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Article

Assessment of impacts of peak-shaving programs on energy costs in the residential sector

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ABSTRACT

Demand-side management, which includes various methods and mechanisms, plays a significant role in the management of energy systems. This paper examines the impacts of different demand-side management methods on energy costs of a residential load. In this regard, three scenarios have been developed: on-site energy generation, energy storage, and finally, load shifting during peak hours of energy consumption. The three proposed scenarios along with the basic state, were modeled with the help of the System Advisor Model and MATLAB. The modeling results showed that according to the load management process during the peak hours of the year, all three scenarios lead to a reduction in energy consumption costs.

1. Introduction

Within the last two decades, the increase in world population, as well as technological developments all around the world, have led to an increase in energy consumption. This has caused problems, including depletion of energy sources and environmental pollution due to the energy production process. For the solution of these basic energy issues, traditional grids are being transformed into smart grids (SG). In this regard, one of the research areas in smart grids is demand-side management (DSM) [1]. According to the International Energy Report Agency (IEA), in 2019, the total electricity consumption in the world was equal to 25072.3 terawatt hours [2]. Using energy-saving technologies, electricity tariffs, monetary incentives, and government policies to reduce peak demand rather than increase generation is the focus of demand-side management [3]. Demand response (DR) is one of the DSM measures that has been promoted in different countries since the 1970s [4]. DR is defined as:"a change in electricity consumption by demand-side sources relative to their normal consumption pattern, in response to changes in electricity prices or incentive payments created to encourage less electricity consumption during times of high electricity prices." [5]. Among the main benefits of demand response programs reduction of electricity costs, elimination of transmission line congestion, and increase in grid reliability can be mentioned [6]. Various solutions have been proposed for the implementation of demand-side management [7]. A DSM strategy can be used for different purposes, such as peak shaving, valley filling, load shifting, energy conservation, and strategic load growth [8]. The residential sector plays a very important role in the smart grid and is one of the main contributors to the energy balance of countries [9]. Among all energy-consuming sectors, buildings account for a considerable share; for instance, about 40% of total energy in the US and Europe [10]. In addition, several studies have been conducted on the application of DR and DSM in the residential sector. For example, Ogunjuyigbe et al. [11] proposed a demand-side load management method that was able to manage loads of a residential building in such a way as to reach the maximum level of satisfaction with the lowest cost. Also, Gruber et al. [12] suggested and expanded a model to produce a residential energy consumption profile based on the energy demand contribution of each home appliance using a probabilistic approach. This model offered a highly modular structure that allows for a high degree of flexibility. Lanlan Li et al. [13] proposed a multi-factor simulation model to analyze the efficiency of time-of-use (TOU) pricing of natural gas for refined peak residential consumers. This showed the sensitivity function of the natural gas price according to the gas consumption characteristics of residential users. Their simulation results showed that according to the response of residential users to TOU tariffs, the maximum peak-valley load difference could be reduced by 11.12% by load shifting and electricity substitution. Tul de Salis et al. [14] proposed an adaptive control method to apply "peak shaving" to the grid electricity demand of a building, using a battery energy storage system to reduce the peak demand. The goal was to save money by reducing "demand costs". Yousefi et al. [15] have investigated the technical-economic feasibility of a residential PV system with two pricing methods. The results showed that the tiered pricing method has better economic efficiency than the flat pricing method, where net present value and payback time have relatively better values. Xiongwen Zhang et al. [16] studied the technical and economic evaluation of solar power system installation in residential buildings. Finally, it has been found that using solar electricity in residential buildings can save up to 77% of electricity costs for household customers.

Zhuang Zhao et al. [17] first introduce a general architecture of an energy management system (EMS) in a home area network (HAN) based on a smart grid and then propose an efficient scheduling method for household electricity consumption. Yanxue Li et al. [18] simulated the techno-economic performances of the grid-connected residential PV-battery system based on simulated PV generations, history of household load, technical and economic parameters under the electricity market in Kyushu, Japan. Results indicated that residential PV self-consumption ratios vary significantly between months; it can increase by adding relative battery size, the increasing rate shows obvious variations between months, and its value highly depends on features of the customer load and PV generation profiles. Optimal management strategies for private home storage dispatch showed potential in grid peak load shaving. Jankowiak et al. [19] Introduced a metric of five indexes to evaluate the technical performances of load peak shaving. This metric is applied to a case study based on a photovoltaic and battery system application for a test house in Northern Ireland, whose electricity demand is representative of the average UK demand profile. Two peak shaving strategies are compared with a more usual self-consumption mode, and the impact of the battery size is evaluated. Peak-shaving management strategies showed promising performance by reducing peaks by more than 98%, while still decreasing the yearly consumption by 15%, and avoiding 75% of the photovoltaic-generated energy from being exported back to the grid. In this paper, the topic of residential electricity consumption management is discussed. In this regard, considering different scenarios, the effectiveness of each DSM method is examined. The methodology of the research, including case study and scenarios details, are presented in Section 2. The results are presented and discussed in Section 3. The conclusion of the research is provided in Section 4.

2. Methodology

As mentioned, there are numerous solutions to manage energy consumption and improve consumer energy peak. In this research, the issue of managing the electricity consumption of residential consumers is discussed. In this regard, considering different scenarios, the effectiveness of each scenario will be assessed. System Advisor Model (SAM) and MATLAB software are used for modeling and analysis of the scenarios.

2.1 Case of study

A typical residential load is considered as the case study. Figure 1 shows the load profile of this residential house. The total energy consumption of this residential building is estimated to be around 10830 kilowatt hours and its peak load is around 4.3 kilowatts. This is illustrated in Figure 2 as a heat map. As seen in Figures 1 and 2, the peak load occurs in the months of June to September and from 14:00 to 21:00.

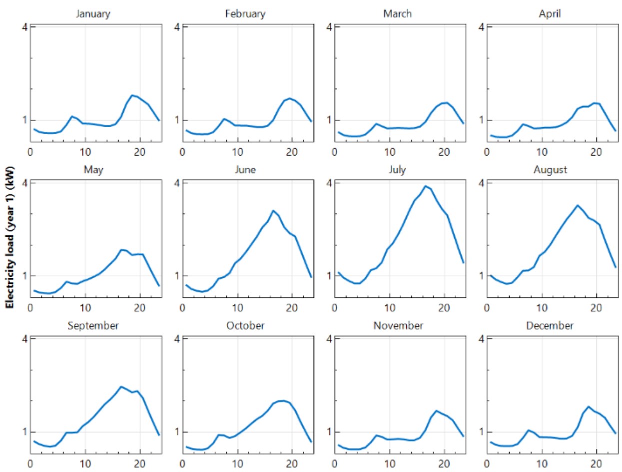

Figure 1. Electric load profile of the residential building

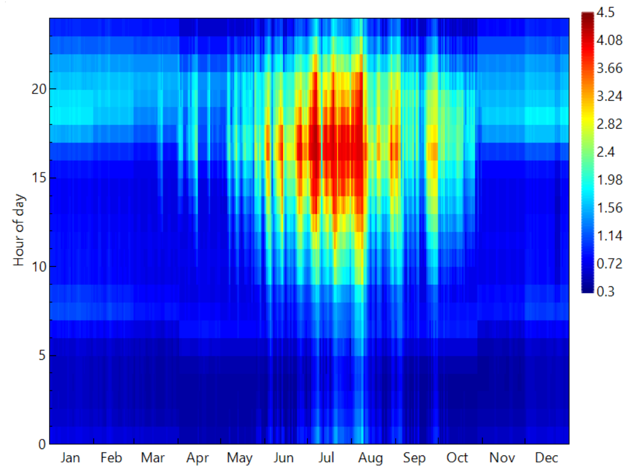

Figure 2. Annual heat map of the building load

2.2 Scenario development

In order to assess the impact of DSM programs on the energy costs of the building, four different scenarios have been considered in this research:

- Scenario S1: Base scenario; Building load supply by the grid.
- Scenario S2: Supplying the load of the building by the grid and a gasoline generator and using it for peak-shaving.
- Scenario S3: supplying the load of the building by the grid and battery and using it for peak-shaving.
- Scenario S4: Using load shifting to manage peak load.

2.2.1 Base case (scenario S1)

In this scenario, which is considered the base case, the building load is fully supplied by the grid. The tiered Time-o-Use tariff of the electricity network is presented in Table 1. According to the calculations in the SAM software, the rates are in dollars (with an exchange rate of 1 dollar = 300,000 IRR). One of the most common demand response programs has been the use of the time-of-use (TOU) tariff system, which is included in the category of price-based methods. Figure 3 shows the details of the TOU tariff considered in this paper.

Table 1. National grid electricity tariff

Consumption level (kWh)	Normal	Off-peak	Peak
100	0.00312	0.0026	0.003744
200	0.0036	0.003	0.00432
300	0.00768	0.0064	0.009216
400	0.01392	0.0116	0.016704
500	0.01596	0.0133	0.019152
600	0.0204	0.017	0.02448
> 600	0.0222	0.0185	0.02664

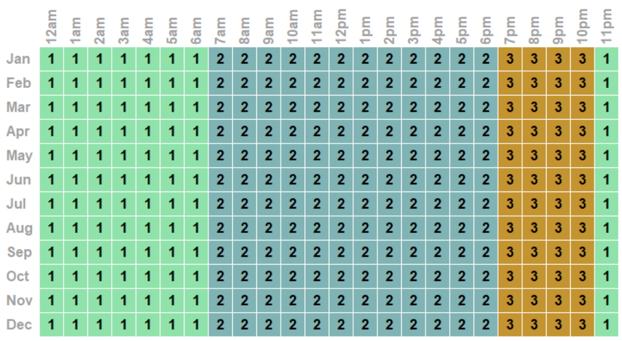

Figure 3. TOU tariff system; 1) off-peak, 2) normal, 3) peak

2.2.2 On-site power generation (scenario S2)

In this scenario, a small HGPG-5360 gasoline-burning generator will be used for peak-shaving. This generator will supply electricity to the building during peak hours throughout the year. The initial cost of providing this system is considered about $0.25/W, and its total cost is about $756. The annual conservation and repair cost is also $10/kW-year. The generator operation strategy is applied according to Equation 1.

$$P_{gen}(i) = \begin{cases} 0 & P_{load}(i) < 2 \\ 2.5 & P_{load}(i) \geq 2 \end{cases} \tag{1}$$

Where P is the power in kW, i is the calculation time step in hours, and gen and load are generator and load symbols, respectively.

2.2.3 Energy storage (scenario S3)

In this case, it is recommended to use the battery for peak shaving. In this regard, a storage system is considered for the building. A 6000V (4.8kW) battery pack with a cost of $280/kW DC was included in the modeling. There are two methods for planning the battery performance, which are mentioned as follows.

I. Peak shaving with forecast for the next day

In this mode, for each day, the battery is controlled based on the load profile data over the next 24 hours. The look-ahead mode provides perfect load prediction as the battery performance control (charge and discharge) is adjusted simultaneously with the building load.

II. Peak shaving with price signal prediction

The price signal prediction option uses the battery to minimize the electricity bill based on a price estimate that shows the cost to the consumer to buy electricity from the grid every hour. For this mode, battery performance control depends on the following:

- 24-hour forward-looking forecast of building load. This case is a complete prediction because the used algorithm uses the output data and the building load obtained from the simulation results for prediction.
- Energy and demand rates (flat (fixed), time of use (TOU) or) tiered()
- Battery charging mode and available capacity
- Loss of battery performance
- Battery replacement cost in the future

2.2.4 Load shifting (scenario S4)

In this case, the existing technologies are not used to perform peak shaving, but this is done with consumption management methods. Figure 4 shows different modes of load management. In this scenario of the paper, by using an algorithm, the current load of the building is managed, and load shifting and load reduction mechanisms are applied. After that, the obtained load pattern is modeled under the conditions of the basic scenario (power supply through the power grid), and the results are analyzed. Figure 5 shows the flowchart of this algorithm. Based on this algorithm, the corresponding code was implemented in the MATLAB environment. The first step in implementing the load management algorithm is to determine the upper limit of the power consumption. For this purpose, the power curve should be analyzed before implementing the algorithm. Figure 6 shows the curve of the probability density function (PDF) and cumulative density function (CDF) of building load throughout the year. As can be seen in Figure 6, most of the load of the building is in the range of less than 2.5 kW during the year, and the histogram diagram is the most frequent in these points. Loads greater than 2.5 kW are much less frequent throughout the year, and the CDF curve for the value of 2.5 and above, becomes almost saturated. Hence, this value is considered the basis of the calculation of the load management algorithm and the upper limit of the permitted power of the building.

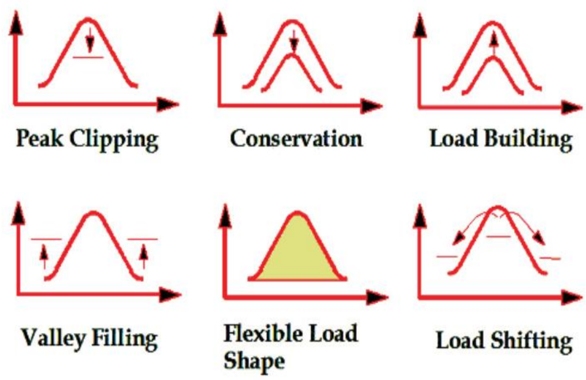

Figure 4. Different mechanisms for load management

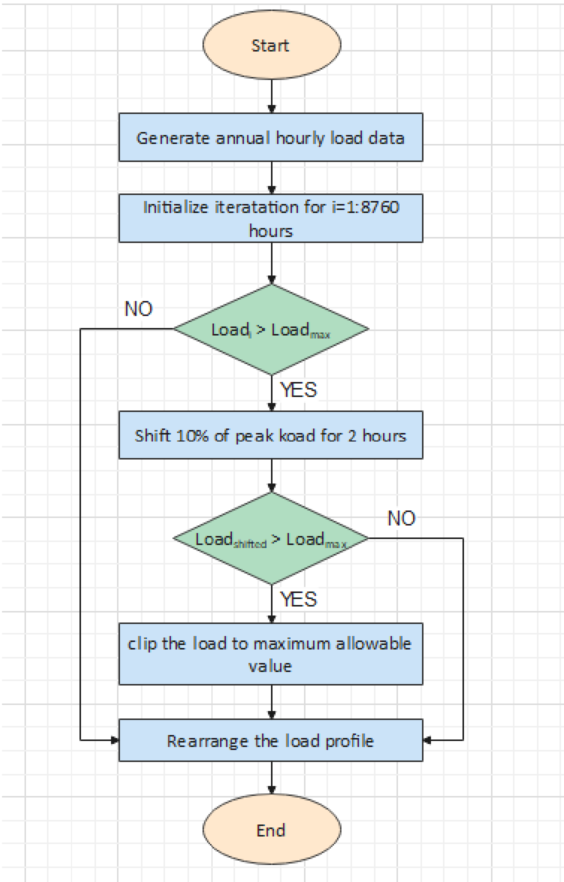

Figure 5. Flow chart of load shifting and load reduction step

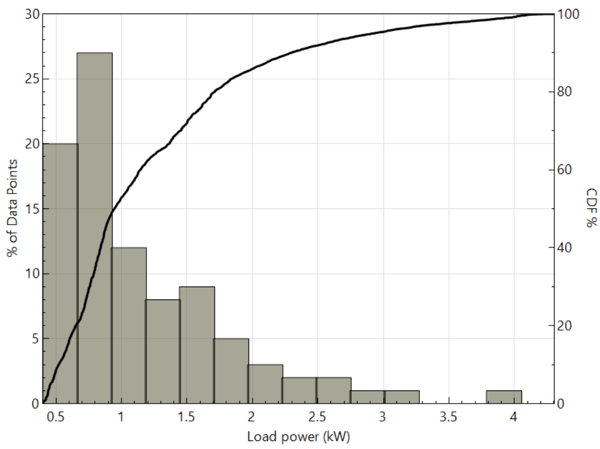

Figure 6. Graph of PDF and CDF functions of the load before the implementation of the load management algorithm

3. Results and Discussion

3.1 Scenario S1

The amount of electricity cost paid in a year is considered an important indicator for comparing different situations. After doing the modeling in this case, the cost of electricity for the whole year of the building is equal to 986 dollars. Figure 7 shows the cost of payment during 12 months of the year. As it can be seen, with the intensity of consumption in the middle months of the year, the amount of payment will increase accordingly.

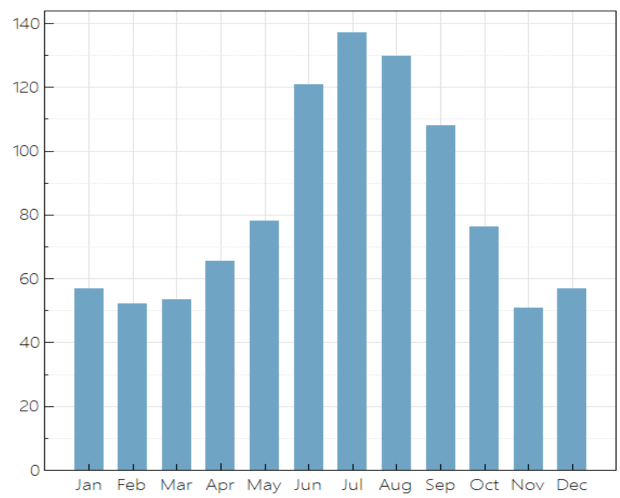

Figure 7. Amount of monthly electricity bill paid in scenario S1

3.2 Scenario S2

After performing the calculations, the performance of the system is obtained in this mode. Figure 8 shows the annual generator production heat map. As it is clear from the Figure 8, the main generation time of the generator is from May to October, mainly between 10 and 22. In this scenario, the annual energy cost is calculated to be $676, which is an improvement compared to the base scenario. The 12-month load profile of the building can be seen in Figure 9, along with the amount of generator production. As it is clear in this figure, in the middle months of the year, which often have peaks, the role of the generator of electricity production is evident. Also, Figure 10 shows the monthly energy cost of the building. As it happens, the cost is significantly reduced in the months and hours the generator is used.

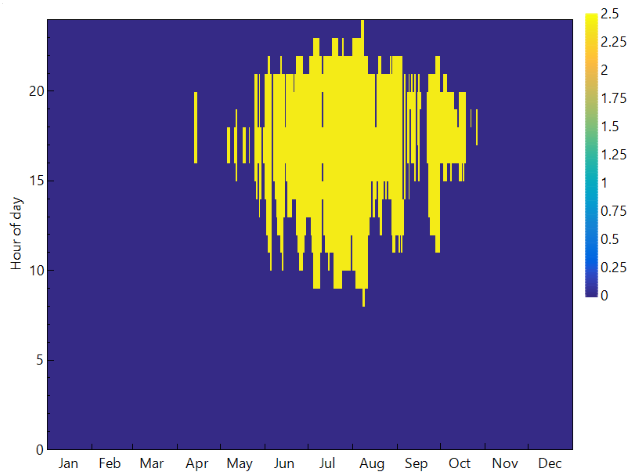

Figure 8. Heat map of generator power production in the second scenario

3.3 Scenario S3

It can be seen that in the first case of scenario S3, namely peak shaving with forecast for the next day, the amount of energy cost of the building is significantly reduced and reaches 167 dollars per year. This is because, according to the adopted strategy, the battery is charged during off-peak hours and supplies the load during peak hours, saving energy costs. Figure 11 shows the amount of battery energy transactions during the year. As can be seen in this figure, the maximum amount of battery charging occurs in the early hours (and to some extent at the end) of the day, and energy is delivered to the load in the middle hours. This issue is clearly intensified in the middle months of the year. In order to better understand and check the performance of the system in peak shaving, the 24-hour profile chart is analyzed for 12 months of the year. Figure 12 shows this diagram. As can be seen, the battery is optimally charged by the grid during off-peak hours and delivers this energy to the building during peak hours. This clearly leads to the reduction of costs caused by electricity consumption during peak hours and also reduces the pressure on the grid. Figure 13 shows the heat map of battery energy exchange throughout the year for the second case of scenario S3, peak shaving with price signal prediction. As can be seen in the figure, in this strategy, the impact of the battery is focused on the middle months of the year, and it has not performed much in the months with low consumption, so the battery system is operating from the beginning of June to the beginning of October and is almost unused in other months. In this case, the 24-hour profile for 12 months of the year is reviewed. As can be seen in Figure 14, the main performance of the battery peak, in this case, occurs in July and August.

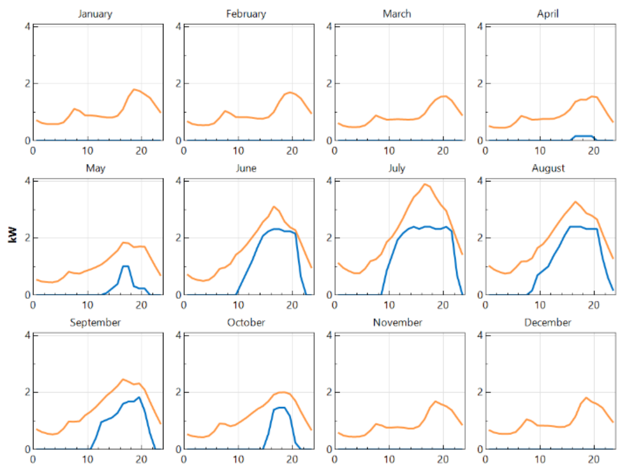

Figure 9. Load profile (orange) versus generator output (blue)

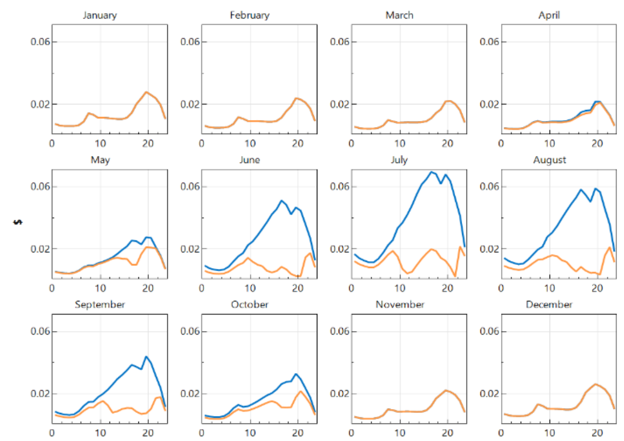

Figure 10. Monthly electricity; base mode (blue); with generator (orange)

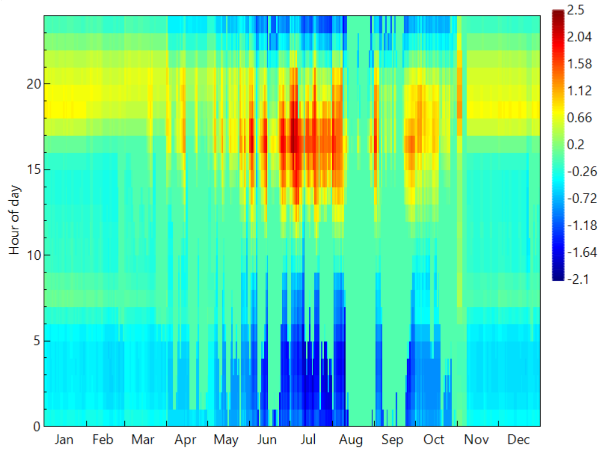

Figure 11. Battery energy transaction with grid and load during the year (peak shaving with forecast for the next day)

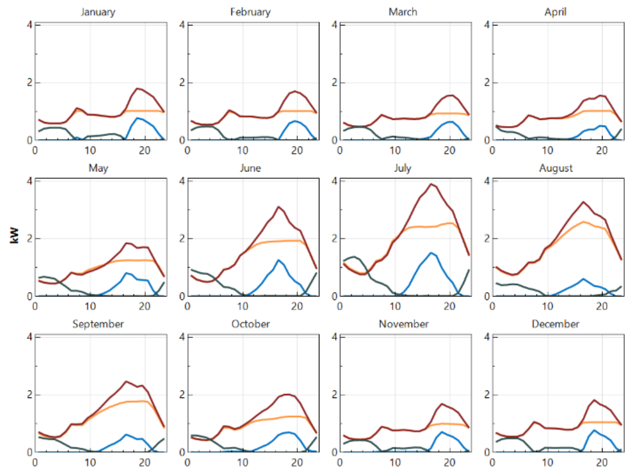

Figure 12. 12-month profile of load (red), power received from the grid (orange), power received from the battery (blue), and power from the network to the battery (dark blue)

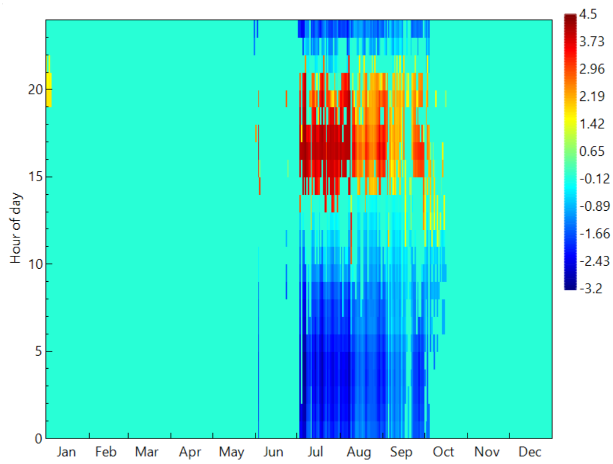

Figure 13. Battery energy transaction with grid and load during the year (peak shaving with price signal prediction)

Table 2. Statistical characteristics of the load curve before and after applying load management

	Average daily consumption	Standard deviation	Total annual consumption	Maximum	Minimum	Average
Before load management	0.5363	0.7681	10830	4.3045	0.401	1.2362
After load management	0.5363	0.6495	10468	2.5	0.401	1.195

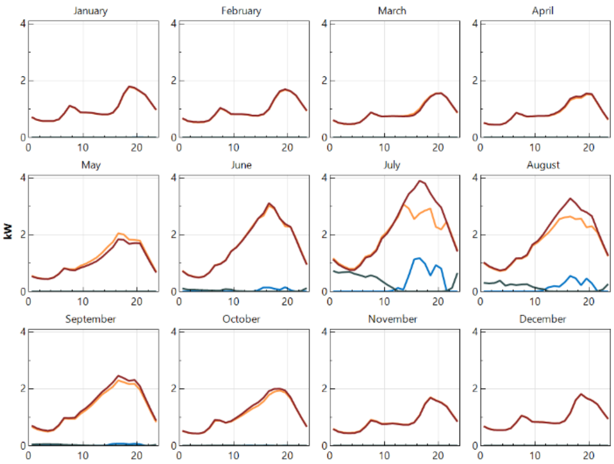

Figure 14. 12-month load profile (red), power received from the grid (orange), power received from the battery (blue), and power from the grid to the battery (dark blue)

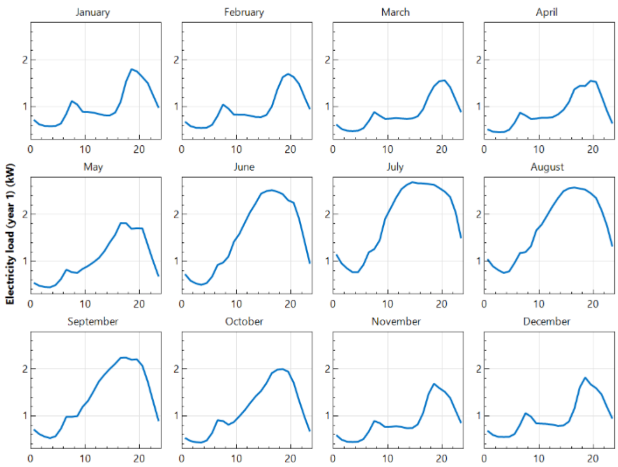

Figure 15. Daily load curve for 12 months of the year and the effect of load management in the middle months of the year

3.4 Scenario S4

By implementing the load management algorithm and preparing a new load profile, two load curves should be compared with each other. The general information of two load curves before and after load management is presented in Table 2. As can be seen, the average consumption and maximum load have decreased after applying the algorithm. Also, the total annual consumption has decreased from 10,830 to 10,468 kilowatt-hours, and actually 362 kilowatt-hours of energy consumption has been cut. In other words, by applying the right method of load management, we only needed to reduce consumption by 3% throughout the year.

After applying the load management, the new load curve is entered into the SAM software, and modeling is done under the constraints of the first scenario. In this case, it can be seen that the annual electricity cost of the building is reduced from $986 before load management to $837, representing a 15% improvement. Figure 15 shows the 24-hour load curve for 12 months of the year after applying consumption management. As can be seen, the effect of applying load management in the months of June to September is very impressive, and the load curve is correctly peak shaving.

4. Conclusion

There are various methods to perform peak correction, demand side management, and reduce cost and consumption during peak hours. In this research, this issue was addressed from three dimensions, and its effect on consumption management in a residential building was investigated. For this purpose, the concepts of a) on-site production, b) power storage, and c) load management were applied and assessed. As stated, each of the methods used has a favorable effect on the energy cost of the building and, at the same time, has led to a reduction of the pressure on the grid during peak hours. In this regard, the storage system has a higher initial cost and has provided more effectiveness. Also, applying load management methods can lead to the reduction of peak consumption without cost and thus cost reduction.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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