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Original Article

Electrical Load Estimation and Management Approach of a Small Rural Community in Saudi Arabia

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***Abstract* - Global difficulties include problems with environmental, energy, and economic issues. Increasing energy capacity, especially electric power and its reliability, is motivated by people's desire to raise their standard of living. One of the most important components of the electric power supply system is the electrical distribution system of residential buildings. The estimated electrical demand is a key factor affecting the design and construction of electrical energy systems. Houses' functioning and design have always depended on the difficulty of precisely estimating electricity consumption and the highest possible electrical load. Due to the random nature of fluctuations in electrical consumption caused by population expansion and an increase in the number of electrical equipment in use, it is difficult to determine residential loads with any degree of accuracy. Renewable energy sources offer a competitive alternative for off-grid regions because fossil fuels are becoming scarce and extending the national grid is expensive. An electrical load estimation and management strategy for a small remote area with ten families in Hafar Al Batin, Northern Saudi Arabia, will be discussed in this paper. HOMER software was used to evaluate solar Photovoltaic (PV) and Wind Turbine (WT) systems in order to identify the best combinations. The study focuses on daily consumption patterns, seasonal load profiles, and load management techniques aimed at lowering peak demand. According to the results, efficient load shifting can lower the maximum load by up to 15.69%, increasing system efficiency and reducing energy costs.*

***Keywords* - Hybrid Renewable Energy System (HRES), Electrical Load Estimation, Load Management, Shifting Loads, Off-Grid Communities.*

1. Introduction

People's need to improve their quality of life is contributing to an increase in energy capacity, particularly in electric power and its dependability. Residential homes' electrical distribution systems represent some of the most essential elements of the electric power supply system. The forecasted electrical load is one of the most important variables affecting the design and construction of electrical energy systems. Accurately calculating the consumption of electricity and a home's maximum electrical load has traditionally been a challenge for both design and operation. It is difficult to calculate household electrical loads with any level of accuracy due to population growth and an increase in the total number of electric devices in use, causing fluctuations in electrical loads to be unpredictable.

Since the decreasing reserves of fossil fuels and the high cost of expanding the national grid, renewable energy sources represent a viable option for off-grid areas. Electrical load troubles in new settlements occur on the supply as well as the demand side, and they could be technical, economic, or even political in structure. These issues have typically been addressed by increasing generation and transportation facilities, importing electricity, or implementing load management. Load Management (LM) is a techno-economic approach for balancing supply and demand relationships, maximizing power generation, and avoiding high-demand loads. The question of electrical load demand and load management in residential buildings was investigated in this study. The primary goal is to examine load demand variance and load control options in the residential sector, namely semi-detached dwellings. Techno-economic and environmental concerns are investigated [1, 2].

A simplified model of all of these variables takes varied values based on different numbers and types of electrical loads that make up the evaluated structure [3]. Modern energy distribution utilities require precise load statistics, power generation planning, load management, and excellent client service. The most important load information is how an individual or group of customers uses electricity at different times of day, days of the week, seasons of the year, and the total load. The purpose of load management is to optimize the functioning of clients with unique contracts. In the recent decade, global climate change and global warming have been caused by increased industrialization and population development, which have resulted in an increase in electricity demand.

Furthermore, the global depletion of conventional energy resources such as fossil fuels, as well as the high cost of grid extension, has prompted the search for alternative options. Traditional energy contributes to raised greenhouse gas emissions, specifically carbon dioxide (CO_2). Clean and renewable energy sources protect the earth and improve the lives of everyone who lives on it. Renewable resources contribute to power generation with zero or low environmental impact. In Zaragoza, Spain, Juan et al. [4] demonstrated a load management strategy for optimizing the use of renewable energy in systems that include WT, B, and DG. When compared to the situation without load management, the results showed that the load management process improves wind power consumption by moving regulated loads to wind power peaks, enhancing the battery SOC, and reducing DG running time. In actuality, normal distributions are not always provided by users' actual energy and power consumption [5].

Based on the daily electrical load of the house and precise location radiation data, El Shenawy et al. investigate the structure and implementation of a standalone PV system [6]. Hasan, N. et al. use scenarios including stored energy to examine the load pattern monitoring for domestic PV storage arrays. [7]. A load survey and estimations for an ordinary isolated remote decentralized hybrid energy generating unit in remote places are provided by X. Liu et al. [8]. Energy demand and estimations for the ensuing decade were estimated using the submitted data. For an HRES in Nigeria, A.S. Oladeji S. and B.F. Sule performed an electrical load study and prediction [9]. Household electricity use and the overall use of energy are used as dependent variables in this study [10]. In a Chinese island standalone microgrid, Jiyuan, Z. et al. investigated PV-DG-B energy management [11]. Using normative specific load, Soluyanov, Yu. et al. estimated the power consumption of residential and public buildings in Russia [12].

An initial load evaluation methodology for homeowners utilizing demand profile grouping was evaluated by Kangping, Li, et al. [13]. The technological and economic suitability of the HRES that Abdelkareen, R., et al. presented for remote electricity supply in an Egyptian village, [14]. For a remote village close to the Kech district in Pakistan, Jamil, A., et al. conducted a technological-economic feasibility assessment of an off-grid HRES [15]. The simulation results indicate that such a system is capable of meeting the average daily essential load of 197.74 kWh at a maximum demand of 27.8kW at an NPC of 127,345 $ and a COE of 0.137 $ per kWh. Ahmed et al. [16] additionally looked into how corporate entrepreneurship and green innovation are promoted by environmental constraints. Ahmed et al. [17] and Basu [18, 19] have made substantial progress in the development of optimization techniques for power transportation challenges. Al-Rawashdeh et al. [20, 21] analyzed the performance of a hybrid renewable-energy system for green buildings under a number of conditions. For hybrid systems to be effective and economical, Akram et al. need control component sizes and power management [22]. Renewable energy sources like wind, solar, batteries, and diesel engines can be incorporated in a variety of ways.

Many research efforts on grid-connected and/or off-grid systems have implemented similar studies. Regularly utilize HOMER Pro software for system modeling and component optimization, including battery systems B, diesel generators DG, wind turbines WT, and Photovoltaics (PV). (Chowdhury et al., [23]; Hemeida et al., [24]; Hermann et al., [25]; Poonam et al., [26]; Younsi et al., [27]). Moreover, optimization research combines both mathematical and classical methods. In contrast, Das et al. [28] investigated a hybrid renewable energy system resulting in a COE of 0.234 $/kWh.

The optimal economic scale for standalone HRES with PV/WT/DG/B units was studied by Saraswat and Suhag [29] with a focus on an Indian community, while Dehaj and Hajabdollahi [30] investigated the multi-objective optimization of HRES in different climatic zones of Iranian urban areas. Two simultaneous objective functions-the fuel ratio and the total annual cost-were selected. For a seawater RO system, El Boujdaini et al. [31] developed both off-grid and grid-connected versions of an HRES system with compressed air storage. An optimal method for managing electricity in homes was proposed by Liu et al. [32]. Lu et al. [33] conducted a comprehensive study demonstrating the benefits of using advanced hybrid metaheuristics techniques in energy systems, leading to an improved system that produces fewer pollutants and consumes less energy.

The techno-economic study of a cogeneration system that generates electricity and freshwater using a freestanding solar photovoltaic PV system was investigated by Abdulrahman et al. [34] in Al-Khobar City, Saudi Arabia. The aim is to operate a Reverse Osmosis (RO) desalination plant with surplus electricity from the photovoltaic system. In this study, three types of additional power storage devices were investigated. These three storage options are taken into consideration when optimizing the PV array using MATLAB. According to the statistics available, the hybrid battery/water tank system has the lowest levelized water cost, at \$1.874 per cubic meter (m^3). Mokhtara et al. [35] investigated how climate variance and structural energy efficiency affect the ideal HRES sizing decision. On-grid systems had a COE of 0.12 dollars per kWh, whereas standalone systems had a COE of 0.34 dollars per kWh, according to the report. In an associated study, a hybrid PV/WT/Bat reverse osmosis desalination system was investigated by Pronob et al. [36].

2. Site Description and Weather Information

Site selection is crucial for the development and assessment of a Hybrid Renewable Energy System (HRES). Hafar Al Batin, Saudi Arabia, was chosen as the case study location for this analysis due to several major criteria, such as its remoteness from the national electricity system, substantial exposure to solar radiation, and suitable average wind speeds.

2.1. Statistics on Solar and Wind Energy

The coordinates of Hafar Al Batin are 45.95708° longitude and 28.33202° latitude. The Joint Research Centre Institute for Environment and Sustainability Renewable Energies Unit of the European Commission provided the site's solar radiation data [36].

Figure 1 displays the monthly average of the clearness index and solar radiation. As can be seen, June, July, and August are the summer months with the greatest values. The average monthly wind speed data, derived from daily measurements from January 1, 2017, to January 1, 2020, is also shown in Figure 2 [37]. The site is interesting for hybrid solar-wind applications because the peak wind speeds also happen in the summer, when solar radiation patterns are most favorable.

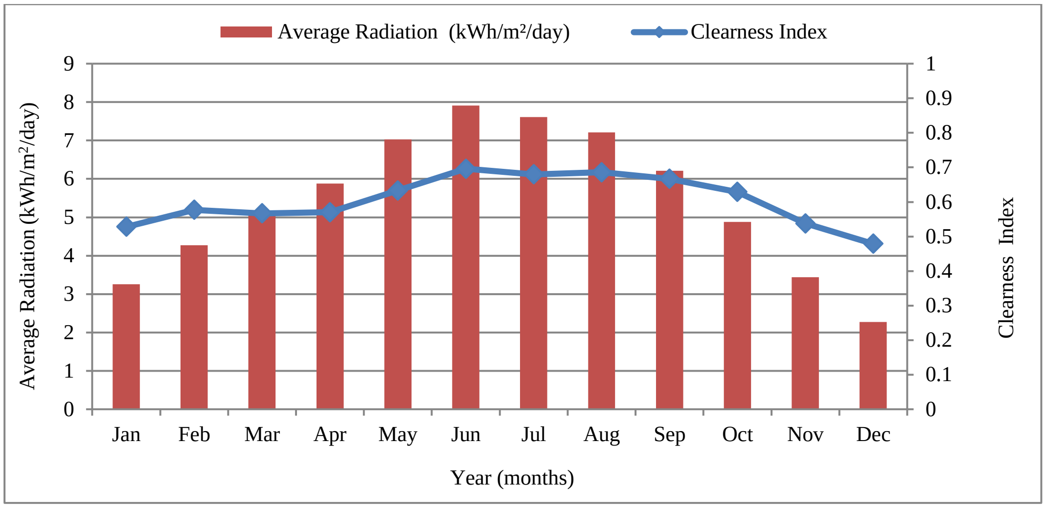

Fig. 1 Average monthly solar radiation and clearness index [36]

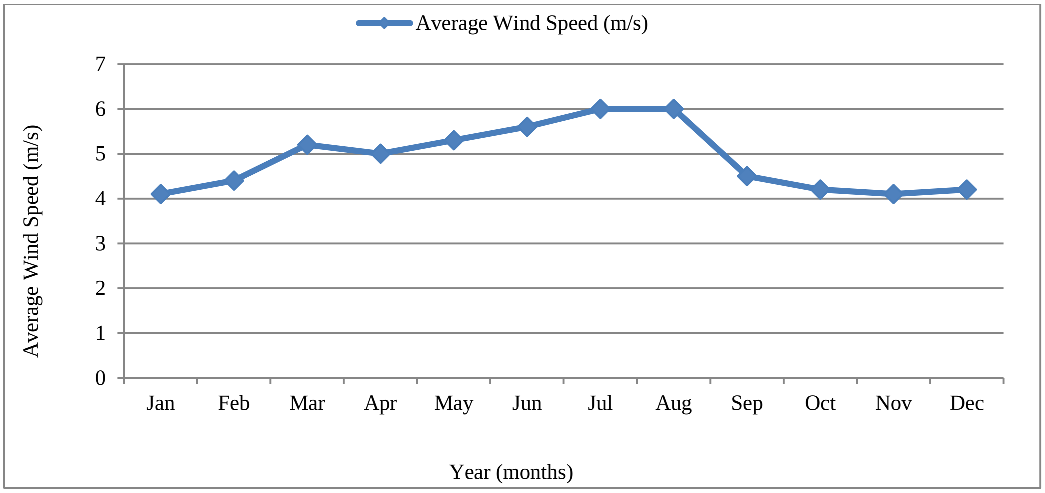

Fig. 2 Average monthly wind speed [37]

2.2. Techniques for Load Evaluation

Load evaluation is an important step in energy system sizing and determining suitable voltage and current values in order to select the best PV array and inverter [38]. In each of the four seasons, the proposed HRES is intended to supply the electrical requirements of ten families.

Air conditioners, refrigerators, washing machines, kettles, radios, televisions, fans, lighting fixtures, and a communal water pump represent some of the necessities included under this group of items. Based on field observations and conversations with the inhabitants, several hypotheses were put out to estimate the total load:

- The system is designed for ten families.
- Every family consists of six people.
- Each household contains 3 rooms, a kitchen, and a bathroom; each equipped with one lamp.
- A water tank is used for domestic water storage.
- Each home includes the following appliances:

- TV set (200 W)
- Radio set (40 W)
- Refrigerator (300 W, operating 50% of the time)
- Washing machine (1000 W, operating 1 hour every 3 days)
- Four fans per household (100 W each)
- Two air conditioning units (3000 W each)
- Electric kettle (1200 W)

- A shared water pump operates at 1888 W in summer and 1416 W in winter.
- Electrical load patterns for autumn and spring are assumed to be identical.

2.3. Power Required for Pumping Water

Water pumping requirements vary between summer and winter.

2.3.1. The Season of Summer

The following hypotheses are used to calculate the electricity needed for summertime water pumping:

- Each family consists of 6 individuals.
- Daily water usage is approximately 1 m^3 per person.
- The pump operates for 10 hours per day.
- Water head H is assumed to be 50 meters.
- Combined pump and motor efficiency η is 0.8 [39].

The total daily water consumption is calculated as:

$$Q_{\text{total}} = 6 \text{ persons } \times 10 \text{ families} = 60\, m^3/day$$

The hourly flow rate becomes:

$$Q = \frac{60\, m^3}{10\, hours} = 6\, m^3/hr$$

The required average power is given by the formula:

$$P = \left(\frac{\gamma Q H}{75 \times \eta}\right) \times 1.36$$

Substituting the values:

$$P = \left(\frac{\gamma \times 6 \times 50}{75 \times 0.8}\right) \times 1.36 = 1.888\, kW$$

2.3.2. The Season of Winter

For the winter season, the assumptions are similar except for reduced water usage:

- Daily water usage per person is 0.75 m^3.
- The pump runs ten hours every day.

The sum of daily water consumption is calculated as:

$$Q_{\text{total}} = 0.75\, m^3 \times 6 \text{ persons } \times 10 \text{ families} = 45\, m^3/day$$

The hourly flow rate becomes:

$$Q = \frac{45\, m^3}{10\, hours} = 4.5\, m^3/hr$$

The required average power is given by the formula:

$$P = \left(\frac{\gamma \times 4.5 \times 50}{75 \times 0.8}\right) \times 1.36 = 1.416\, kW$$

2.4. Hourly Load Requirements Data (Load Profile)

Accurate hourly load data is important for evaluating electrical demand profiles and designing a reliable energy system. To support this analysis, data on hourly electricity consumption and total energy production were collected from various local organizations. However, the available data did not specify the origin of the generated electricity, making it difficult to determine which energy sources were contributing at any given hour. In Saudi Arabia, especially during the summer months, electricity demand increases significantly due to high ambient temperatures and widespread use of air conditioning. Residential energy consumption varies substantially throughout the day, with demand peaks typically occurring around midday and in the evening. For simulation purposes, it was necessary to compute the total electrical load and the corresponding hourly distribution based on the expected operation of household appliances and utilities. The hourly load profile represents the sum of the power consumed by all appliances operating during each hour of the day. This profile plays a vital role in assessing energy system sizing, optimizing resource use, and evaluating the effects of load management strategies. The load factor is estimated by dividing the average hourly demand over a year by the peak hourly demand during the same period. This factor ranges between 0 and 1. A load factor of 1 indicates a flat demand profile without peaks, representing an ideal energy consumption distribution. Conversely, a low load factor signifies significant demand variation, which may necessitate load shifting or peak reduction strategies to improve efficiency.

The assumptions used to define the hourly distribution of appliance usage are as follows:

- A full 24-hour day is considered for load simulation.
- Refrigerators operate uniformly throughout the day, at 50% of their rated power.
- Lighting is assumed to be constant in each room per household.
- Washing machines are used for one hour each morning per household.
- In summer, fans operate between 09:00 and 22:00.
- Water pumping is scheduled as follows:
  - In summer, continuous operation is from 01:00 to 10:00.
  - In winter, the operation is from 01:00 to 09:00 and again at midnight.

Table 1 provides a detailed summary of the electrical appliances in ten households, including power ratings and estimated daily usage durations. This data forms the basis for calculating the total power and energy requirements of the HRES. Notably, the washing machine usage is assumed to remain consistent across all seasons, operating for one hour every three days.

Table 1. Total load power and energy for 10 families

<table>
<tr><th rowspan="2">Item</th><th rowspan="2">Power (W)</th><th rowspan="2" colspan="2">Total Power (W)</th><th colspan="3">Total Energy (kWh/day)</th></tr>
<tr><th>Summer</th><th>Winter</th><th>Autumn or Spring</th></tr>
<tr><td>TV Set</td><td>200</td><td colspan="2">2000</td><td>20</td><td>16</td><td>18</td></tr>
<tr><td>Radio set</td><td>40</td><td colspan="2">400</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td>Refrigerator</td><td>150 (half rated power 300/2)</td><td colspan="2">1500</td><td>36</td><td>30</td><td>33</td></tr>
<tr><td>Washing machine</td><td>1000 W Operating one hour every three days (3000/3)</td><td colspan="2">10000</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td>Lighting</td><td>100 ($10_{\text{No of lamps per family}}$ *10_{W})</td><td colspan="2">1000</td><td>12</td><td>15</td><td>13.5</td></tr>
<tr><td>Fans</td><td>400 ($4_{\text{No of fans per family}}$*$100_{\text{W}}$)</td><td colspan="2">4000</td><td>48</td><td>----------</td><td>32</td></tr>
<tr><td>Air Condition</td><td>6000 (2 per family * 3000)</td><td colspan="2">60000</td><td>600</td><td>---------</td><td>300</td></tr>
<tr><td>Kettle</td><td>1200 W</td><td colspan="2">12000</td><td>12</td><td>12</td><td>12</td></tr>
<tr><td>Pump</td><td>1888</td><td>Summer 1888</td><td>Winter 1416</td><td>22.656</td><td>18.88</td><td>20.768</td></tr>
<tr><td>Total energy (kWh/day)</td><td></td><td colspan="2"></td><td>762.656</td><td>103.88</td><td>441.268</td></tr>
</table>

3. Load Management Strategy

Load Management (LM) encompasses a range of techniques designed to regulate and shift power consumption patterns to align with system generation capabilities. By modifying the timing and magnitude of demand, LM allows utility systems or standalone configurations to meet power requirements more economically and efficiently. In hybrid systems, effective load management helps reduce reliance on high-cost energy sources, improve component utilization, and enhance overall system performance.

The main objective of the LM approach is to reduce peak electricity demand and redistribute loads to off-peak periods. This strategy not only enhances system stability but also minimizes operational costs by reducing the NPC and COE. Demand-side interventions were examined to control large residential loads during peak hours and to exploit off-peak generation periods for optimal usage.LM approaches often involve demand response measures, load shifting, and reducing peak loads. The purpose of this study was to flatten the load profile and minimize peak occurrences by carefully scheduling controllable domestic loads, such as air conditioners, washing machines, and electric kettles.

A portion of the approach used in this work was developed by a novel load limitation technique that was established in a campus microgrid by K. Vishal Raj et al. [40]. The optimal method for controlling a standalone photovoltaic system for off-grid electrification in Tunisia was examined by S. Slouma et al. [41]. Their results demonstrate the importance of LM in reducing system costs and enhancing energy efficiency. A technological, economic, and environmental assessment of hybrid generation systems under various conditions was carried out by Choudhary et al. [42].

3.1. Estimated Daily Load Power Curve

This section examines the hourly variation in electrical load throughout a typical day across different seasons, providing insight into peak demand periods and potential load management interventions. During the summer season, electricity demand is notably high, primarily due to extensive use of air conditioning and other cooling appliances. As illustrated in Figure 3, the summer daily load curve exhibits multiple peaks, with the most significant occurring around 20:00 hours. The lowest demand is observed between 01:00 and 06:00 hours, when household activity is minimal. Figure 4 presents the daily load power curve for the winter season. In contrast to summer, the winter load is generally lower and more evenly distributed, with less pronounced peaks due to the reduced need for cooling and consistent lighting usage. The daily load profile for autumn and spring, shown in Figure 5, demonstrates a balanced consumption pattern, with moderate fluctuations throughout the day. This is attributed to the milder weather conditions that reduce the reliance on energy-intensive heating or cooling systems. A comprehensive comparison of seasonal load profiles is provided in Figure 6, which overlays the daily curves for all four seasons. The figure confirms that the summer season consistently exhibits the highest peak demand, particularly in the evening hours, while the lowest consumption levels occur during the early morning hours (01:00 to 06:00) across all seasons. Understanding these seasonal and hourly demand patterns is essential for optimizing hybrid energy system configurations and implementing effective load management strategies tailored to the specific needs of each period.

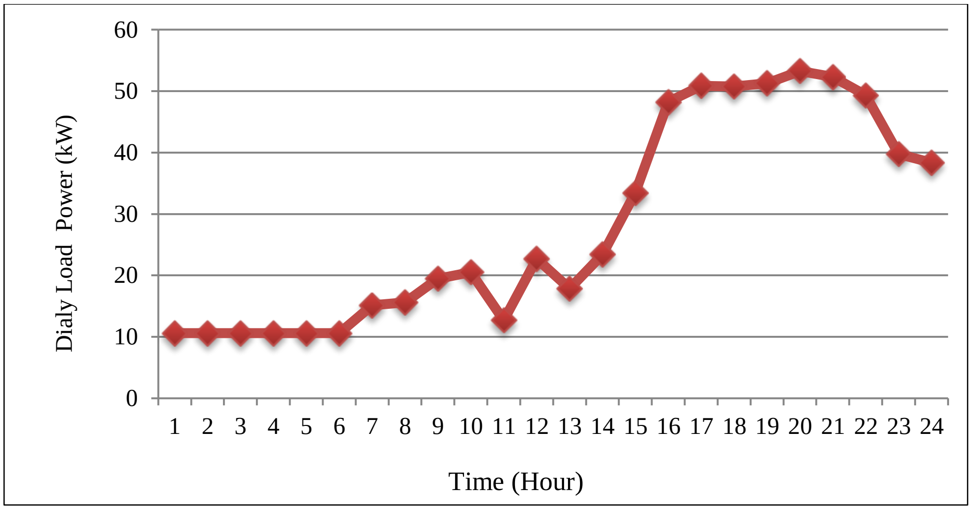

Fig. 3 Summer daily load power curve

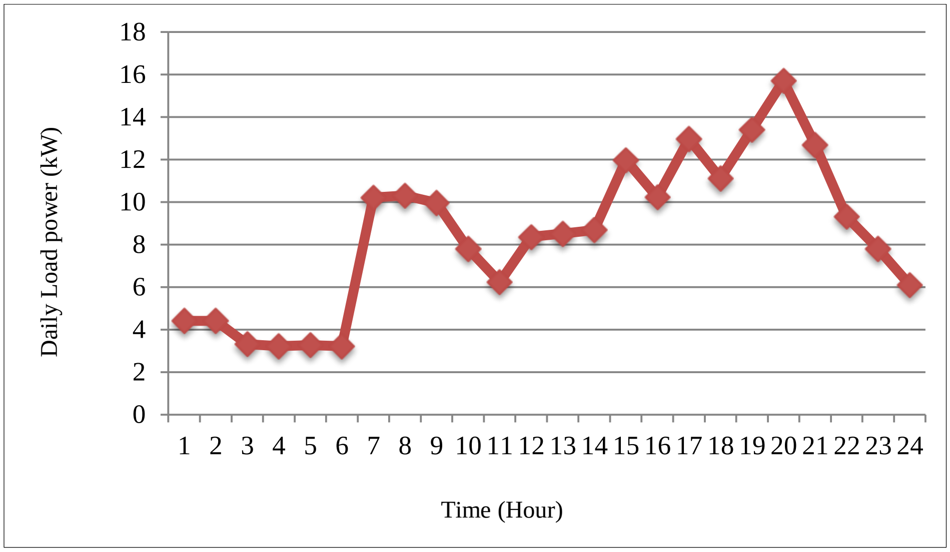

Fig. 4 Winter daily load power curve

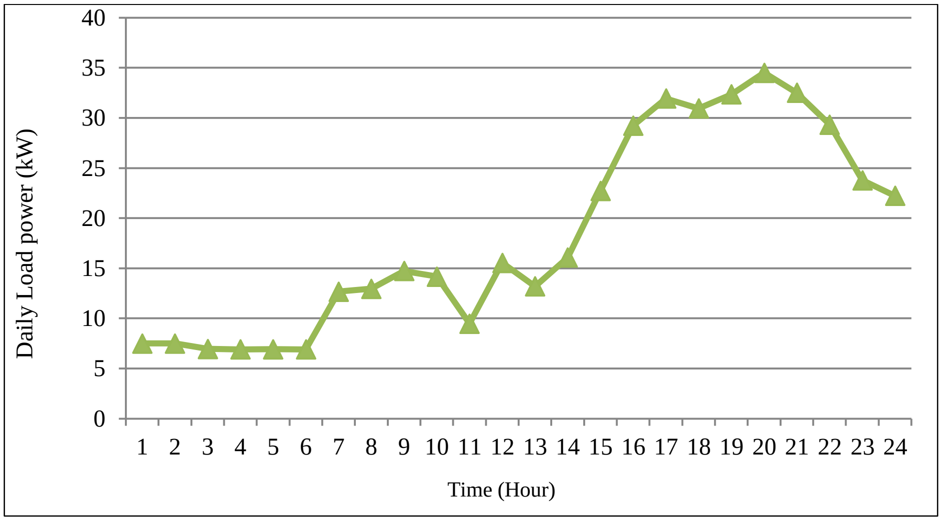

Fig. 5 Autumn or spring daily load power curve

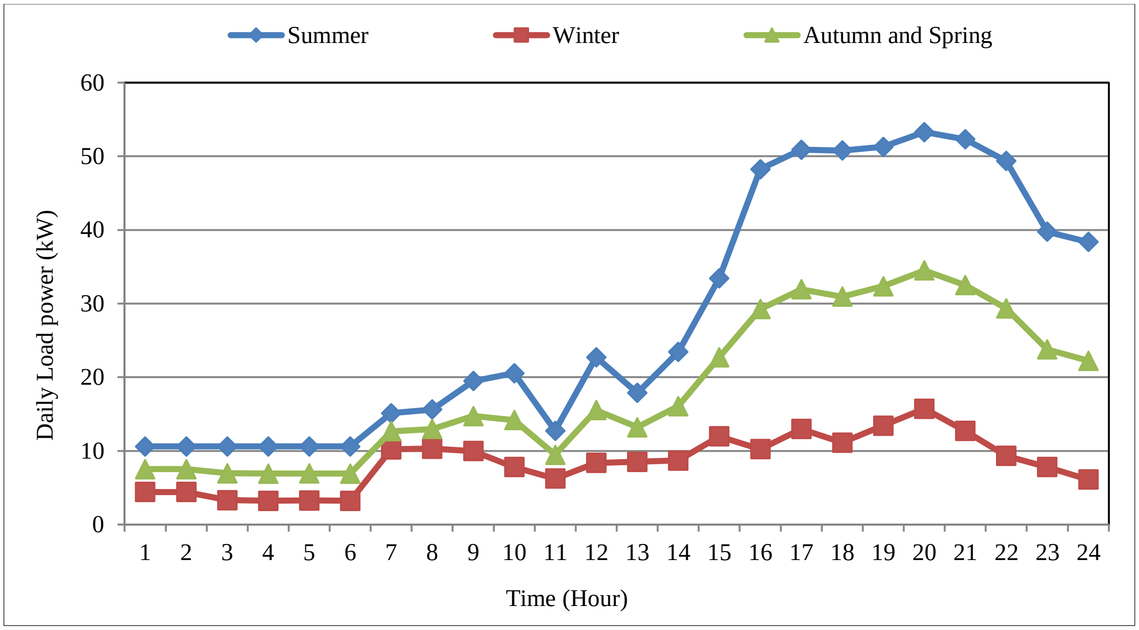

Fig. 6 Daily load profile curves for the four seasons

3.2. Optimum Load Management Strategy

The load management strategy implemented in this study seeks to enhance the system's performance by shifting controllable loads to off-peak hours.

This redistribution of demand significantly improves the daily load profile and contributes to the reduction of peak loads.

As a result, the overall NPC of the system is lowered when compared to the scenario without load management.

By strategically managing the timing of energy-intensive appliances, the HRES can operate more efficiently, avoid oversizing of components, and maintain a better balance between supply and demand across seasons.

3.3. Load Shifting Strategy

To achieve a more uniform load distribution, several high-consumption electrical appliances were rescheduled or partially curtailed.

The specific load-shifting actions taken include:

- Washing Machine: Limited to morning operation, running for one hour every three days, totaling approximately 10 uses per month per household.
- Air Conditioning: Reduced usage during nighttime hours to alleviate peak demand in the evening.
- Fans: Operation is curtailed during late-night hours to minimize the continuous cooling load.
- Lighting: Non-essential lighting is reduced during late evening and early morning hours.

3.4. Results of Load Management

The impact of the load management strategy is illustrated in Figures 7, 8, and 9, which compare the daily load profiles with and without load management across three seasonal scenarios:

- Summer Season (Figure 7): Maximum demand reduced from 53.288 kW to 48.395 kW, achieving a 9.18% decrease.
- Winter Season (Figure 8): Peak load decreased from 15.717 kW to 13.25 kW, representing a 15.69% reduction.
- Autumn/Spring (Figure 9): Load dropped from 33.502 kW to 30.769 kW, reflecting an 8.15% reduction in peak demand.

Figure 10 presents the optimized daily load management curves for all four seasons. As illustrated, the highest peak remains during the summer at 20:00 hours, while the lowest demand consistently occurs between 01:00 and 06:00 hours across all seasons.

To capture broader seasonal trends, Figures 11 and 12 display the monthly and daily load profiles, respectively. A 5% day-to-day variability factor and a 10% hour-to-hour variation were applied to simulate realistic demand fluctuations.

As confirmed by the results, the ten families in Hafar Al Batin have a daily load requirement that ranges between the minimum of 3.5 kW and the maximum of 13 kW. Electricity must be supplied within this range by the HRES in order to ensure a steady and reasonably priced supply during the year.

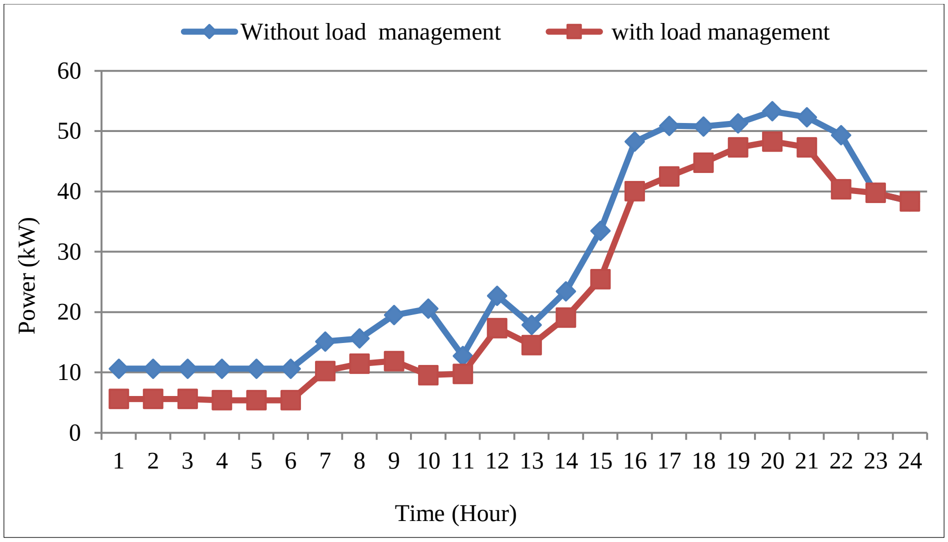

Fig. 7 Summer daily load management

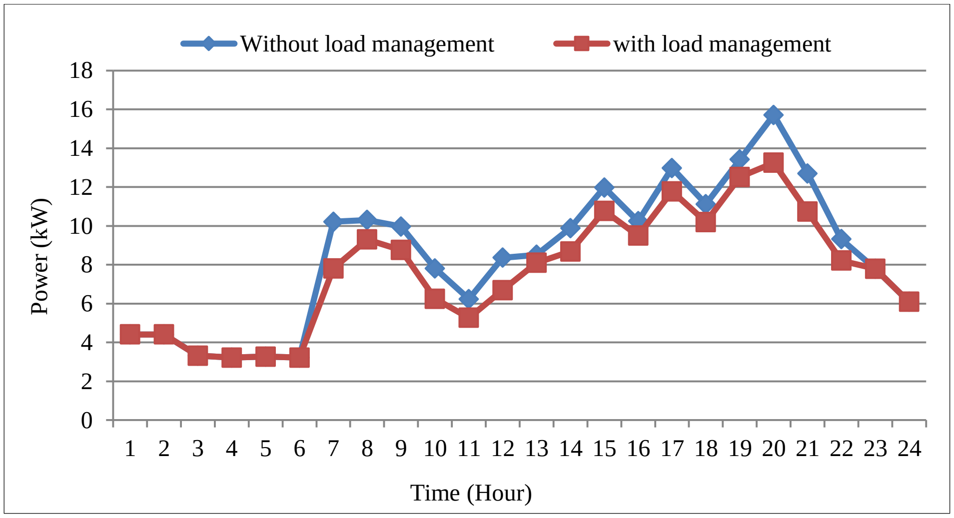

Fig. 8 Winter daily load management

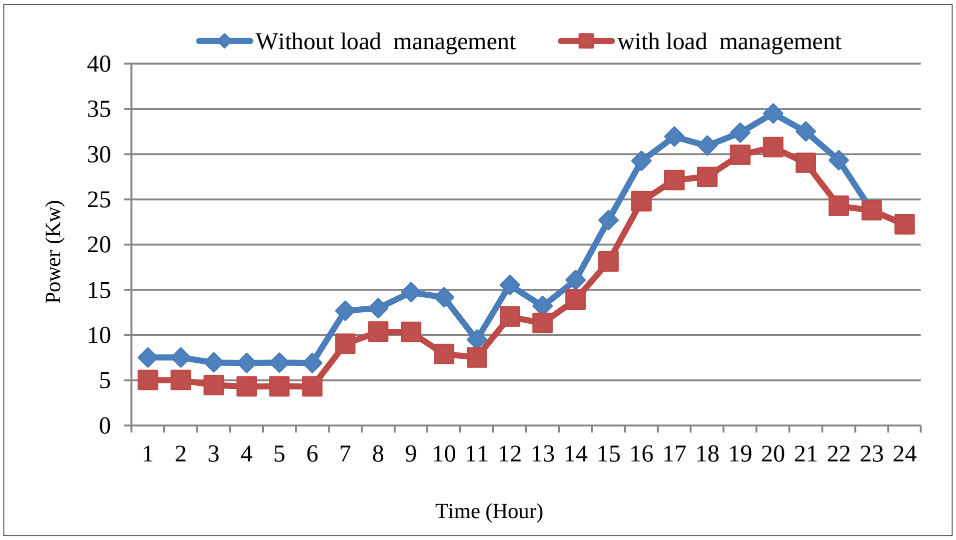

Fig. 9 Autumn or spring load management curve

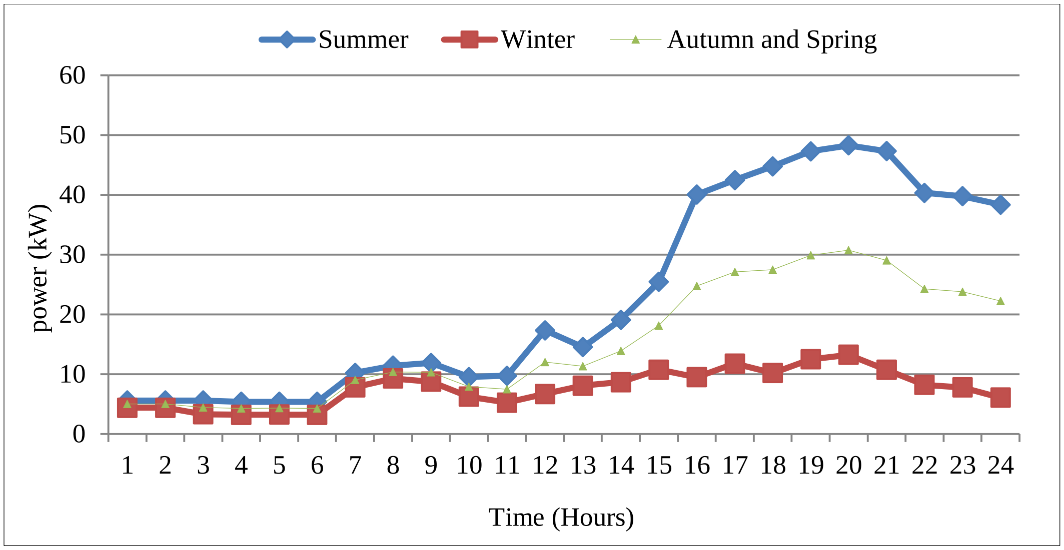

Fig. 10 Daily load management profile curves for the four seasons

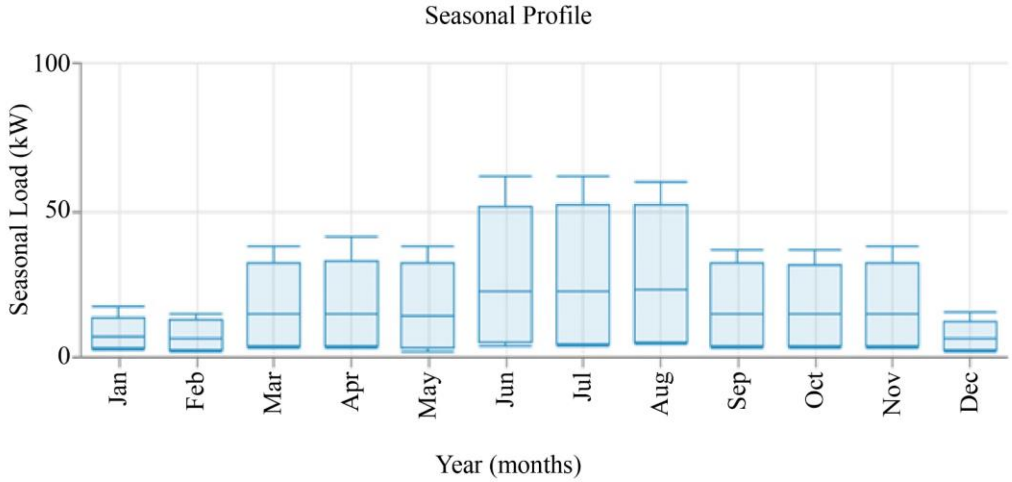

Fig. 11 Seasonal load profile

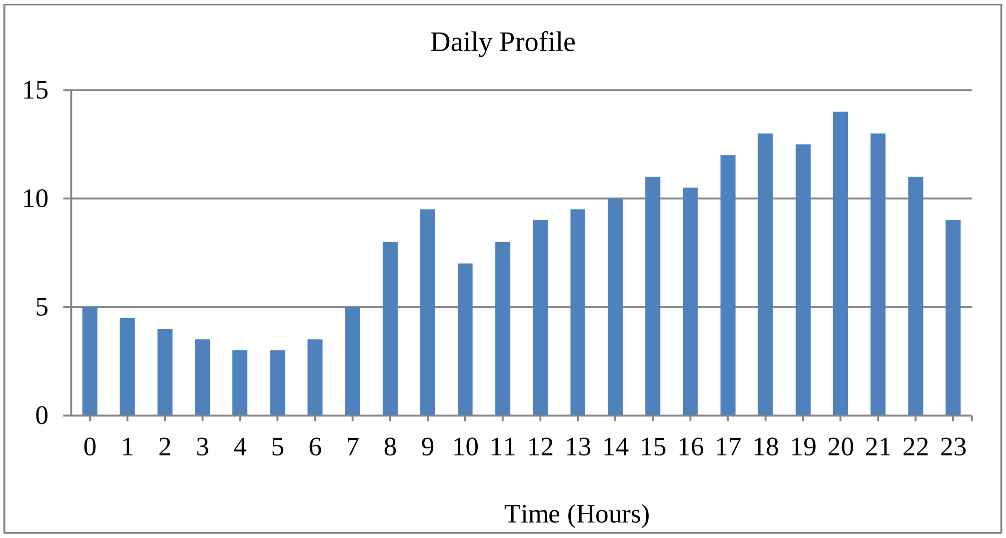

Fig. 12 Daily load profile

4. Conclusion

Rural communities require continuous access to water and electricity in order to sustain themselves. The lack of fossil fuels and the considerable expense of grid extensions in remote locations like Hafar Al Batin in Northern Saudi Arabia demonstrate how urgent it is to convert to renewable energy sources. Through the use of an HRES that combines PV, WT, battery storage, and a backup diesel generator, the study's objective was to evaluate the electrical load requirements and management strategies for a small community with 10 households. Hourly and seasonal variations were used to produce load demand profiles, which showed that cooling loads were the main reason for the summer's largest peak demand. The study additionally examined the effect of load management techniques, such as moving high-power equipment to off-peak hours and reducing usage during peak hours. The following are the primary findings of the study:

- Summer Season: Load management reduced the peak demand from 53.288 kW to 48.395 kW, resulting in a 9.18% decrease.
- Winter Season: Peak demand decreased from 15.717 kW to 13.25 kW, representing a 15.69% reduction.
- Autumn/Spring Seasons: The maximum load dropped from 33.502 kW to 30.769 kW, reflecting an 8.15% reduction.
- The estimated daily demand for the community ranges between 3.5 kW and 13 kW, which the HRES must supply reliably and economically.

These findings demonstrate that applying targeted load management strategies can significantly reduce peak load demand, improve system efficiency, and lower both operational and investment costs. Furthermore, behavioral differences had no effect on the load profile because the group under study had similar family features and cultural traditions.

Future Work Could Extend this Research by,

- Scaling the system for larger or more diverse communities.
- Integrating advanced storage technologies for increased resilience.
- Assessing the long-term impact of behavioral change on energy consumption.
- Conducting field surveys or questionnaires to refine demand modeling and improve user participation in demand-side management.

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