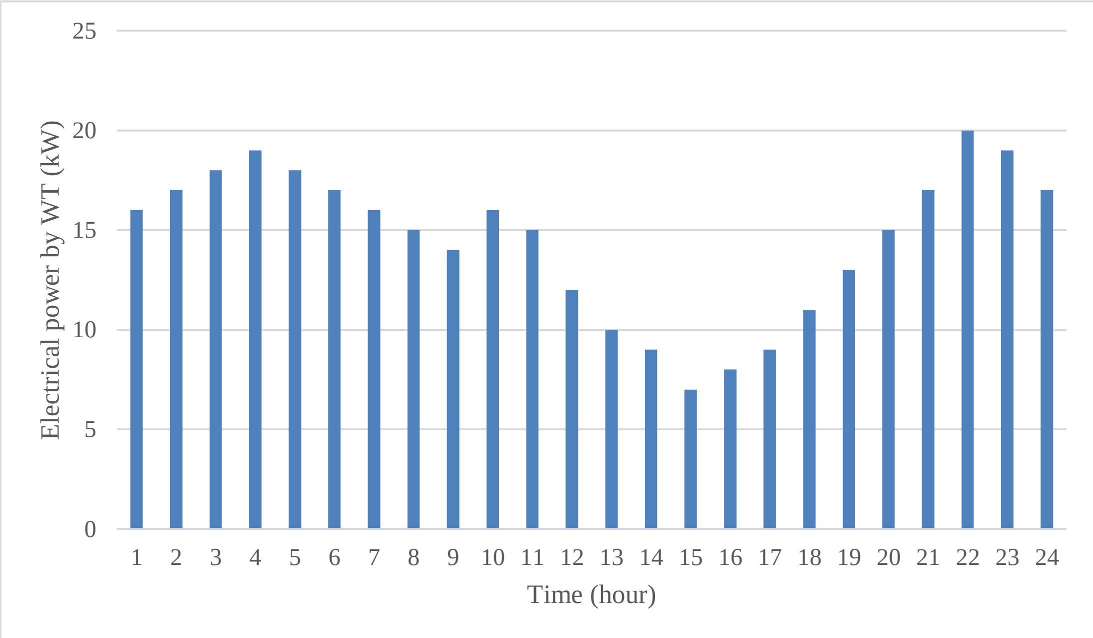


Figure 2. Electrical power by WT [2].

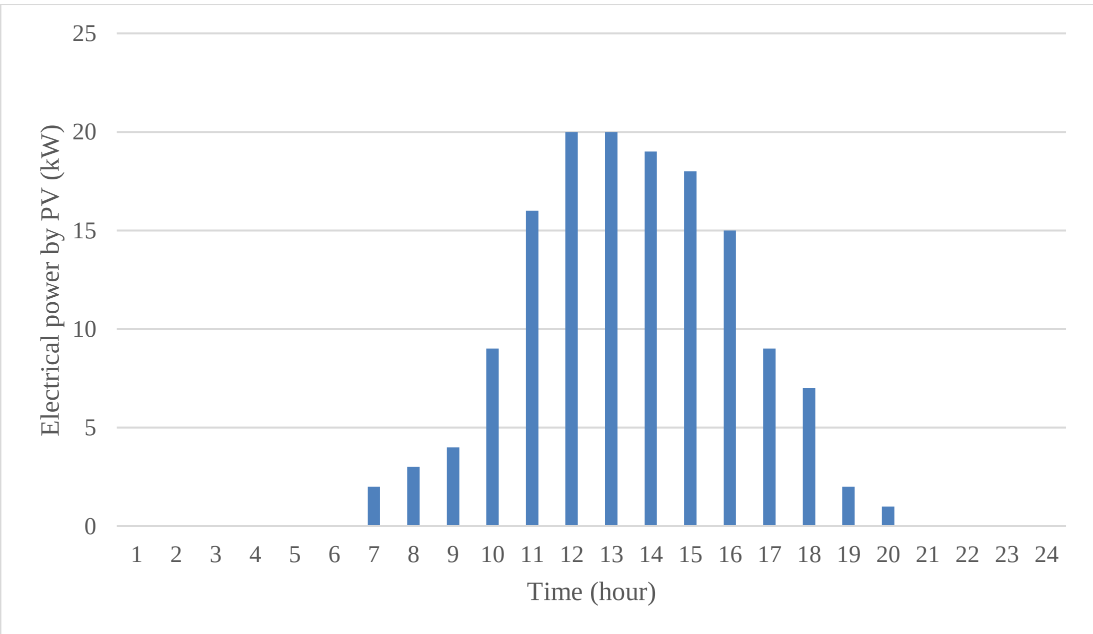


Figure 3. Electrical power by PV [2].

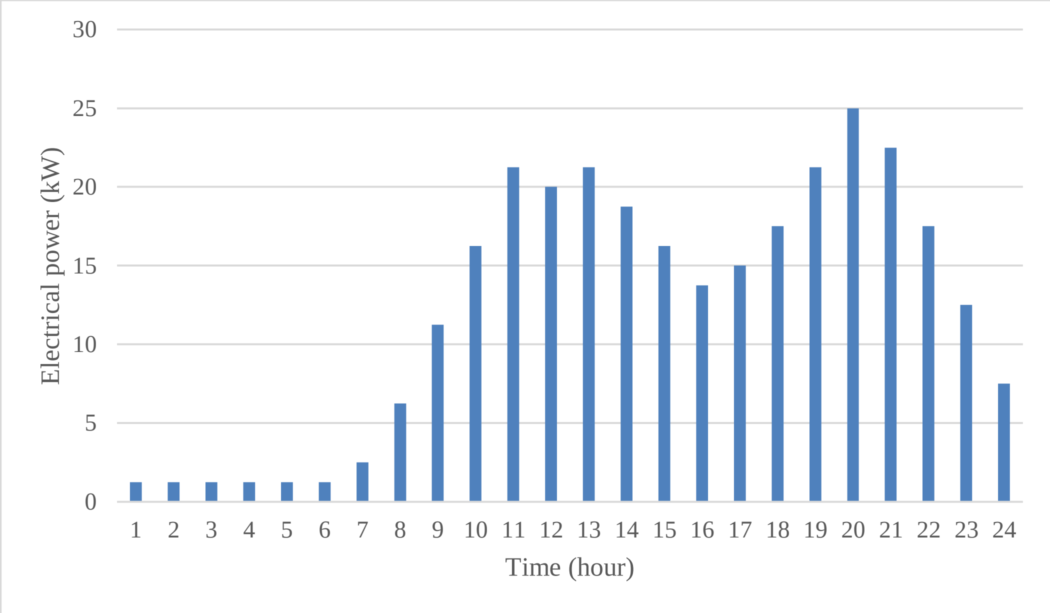


Figure 4. Daily load profile for Load 3 [2].

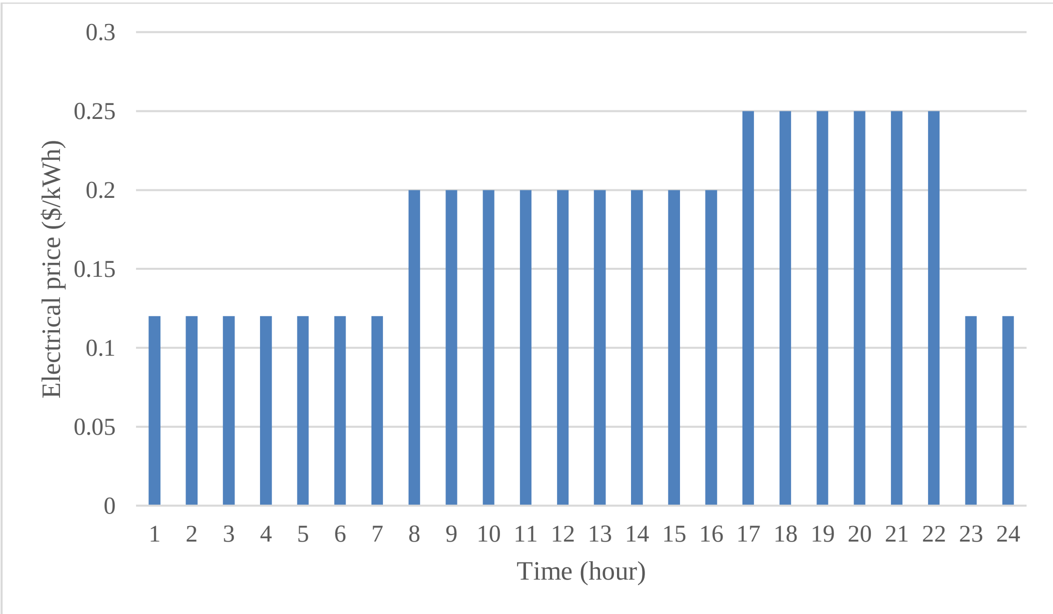


Figure 5. Daily electrical price [20].

5. Numerical Results

The introduced model is simulated on the given residential building by using hybrid sine cosine shuffled frog leaping algorithm (HSC-SFLA) based on hybrid shuffled frog leaping algorithm (HSFLA) [8] and sine cosine algorithm (SCA) [22]. In the first step, Table 1 presents the energy cost of residential buildings with and without renewable resources. The use of the WT system and the PV system reduces the energy cost from 98,687 ($ / day) to 7,607 ($ / day), which is a reduction of 91.08 ($ / day). The proposed model can correctly exploit all the possible energy of the WT and PV systems and manage the energy via the given load control program. Such an operation reduces the energy costs specified below by 92.29%.

The electrical energy exchanged between the building and the network is illustrated in Figure 6 for two cases with and without renewable resources. The building receives total energy from the grid when renewable resources are not installed. On the other hand, when the renewable resources are connected, the profile of the electrical energy is considerably changed. The plan exploits all the energy of the WT and PV systems to minimize energy costs. In addition, planning sends energy to the grid at costly times, such as 8 to 18 hours, reducing the building's energy costs. The results verify that energy is received from the grid for low-cost periods and that surplus energy is sent to the distribution grid at high-cost periods.

The results of the load control program are listed in Table 2. The optimal programming of the distribution of the five loads is obtained and listed below. Load 1 is an interruptible load and there are some interruptions in the operation. Planning runs the load in low-cost hours to minimize operational costs. The load 2 is the constant energy load and its operation is optimized, while the required energy (50 kWh) is reached. Load 3 is a constant power load and follows its defined pattern. Charging 4 to 6 hours of consecutive operation and is powered by scheduling in the low-cost hours. Load 5 is the specified percentage of each load type, as explained in Section 4. Planning optimizes the distribution of all loads to minimize the total energy cost of the building and to optimize the use of energy resources renewable.

Table 1. Energy cost for residential building with and without renewable resources.

	With WT-PV	**Without WT-PV**
Total daily cost ($)	98.687	7.607

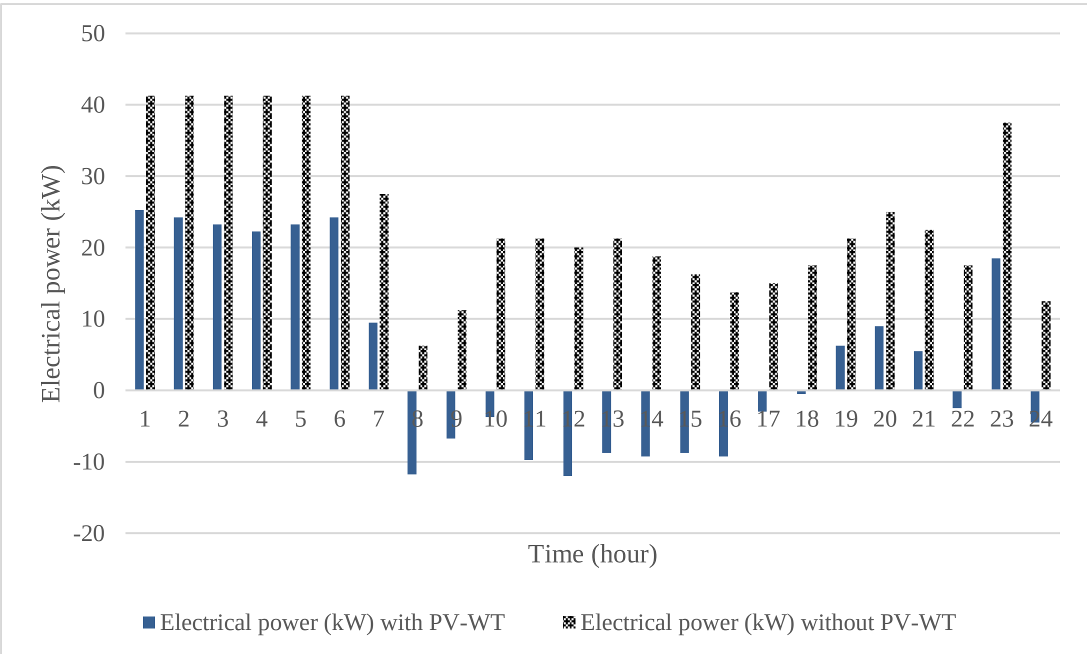


Figure 6. Exchanged electrical power between building and utility network with and without renewable resources.

Table 2. Optimal daily load control.

Time (hour)	Load 1 (kW)	Load 2 (kW)	Load 3 (kW)	Load 4 (kW)	Load 5 (kW)
1	20	5	1.250	15	37.125
2	20	5	1.250	15	37.125
3	20	5	1.250	15	37.125
4	20	5	1.250	15	37.125
5	20	5	1.250	15	37.125
6	20	5	1.250	15	37.125
7	20	5	2.500	0	24.75
8	0	0	6.250	0	5.625
9	0	0	11.25	0	10.125
10	0	5	16.25	0	19.125
11	0	0	21.25	0	19.125
12	0	0	20.00	0	18
13	0	0	21.25	0	19.125
14	0	0	18.75	0	16.875
15	0	0	16.25	0	14.625
16	0	0	13.75	0	12.375
17	0	0	15.00	0	13.5
18	0	0	17.50	0	15.75
19	0	0	21.25	0	19.125
20	0	0	25.00	0	22.5
21	0	0	22.50	0	20.25
22	0	0	17.50	0	15.75
23	20	5	12.50	0	33.75
24	0	5	7.500	0	11.25

5.1. Line Capacity Analysis

The line capacity between the distribution network and the building plays a significant role. To analyze this role, two cases with a line capacity of 42 kW as case A and a line capacity of 32 kW as case B are simulated and discussed. The results for these two cases are shown in Table 3. It shows that the decrease in line capacity increases the total energy cost by 51.68%. The electrical energy exchanged between the building and the distribution network is illustrated in Figure 7 in two cases. Comparing Figures 6 and 7, the decreasing line capacity forces the building to receive power from the utility network at expensive times such as periods 8, 9, 10, 15, 16, 18, resulting in an increase in energy costs of the building. On the other hand, a larger line capacity allows the building to provide its energy at low-cost times. Not only does the building not receive grid energy at the costly times mentioned, but it also sends energy to the upstream grid and generates profits. Table 4 summarizes the optimal load distribution in case B. The interruptible operation of the load 1 is optimized. The energy required for the load 2 is also satisfied while its operation is optimized. The load 3 follows its constant pattern and the load 4 displays 6 consecutive hours of operation. The charge 5 is offsets that can be shifted. It should be noted that the optimal load distribution in Case A is presented earlier in Table 2.

Table 3. Energy cost under different line capacities.

	Case A	Case B
Total daily cost ($)	7.607	15.743

Table 4. Optimal daily load control for Case B.

Time(hour)	Load 1 (kW)	Load 2(kW)	Load 3(kW)	Load 4 (kW)	Load 5(kW)
1	0	5	1.25	15	19.125
2	0	5	1.25	15	19.125
3	0	5	1.25	15	19.125
4	0	5	1.25	15	19.125
5	0	5	1.25	15	19.125
6	0	5	1.25	15	19.125
7	20	5	2.5	0	24.75
8	20	5	6.25	0	28.125
9	20	0.95	11.25	0	28.98
10	20	0.75	16.25	0	33.3
11	0	0	21.25	0	19.125
12	0	0	20	0	18
13	0	0	21.25	0	19.125
14	0	0	18.75	0	16.875
15	20	0	16.25	0	32.625
16	20	0	13.75	0	30.375
17	0	0	15	0	13.5
18	0	0	17.5	0	15.75
19	0	0	21.25	0	19.125
20	0	0	25	0	22.5
21	0	0	22.5	0	20.25
22	0	0	17.5	0	15.75
23	20	3.3	12.5	0	32.22
24	20	5	7.5	0	29.25

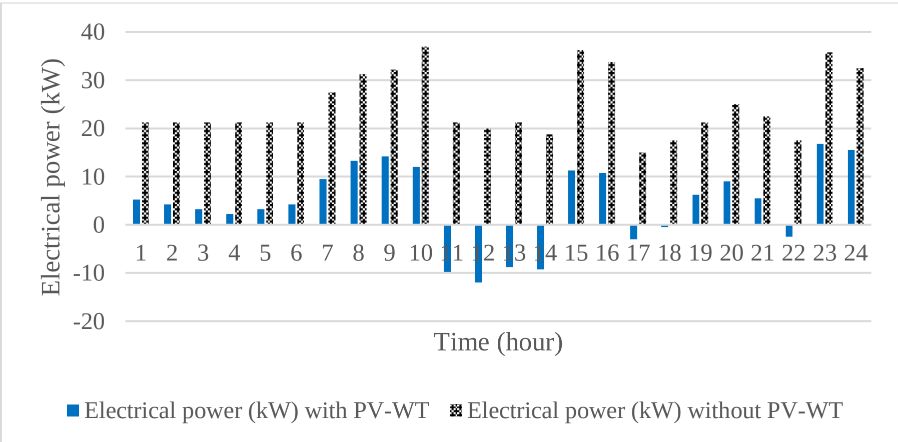


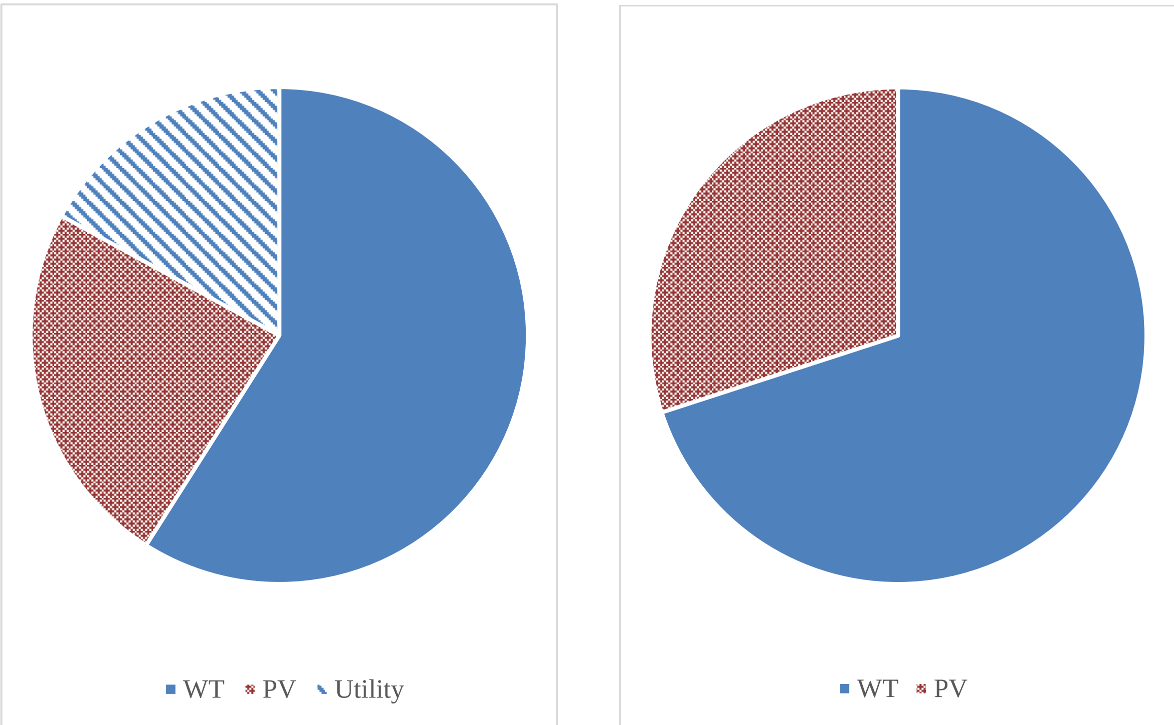
Figure 7. Exchanged electrical power between building and utility network under different line capacities.

5.2. Uncertainty Analysis and Island Operation

During planning, the uncertainties associated with the WT and PV systems are managed by the proposed load control program. The charges are correctly adjusted by the program to deal with such uncertainty. The results of the simulation show that the total cost of energy is $ 7,607 and $ 3,295 per day, with and without uncertainty about renewable energy, respectively.

The grid with renewable energy uncertainty has to manage this uncertainty through a load control program, which increases the energy cost. On the other hand, when renewable energy uncertainty is not included, the charges are not adjusted to manage the uncertainty of renewable energies, but they are to minimize the total cost of energy. As a result, the energy cost is reduced beyond the level reached by the case, including the uncertainty related to renewable energies.

The island operation of the building requires more WT and PV systems. Thus, the WT and PV systems have gone from 20 kW to 24 kW and 25 kW, respectively. Figure 8 shows the energy of the building in connected and island operations. In connected mode, most of the energy is provided by the WT and PV systems and a small part comes from the distribution network. In island mode, WT and PV respectively provide 70% and 30% of the charges. It should be noted that the total daily operating cost of an island is increased by 62%.



A: Connected operation **B**: Island operation

Figure 8. Energy of building under connected and island operations.

6. Conclusions

This document presents optimal energy management in the residential building, including different types of loads. Five types of loads, including interruptible, constant energy, constant power, uninterruptible and switchable loads, are modeled. The building is also equipped with renewable energy sources, including WT and PV systems. The building is connected to the distribution network and the electrical energy is exchanged between the building and the distribution network.

The simulation results show that the renewable energy assembly reduces the energy cost from 98.687 ($ / day) to 7.607 ($ / day), which represents a reduction of about 92.29%. The building without renewable energy must receive its energy from the grid, while the building with renewable resources uses all the energy of the WT and PV systems and even sends energy to the utility network at expensive hours such as hours. 8-18. The load control program successfully adjusts all building loads to minimize the total daily cost of energy, as well as the uncertainties associated with the management of renewable energy resources.

The results show that the reduction of the capacity of the line between network and building from 42 kW to 32 kW increases the cost by 51.68%. Under such conditions (limited line capacity), the building must be supplied with power by the utility network at expensive times, such as time periods 8,9,10,15,16,18, resulting in an increase in the building's daily energy costs to meet the costs.

The impact of renewable energy uncertainty on the cost of energy is also studied and it is shown that neglecting this uncertainty reduces the cost by about 56%, because the charges are adjusted only to minimize the total cost of energy. energy. Finally, it is shown that building island operation requires more WT and PV systems to meet the loads, and that connected operation reduces the total energy cost by 62% compared to island operation. For future work, it is recommended to use different types of renewable and non-renewable energy resources.

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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. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Behdad Arandian: Conceptualization, Formal analysis, Project administration, Supervision, Validation, Roles/Writing - original draft, Investigation, Methodology, Resources, Visualization, Writing - review & editing.

Bibliography

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