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# IoT-Based Smart Energy Management and Load Shifting for Residential Consumption Optimization

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## Abstract

The increasing energy demand and rising electricity costs have intensified the need for efficient energy management in residential buildings. Load imbalances in power grids and cost surges during peak demand periods are pushing consumers toward more strategic and conscious consumption models. This study focuses on optimizing household electricity consumption through load shifting strategies. To achieve this, a low-cost, Internet of Things (IoT)-based Smart Energy Management System (SEMS) was developed and implemented in a real household. Its performance was then compared with a commercial reference device, revealing an impressive accuracy rate of 99.98%. Electricity consumption data recorded over a one-year period using SEMS was analyzed to assess voltage fluctuations, frequency variations, and energy usage patterns. Daily, weekly, and seasonal consumption trends were identified. Moreover, classifying shiftable and non-shiftable loads enabled a comprehensive evaluation of the load-shifting potential. Scenario-based analyses demonstrated that shifting 25%, 50%, and 75% of shiftable loads to lower-cost tariff periods could result in 9.8%, 17.6%, and 26.1% cost savings, respectively. These findings indicate that SEMS enhances energy efficiency and reduces electricity costs. With its user-friendly interface and low installation cost, SEMS is well-suited for widespread adoption and presents an effective solution for time-based load shifting. Additionally, by encouraging users to adopt more efficient consumption habits, SEMS is expected to contribute to sustainable energy management.

**Keywords:** Energy saving, energy management, power quality, load shifting, internet of things.

## 1. Introduction

Energy is a fundamental element of modern life, making its efficient use essential for a sustainable future. Due to population growth and technological advancements, energy demand is rapidly increasing, making energy efficiency and sustainable energy consumption more critical than ever. In Turkey, total electricity production in 2023 reached 326.3 TWh, with 57.15% of this generation coming from fossil fuels (coal, natural gas), while the remaining 42.85% was derived from renewable sources (hydropower, wind, solar, and geothermal)[1]. The widespread use of fossil fuels leads to serious issues such as climate change, air pollution, and environmental degradation. Therefore, reducing fossil fuel consumption and promoting renewable energy sources have become top priorities in energy policies. Notably, energy consumption in buildings accounts for approximately 40% of global total energy demand [2]. IoT is a technology that enables various devices and systems to connect, collect data, analyze information, and automate decision-making processes [3]. In the context of energy management, IoT-based systems leverage smart meters to monitor real-time energy consumption, analyze user habits, and optimize usage patterns. IoT is widely applied in smart homes [4], smart cities [5], smart healthcare [6], Industry 4.0 [7], and smart agriculture [8]. These systems enhance energy efficiency by enabling monitoring, analysis, and optimization of energy consumption. In smart grids, IoT devices play a crucial role in maintaining the balance between energy generation and consumption [9]. By utilizing big data and machine learning techniques, IoT can analyze energy consumption patterns and provide recommendations for cost savings. For instance, forecasting electricity demand can help improve grid load balancing. Additionally, these systems learn user behaviors to enhance energy efficiency [10]. This study focuses on developing a low-cost IoT-based SEMS to monitor and analyze energy consumption habits in smart homes. The proposed system raises awareness

of energy management by providing users with real-time feedback that encourages energy savings.

This study offers the following key contributions to the field:

• A low-cost IoT-based SEMS was developed.

• SEMS monitors energy consumption using non-invasive single-point power measurement.

• Energy consumption was analyzed alongside power quality using real-time data.

• Remote monitoring and control were enabled through the integration of the open-source TCP/IP protocol and the Blynk 2.0 IoT platform.

• SEMS allows for time-based load shifting strategies, optimizing energy consumption.

The remainder of this paper is structured as follows: Section 2 discusses previous studies on smart home energy management systems. Section 3 explains the methodology of the proposed system. Section 4 presents the implementation results and discussions. Finally, Section 5 summarizes the key findings and conclusions of the study.

## 2. Related work

Energy consumption is rapidly increasing due to population growth, climate change, urbanization, and the widespread use of electrical appliances [11]. This situation presents significant challenges for energy security and environmental sustainability [12]. To reduce energy consumption, energy management systems (EMS) utilize smart technologies and optimization strategies to enhance energy efficiency [13].

In traditional home energy management methods, homeowners have limited ability to monitor and control their energy consumption. The periodic arrival of monthly electricity bills and the risk of high charges make it difficult for users to regulate their energy usage habits. However, smart home energy management systems (SHEMS) provide users with greater control and transparency over their energy consumption, promoting cost savings [14]. Smart energy management systems are designed to optimize energy consumption and reduce costs using IoT technology. These systems employ IoT devices and big data analytics to monitor, analyze, and control energy usage [15]. One common strategy for managing energy demand during periods of excessive energy production is dynamic pricing tariffs, which adjust energy costs throughout the day. This method encourages consumers to shift a portion of their energy usage from peak hours to lower-cost periods, thereby optimizing energy generation and transmission within the power system [16]. Smart meters have a broad range of applications, including monitoring energy consumption in smart homes and industrial settings, identifying household consumption profiles, predicting electricity demand within national grids, assessing power

quality, and conducting general consumption analyses [17]. Smart homes [18], [19] are among the most significant application areas of IoT technology. IoT enables household devices to connect to each other and the internet, facilitating advancements in home automation [20], security [21], user comfort [22], and energy management and efficiency [23]. One effective way to optimize energy consumption and lower electricity costs through SHEMS is to schedule the operation of household appliances [24]. Dynamic pricing models allow for energy optimization by helping users reduce costs and decrease consumption [25]. Additionally, smart energy management and consumption optimization contribute to preventing outages and reducing both the peak-to-average ratio (PAR) and energy costs [26]. Demand Response Programs and smart meters adjust energy consumption based on demand periods, reducing electricity costs and balancing grid loads. Smart meters provide real-time energy monitoring and optimization [27]. These smart energy management systems enable cost-efficient energy consumption by shifting appliance usage to lower-cost time periods. Devices can be categorized into two main types: shiftable loads and non-shiftable loads [28]. Shiftable loads include appliances that perform energy-intensive tasks at specific times and have flexible usage schedules. Examples include washing machines, dishwashers, electric water heaters, electric vehicle chargers, air conditioners, and dryers, all of which can be operated during off-peak or lower-cost periods. This approach reduces energy expenses without compromising user comfort [29]. These shiftable loads play a significant role in reducing energy costs and contribute to more sustainable energy consumption [30].

## 3. Materials and Methods

### 3.1. SEMS System Architecture

SEMS provides an IoT-based solution for monitoring, analyzing, and optimizing energy consumption in smart homes. Figure 1 illustrates the proposed low-cost SEMS architecture. The system utilizes the PZEM-004T power sensor to collect energy data. This sensor accurately measures current, voltage, energy, power, frequency, and power factor in real-time and transmits the processed data to a microcontroller. At the core of SEMS is the Wemos D1 Mini, an ESP8266 (Espressif Systems, Shanghai, China) based microcontroller. This microcontroller processes sensor data and transmits it wirelessly to an IoT platform. The collected data is stored on Blynk 2.0 (Blynk Inc., New York, USA) and visualized through a user-friendly interface. Additionally, users can download this data for detailed analysis. Blynk 2.0 has been selected as a robust IoT platform due to its capabilities in real-time data visualization, device management, and user access control.
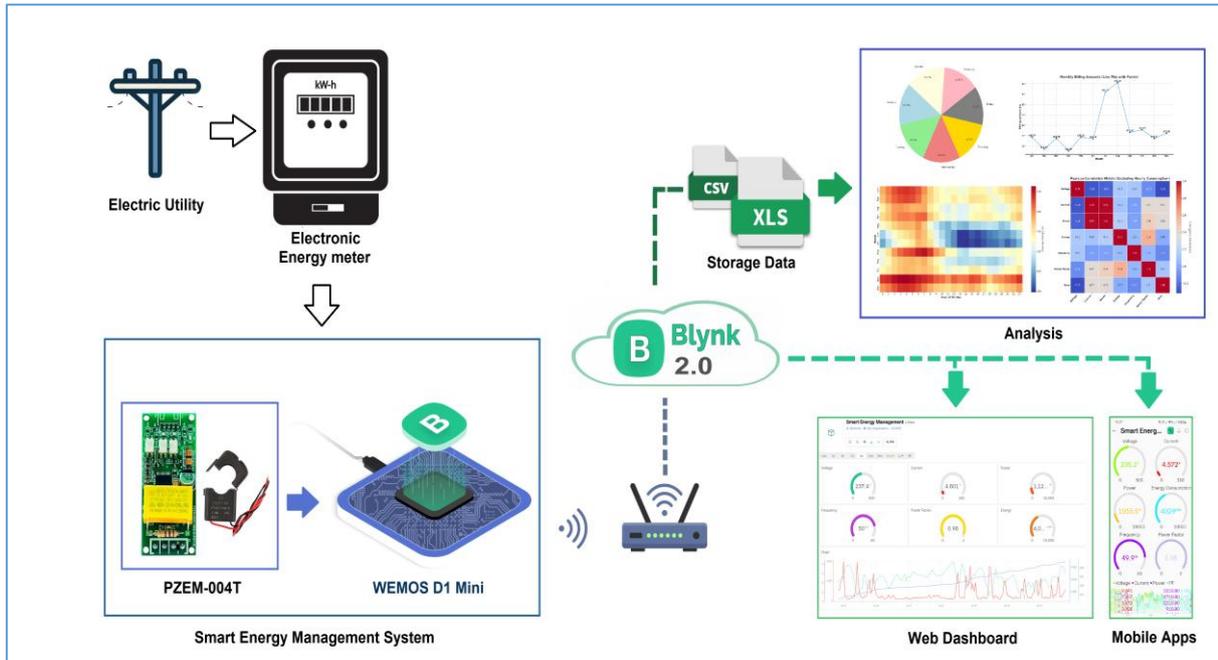
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**Figure 1.** Proposed low-cost SEMS architecture

SEMS not only enables the monitoring of energy consumption data but also facilitates long-term data storage and analysis, allowing users to develop energy efficiency strategies based on this information. With its low-cost components and robust IoT integration, the system effectively enhances energy management.

**Table 1.** SEMS cost breakdown

| Component | Cost [$] |
|---|---|
| Wemos D1 Mini | 3 |
| PZEM-004T Power Sensor | 13 |
| Blynk 2.0 (maker plan, monthly price) | 2 |
| 5V-1A DC Power Supply | 3 |
| Box, other | 4 |
| Total | $ 35 |

Table 1 provides the components of SEMS along with their cost details. While many commercially available Wi-Fi-enabled smart power meters have the capability to store data on a server, these records are typically limited to hourly averages. Although such data can be used to calculate total energy consumption, they are insufficient for detecting power quality issues such as voltage and frequency fluctuations. The proposed SEMS overcomes this limitation by transmitting data on five different power parameters to the server at 5-second intervals, where the server stores the data as 1-minute averages. This approach allows for more precise analysis of instantaneous variations compared to commercial devices and provides real-time feedback to users based on predefined threshold values for energy quality and consumption monitoring. For system validation, a Kohler-brand single-phase, two-wire energy meter was used as a reference device. This meter is a commercially certified measurement device used for billing purposes. To verify the measurement accuracy of the proposed system, the values recorded by the PZEM-004T power sensor were compared against those of reference energy meter. Absolute and percentage error calculations were performed to evaluate the system's reliability and precision. The results confirmed that the proposed SEMS operates within an acceptable accuracy range.

### 3.2. Measurement Mechanism and System Integration

The PZEM-004T power sensor by Peacefair was used to measure energy parameters. To assess the accuracy of these measurements, a single-phase Kohler-brand electronic meter was used as a reference device. The PZEM-004T power sensor is a low-cost, high-accuracy sensor that performs non-invasive single-point power measurement and is widely utilized in IoT-based smart meter designs [31]. The PZEM-004T is an effective tool for optimizing energy consumption in smart homes [32]. By offering IoT-based real-time energy monitoring, management features, user-friendly interfaces, and low-cost solutions, it enhances energy efficiency while reducing energy costs [33]. This sensor helps detect anomalies in energy consumption, alerts users, and promotes energy savings. Its integration into smart home environments significantly improves energy management and monitoring processes [34]. Furthermore, when integrated with an IoT platform, the PZEM-004T provides real-time energy insights through user-friendly interfaces and notification systems, simplifying energy management for users.
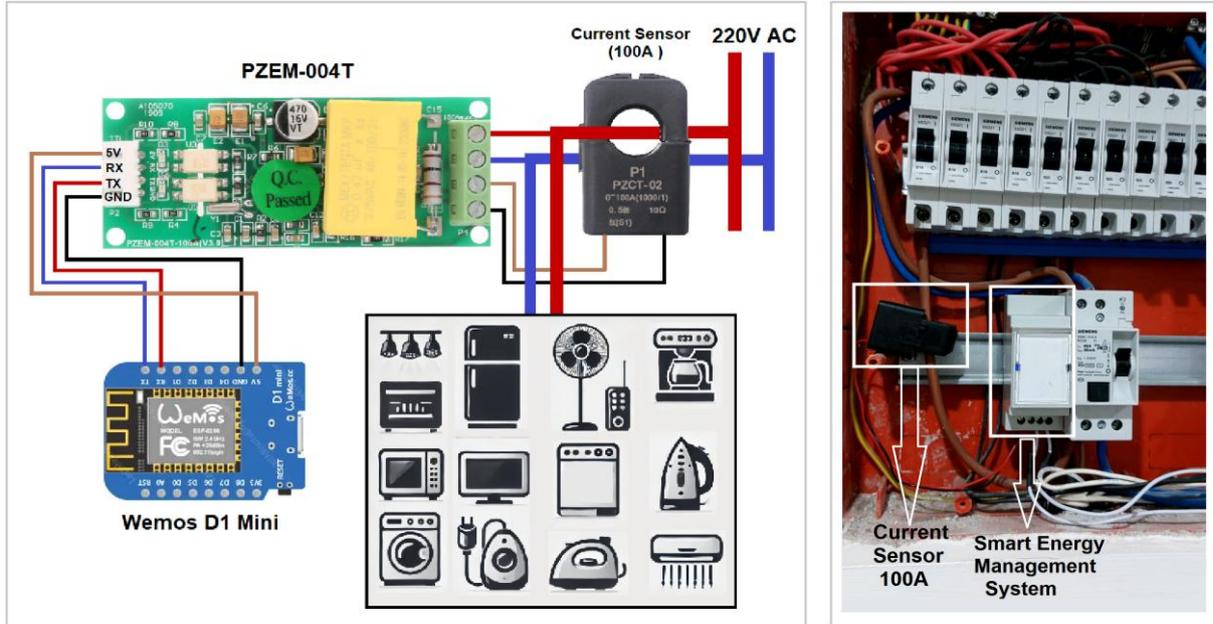
**Figure 2.** PZEM-004T power sensor hardware connection diagram and SEMS electrical panel integration

The power sensor utilizes an internal voltage sensor along with either an internal current sensor (up to 10A) or an external current sensor (up to 100A) to measure electrical parameters. It transmits data to the microcontroller via UART communication, enabling real-time energy consumption monitoring. The IoT-based SEMS hardware connection diagram and electrical panel integration are illustrated in Figure 2. On the left side, the wiring diagram details the communication between the PZEM-004T power measurement module and the Wemos D1 Mini (ESP8266), as well as its integration with power measurement components.

The 100A current sensor is inductively connected to the electrical line to measure current flow, while the PZEM-004T module calculates voltage and power and transmits the data to the microcontroller via the UART protocol. On the right side, SEMS is shown as integrated into the electrical panel, where it is connected to the main power supply line to enhance measurement accuracy and ensure isolation in high-current circuits. The system analyzes load profiles, evaluates power quality parameters, and provides real-time monitoring and decision support mechanisms via the IoT platform.

**Table 2.** Technical specifications of the PZEM-004T power sensor.

| Features | Details |
|---|---|
| Voltage | R: 80-260 V, Res: 0.1 V, Ac: 0.5% |
| Current | R: 0-100 A, Res: 0.001 A, Ac: 0.5% |
| Active power | R: 0-23 KW, Res: 0.1 W, Ac: 0.5% |
| Active energy | R: 0-9999.99 kWh, Res: 1 Wh, Ac: 0.5% |
| Frequency | R: 45-65 Hz, Res: 0.1 Hz, Ac: 0.5% |
| Power factor | R: 0-1, Res: 0.01, Ac: 1% |
| M. Range | 10A , 100A (with External Trans.) |
| Phase | Single phase |
| Physical protocol | UART to TTL communication interface |

The technical specifications of the PZEM-004T power sensor are presented in Table 2. The sensor is capable of measuring voltage within a range of 80–260 V. With an external current transformer, it can measure a maximum current of 100 A and a maximum active power of 23 kW, with a resolution of 0.1 W. Additionally, it can measure active energy up to 10,000 kWh with a resolution of 1 Wh. The sensor supports grid frequency measurement within the 45–65 Hz range, with a precision of 0.001 Hz,

and power factor measurement across the 0–1 range with a resolution of 0.01. In SEMS, data acquisition, processing, and cloud transmission are handled by the Wemos D1 Mini (ESP8266) microcontroller. This microcontroller receives measurement data from the PZEM-004T power sensor, processes it, and transmits it to a cloud-based server. The Wemos D1 Mini is widely utilized in IoT applications due to its integrated Wi-Fi

module, which facilitates seamless data transmission to platforms such as ThingSpeak, Blynk, and Adafruit [35]. The Wemos D1 Mini is equipped with a Tensilica 32-bit RISC CPU Xtensa LX106, operating at 80 MHz, with the capability of overclocking up to 160 MHz. It features low power consumption and operates at 3.3V, making it a highly efficient solution for IoT applications. The microcontroller offers 16 digital I/O pins, along with UART, SPI, I2C, and ADC support, ensuring seamless integration with various sensors and external components. With 4 MB Flash memory and 64 KB SRAM, it provides sufficient storage capacity for data management. The inclusion of a CP2102 USB-TTL converter eliminates the need for an external adapter for programming. The 802.11 b/g/n Wi-Fi support, coupled with an integrated PCB antenna, ensures reliable wireless data transmission. Furthermore, its deep sleep mode is particularly advantageous for applications that demand low energy consumption. From a development perspective, the Wemos D1 Mini is compatible with Arduino IDE, Lua, and MicroPython, facilitating a user-friendly programming experience. Given these features, it serves as a cost-effective and efficient solution for data collection, processing, and remote monitoring in SEMS.

### 3.3. Communication and Data Storage

Blynk 2.0 IoT platform was used as the communication and data storage layer in SEMS. Blynk seamlessly integrates with popular hardware platforms such as Arduino and Raspberry Pi, as well as professional-grade devices, including Particle and Texas Instruments boards, Espressif's ESP8266 and ESP32, NCD.io sensors and gateways, and Zephyr-enabled hardware. This flexibility allows it to support a wide range of IoT project requirements, whether for retrofitting existing products or developing new ones.

Measurement data is stored on the cloud-based Blynk IoT server in three different time intervals: 1-minute averages with 525,600 data points per year, 1-hour averages with 29,000 data points per year, and 1-day averages with 365 data points per year. This data storage approach provides households with insights into their energy consumption patterns, enabling further analysis to enhance energy efficiency.

Blynk 2.0 stands out as an IoT platform due to its user-friendly interface, real-time data collection and monitoring capabilities, multi-device and sensor integration, mobile application support, and security features. These attributes make it a preferred platform for IoT projects [36]. The Blynk IoT platform has been effectively utilized in home security and automation [37], agriculture and irrigation systems [38], healthcare applications [39], and smart energy management [40]. By enabling users to remotely monitor and control their devices, it enhances both efficiency and user experience

### 3.4. User Interfaces and Energy Management

A web-based dashboard and a mobile application, accessible via the Blynk 2.0 platform, were developed to enable users to monitor their energy consumption. This platform provides visual representations of energy consumption trends, real-time data, and historical reports, offering users detailed insights.



(a)      (b)

**Figure 3.** User interfaces developed with the Blynk 2.0 platform: (a) mobile interface, (b) web dashboard.

As illustrated in Figure 3a, the mobile application, and in Figure 3b, the web dashboard, allow users to track their energy consumption in real time and perform long-term analyses by accessing historical data. The interface

design includes functionalities to alert users in case of unexpected high energy consumption or system malfunctions. Additionally, it can send notifications when energy-saving goals are achieved or when special events occur. Furthermore, the developed user interfaces provide real-time notifications based on predefined threshold values, alerting users to optimize power consumption and improve overall energy efficiency. The data transmitted from the microcontroller is stored in Blynk's database, enabling users to analyze their historical energy consumption. Users can download the data in CSV or XLS format for more detailed analysis. Blynk IoT platform provides residents with access to measurement data through both a smartphone application and a web-based interface. This interface allows users to monitor, adjust, and optimize their energy consumption. Additionally, it provides real-time energy consumption and cost information, along with various alert notifications, helping users make informed energy management decisions.

## 4. Results and Discussion

In this section, the data obtained on energy consumption and power quality has been analyzed. The examination covers critical parameters such as hourly, daily, weekly, and seasonal energy consumption trends, voltage and frequency variations, weekday and weekend consumption patterns, as well as billing processes and energy usage based on tariff structures. First, the

dynamics of energy consumption provide a comprehensive evaluation of consumption profiles by revealing variations occurring at different time intervals. In particular, the differences in energy consumption between holiday periods and regular days have been analyzed to detail the impact of user habits on energy management. Additionally, voltage and frequency analyses play a significant role in determining the power quality of the system. The study examines how voltage fluctuations change over time depending on load variations and discusses their effects on system stability. Finally, consumption analyses based on billing and tariff structures evaluate long-term consumption trends, providing key findings on potential energy management measures. These analyses contribute to the development of energy-saving strategies, forming a foundation for policy recommendations aimed at improving energy efficiency.

### 4.1. Temporal Analysis of Energy Consumption

Understanding the temporal patterns of energy consumption contributes to both individual energy savings and the development of energy management strategies. In this context, hourly, daily, weekly, and seasonal variations in energy consumption have been analyzed to evaluate consumption trends over specific time intervals. The data provides insights into both short-term fluctuations and long-term trends, offering valuable clues for enhancing system efficiency.
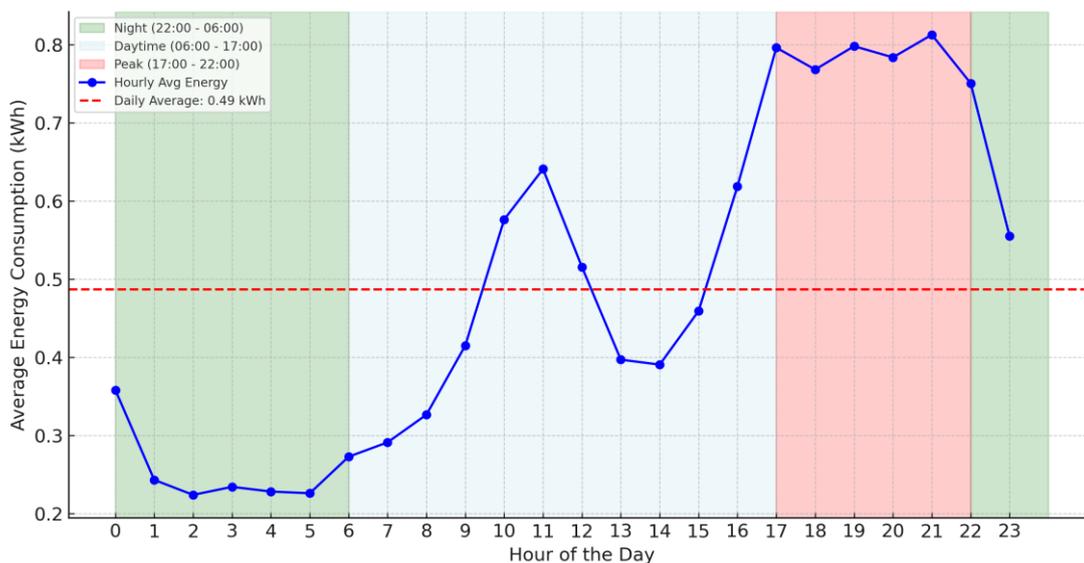


**Figure 4.** Distribution of daily average energy consumption by tariff time intervals (annual basis)

The daily hourly averages of energy consumption and tariff time intervals calculated over one year are presented in Figure 4. During the daytime period (06:00–17:00), consumption exhibits an increasing trend, particularly due to fluctuations in the early morning hours, which result from morning preparations and daytime activities. The peak period (17:00–22:00)

corresponds to the highest energy consumption, influenced by work and school returns. During these hours, there is an increase in the use of cooking appliances, lighting, heating/cooling systems, and entertainment devices. In the nighttime period (22:00–06:00), energy consumption remains at its lowest levels, as most users are asleep, leaving only essential devices

operating. These time-based consumption trends serve as a valuable reference for electric grid management and the development of demand response strategies. Household energy consumption habits generally exhibit significant differences between weekdays and weekends. The differences in hourly average energy consumption for weekdays and weekends are shown in Figure 5.
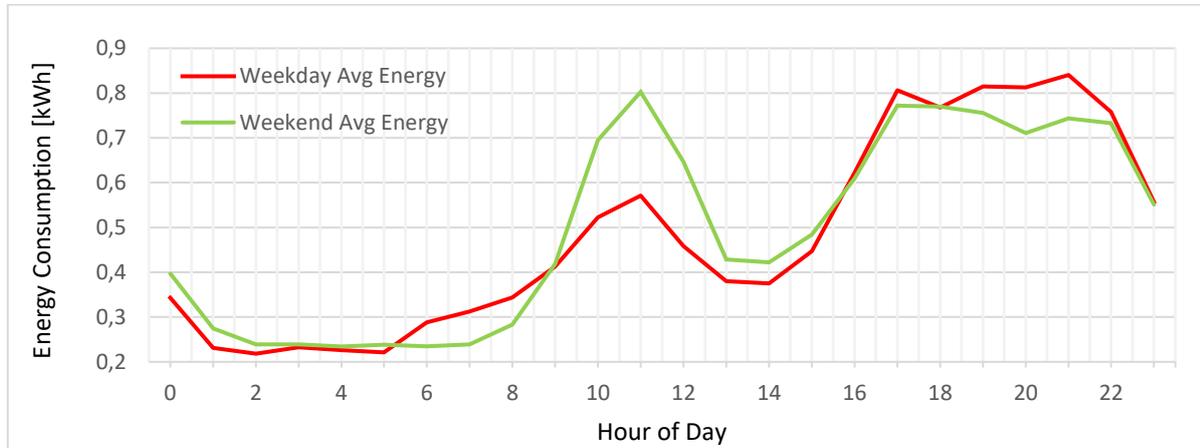


**Figure 5.** Hourly average energy consumption on weekdays and weekends

During weekdays, energy consumption begins to increase at 06:00, whereas on weekends, this increase is observed after 08:00. This difference is attributed to people waking up earlier on weekdays for work or school, while they tend to wake up later on weekends. During midday hours, energy consumption is lower on weekdays compared to weekends, primarily because households tend to stay at home more frequently during weekends. The maximum consumption hour on weekdays is 21:00, reaching 0.84 kWh, while the minimum consumption hour is 02:00, with 0.22 kWh. On weekends, maximum consumption occurs at 11:00 with 0.80 kWh, while minimum consumption is observed at 04:00, with 0.23 kWh. Although peak period consumption (17:00–22:00) shows similarities between weekdays and weekends, it is slightly higher on weekdays. Household energy consumption varies not only on a daily basis but also monthly. A comparative analysis of monthly energy consumption across daytime, peak, and nighttime tariff periods is presented in Figure 6.
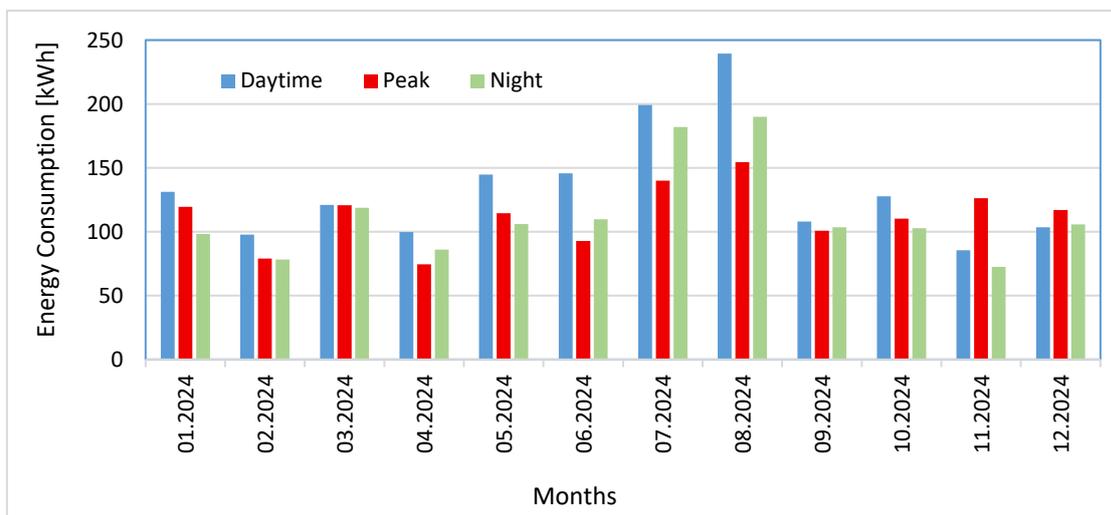


**Figure 6.** Monthly energy consumption distribution by tariff

Energy consumption shows a significant increase during the summer months. In particular, peak consumption reaches its highest levels in July (199.24 kWh) and August (239.3 kWh) compared to other months of the year. The primary reason for this increase is the use of air conditioning systems for cooling during these months. In November and December, nighttime consumption increases, while peak period consumption decreases. Overall, tariff-based analyses reveal how electricity consumption habits are shaped by seasonal variations.
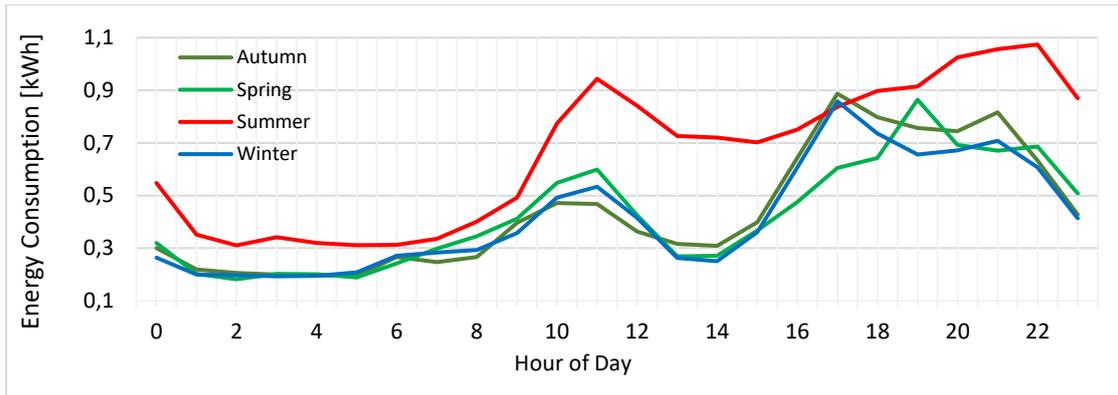
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**Figure 7.** Hourly average energy consumption by seasons

Figure 7 illustrates the hourly energy consumption patterns across different seasons. In winter, an increase in consumption is observed during the morning and evening hours due to the impact of heating systems. In summer, high-energy consumption is particularly noticeable during midday and evening hours, primarily driven by air conditioning usage. Spring and autumn exhibit a more balanced consumption trend due to milder weather conditions.
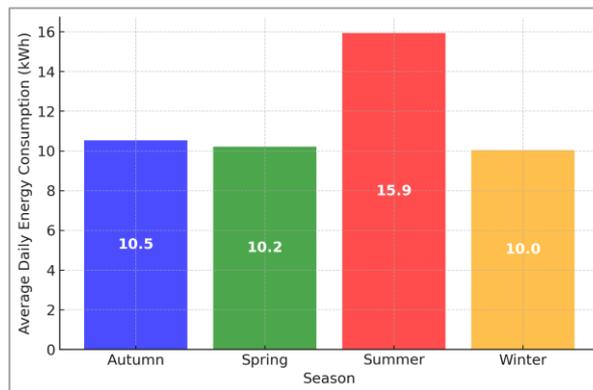


**Figure 8.** Daily average energy consumption by seasons.

Figure 8 presents the daily average energy consumption across different seasons. During the summer months, energy consumption reaches its highest level, with a daily average of 15.9 kWh. This increase is attributed to the heightened use of air conditioning and cooling systems in response to rising temperatures. In contrast, the daily average consumption values in spring, autumn, and winter remain relatively close to each other, exhibiting a more balanced trend.
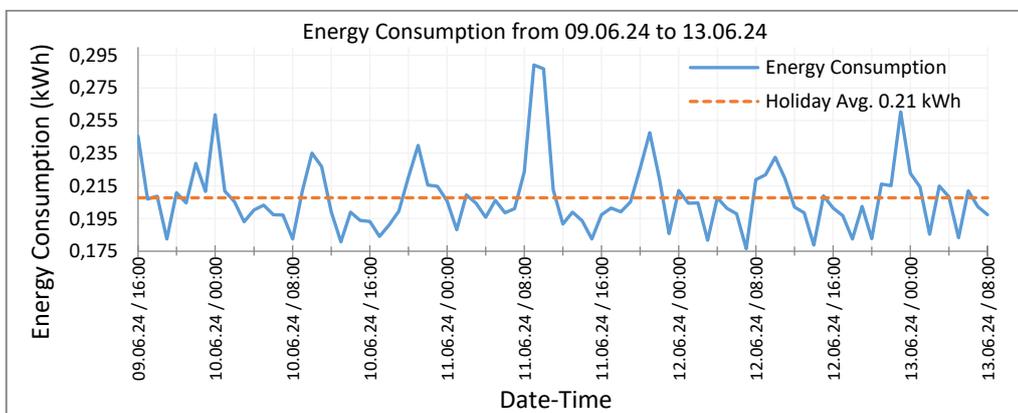


**Figure 9.** Energy consumption during the holiday period (June 9–13, 2024)

The energy consumption pattern during the holiday period from June 9 to 13, 2024, is presented in Figure 9. A significant decrease in energy consumption is observed throughout the holiday. During this period, when energy consumption is at its minimum, the average consumption

of continuous loads such as refrigerators and deep freezers is recorded as 0.21 kWh. These loads maintain a power consumption range between 180 W and 290 W throughout the holiday period.
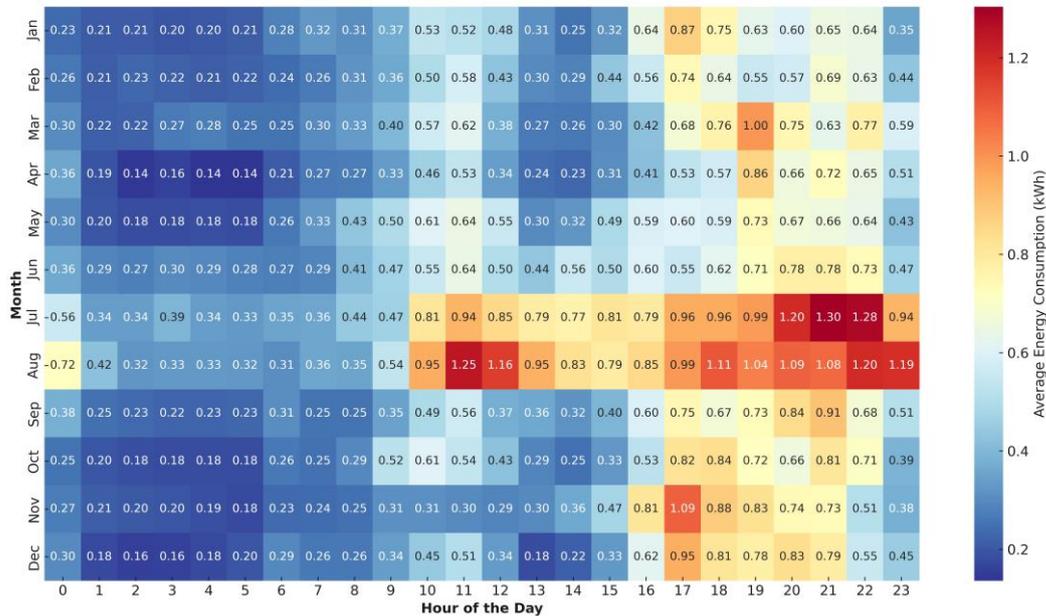


**Figure 10.** Annual hourly average energy consumption heat map

The heat map displaying hourly energy consumption recorded over one year is presented in Figure 10. This map provides valuable insights into daily and seasonal consumption patterns, as well as household lifestyle habits. A notable decrease in consumption between 23:00 and 01:00 indicates the household's sleep period. Conversely, a sharp increase in consumption between 08:00 and 09:00 reflects the morning routine as the day begins. During midday hours (12:00–13:00), energy consumption remains relatively low, which may be attributed to fewer people being at home. In the late afternoon (16:00–17:00), consumption rises again, aligning with household members returning home.

Seasonal demand fluctuations are also observed, with higher energy consumption for cooling in summer and for heating in winter contributing to variations in the heat map. These insights play a critical role in planning smart home automation systems tailored to user habits and in developing energy efficiency strategies. The identified patterns related to sleep, wake-up, departure, and return times can be utilized to optimize the scheduling of various systems such as heating, cooling, and lighting, enhancing both security and energy efficiency.

**4.2. Voltage-Frequency Variation Analysis**

Fluctuations in grid voltage are directly related to load demand, instantaneous consumption changes, and the overall loading condition of the grid. Excessive

variations in voltage levels can negatively impact the efficiency and lifespan of electrical equipment, while also posing risks to grid stability. Therefore, analyzing voltage fluctuations over time is of great importance for the development of balancing strategies in energy systems.
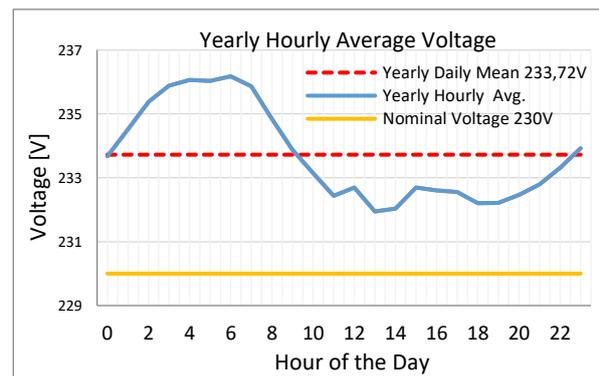


**Figure 11.** Annual hourly average voltage levels

The grid voltage, calculated as hourly averages over one year, is presented in Figure 11. The annual average voltage is 233.72 V, which is approximately 1.67% higher than the nominal 230 V level. During nighttime hours, voltage rises to around 236 V due to lower energy demand, whereas during daytime hours, it drops to 232 V due to increased consumption.

These fluctuations are influenced by factors such as the number of users supplied by the same transformer, consumption habits, and transformer distance. In the long term, this data serves as an important reference for voltage regulation and grid stability management.
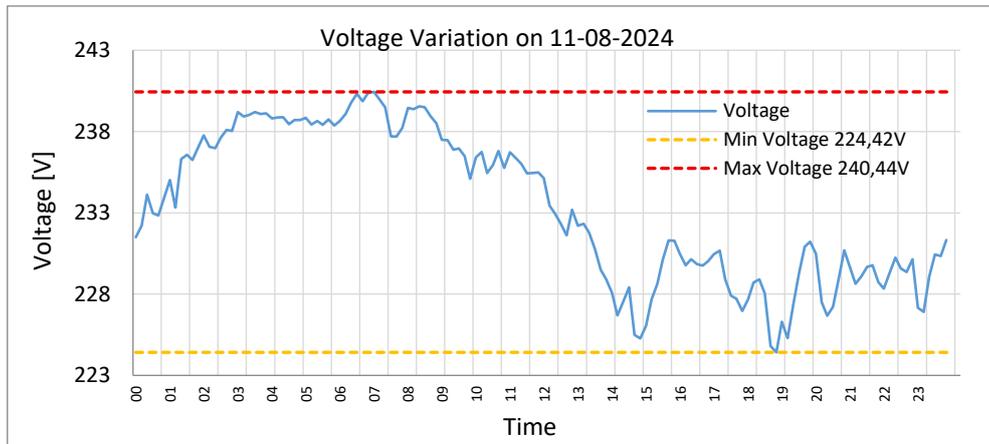


**Figure 12.** Voltage variation recorded on august 11, 2024

The 10-minute average voltage values recorded on August 11, 2024, the day with the highest voltage fluctuation within a 24-hour period, are presented in Figure 12. Throughout the day, voltage varied between 224.42 V and 240.44 V, exhibiting an approximate 4.54% fluctuation.

According to TS EN 50160, IEC 61000-2-2, and IEEE 1159 standards, the acceptable voltage range for nominal voltage is ±10% (207V - 253V). Since the recorded values remain within these limits, the fluctuations are considered within an acceptable range.
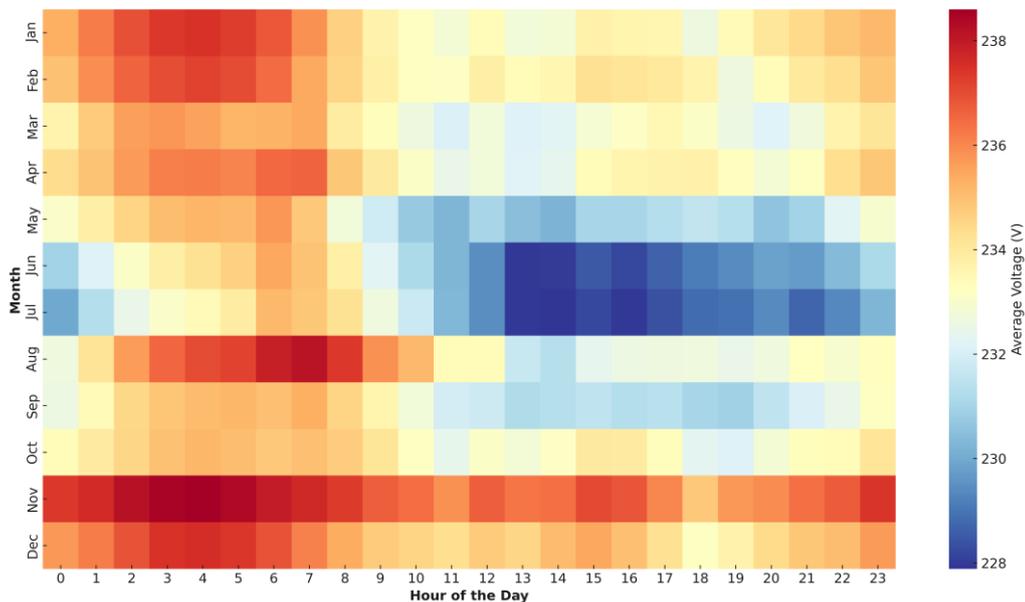


**Figure 13.** Heat map of monthly hourly voltage variations

The heat map displaying monthly hourly average voltage levels is presented in Figure 13. This map highlights voltage fluctuations at different hours of the day and identifies critical time periods where fluctuations are more pronounced. During the summer months, voltage drops are observed due to high energy demand, whereas in November and December, voltage levels remain above the annual average. These findings indicate that grid voltage undergoes significant seasonal variations. Specifically, voltage levels decrease during summer, when energy demand is high, while they tend to increase during seasons with lower energy demand. Understanding daily variations in voltage levels is essential for developing long-term energy management strategies. Figure 14 presents the average voltage values recorded for each day of the week.
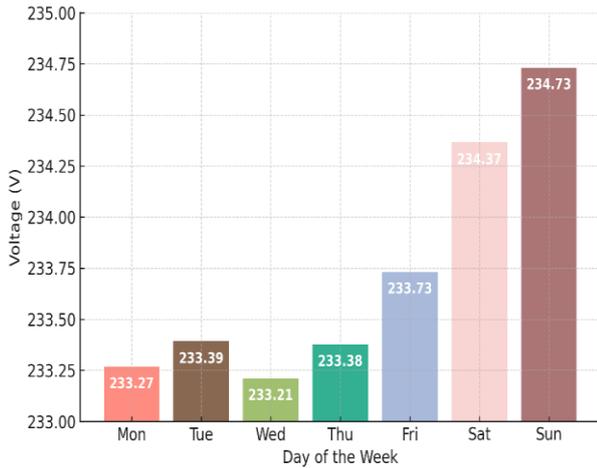
**Figure 14.** Weekly average voltage levels

On Monday, the voltage is approximately 233.27 V, fluctuating within a range of 233.21–233.73 V throughout the weekdays. However, towards the weekend, an increase in voltage levels is observed, reaching 234.37 V on Saturday and peaking at 234.73 V on Sunday. This trend indicates that voltage remains relatively lower during weekdays due to higher energy demand, whereas it rises over the weekend as demand decreases. Grid frequency is one of the most critical parameters in determining the stability of the electrical system. For power generation systems to operate stably, frequency must be maintained within specific limits. Grid frequency serves as a key indicator of the instantaneous balance between energy generation and consumption. A heat map visualizing the hourly average frequency variations for each month over one year is presented in Figure 15.
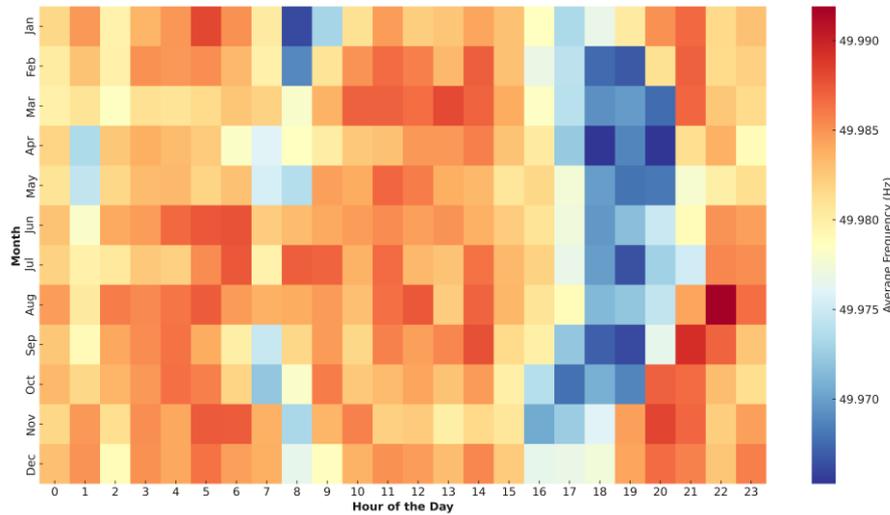


**Figure 15.** 24-hour average frequency values over a 12-month period

Fluctuations in grid frequency vary at different hours of the day due to load changes and instantaneous deviations in generation levels. An analysis of the data reveals that frequency remains relatively stable during morning hours, regardless of the season, whereas fluctuations increase towards the evening hours

## 4.3. Energy Consumption Trends and Billing

Electricity consumption trends play a crucial role in determining energy costs and helping users manage their billing expenses. Analyzing consumption patterns provides opportunities for both individual and industrial users to reduce energy consumption and optimize billing processes. Comparing the accuracy of different energy measurement systems is essential for ensuring reliable energy consumption analysis. Over the course of one year, energy consumption data obtained from the KOHLER meter and SEMS was compared, and the relative error values between both measurement systems are presented in Table 3.

**Table 3.** Monthly energy consumption values for 2024 and measurement errors calculated for SEMS

| Month | KOHLER (kWh) | SEMS (kWh) | A.Error (%) |
|---|---|---|---|
| 2024-01 | 348,77 | 348,10 | 0,19 |
| 2024-02 | 254,91 | 254,82 | 0,03 |
| 2024-03 | 360,36 | 360,54 | 0,05 |
| 2024-04 | 260,12 | 260,23 | 0,04 |
| 2024-05 | 365,20 | 365,08 | 0,03 |
| 2024-06 | 348,22 | 347,63 | 0,16 |
| 2024-07 | 521,14 | 521,92 | 0,15 |
| 2024-08 | 583,86 | 584,73 | 0,14 |
| 2024-09 | 312,30 | 312,20 | 0,03 |
| 2024-10 | 340,60 | 340,27 | 0,09 |
| 2024-11 | 284,46 | 285,93 | 0,51 |
| 2024-12 | 326,15 | 323,51 | 0,81 |
| | **4305,98** | **4305,06** | **0,021** |

An analysis of Table 3 reveals that the error percentage between the reference measurement device (Kohler) and SEMS is remarkably low. The highest error margin was recorded in December at 0.81%, while the lowest error rate was observed in February at 0.03%. The overall error value was calculated as 0.021%, indicating that the two systems produce highly consistent results. The energy consumption values measured by both systems are extremely close, with an accuracy of 99.98%, demonstrating that SEMS does not exhibit any systematic errors. The high correlation between the two measurement systems confirms SEMS's reliability in analyzing consumption trends and ensuring accuracy in billing processes. The monthly electricity bill variations and trends for the household over one year are presented in Figure 16.
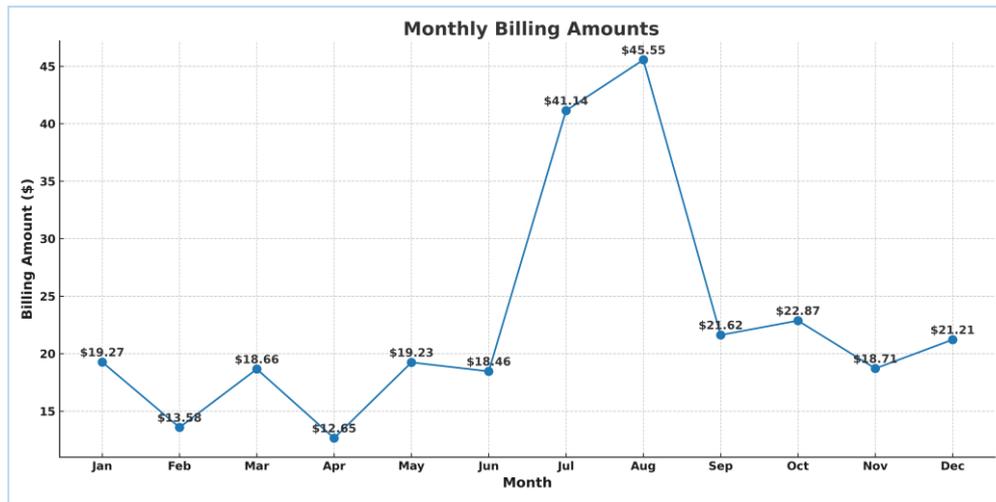


**Figure 16.** Monthly energy consumption and billing amounts

Significant seasonal fluctuations have been observed in billing amounts. In particular, electricity bills peak during the summer months, driven by increased energy demand. Figure 17 presents the distribution of total annual energy consumption across daytime, peak, and nighttime tariff periods. The graph reveals that a substantial portion of energy consumption (31.34%) occurs during the peak tariff period, where energy costs are higher. As part of load shifting strategies, reducing high consumption during peak hours and shifting it to nighttime tariffs can provide significant cost savings. Such strategies benefit both individual consumers by lowering electricity bills and improve grid load balancing.

Electricity tariffs offer different pricing structures to help consumers optimize their energy usage based on time. The household's total annual consumption consists of 37.24% (1,603 kWh) during the daytime tariff, 31.34% (1,349 kWh) during the peak tariff, and 31.43% (1,356 kWh) during the nighttime tariff.

When examining the household's consumption trends, shifting consumption during the high-cost peak period to the lower-cost nighttime or daytime period is necessary to optimize energy costs. In time-based load shifting, the programmability of household loads and user comfort are important factors that need to be considered.

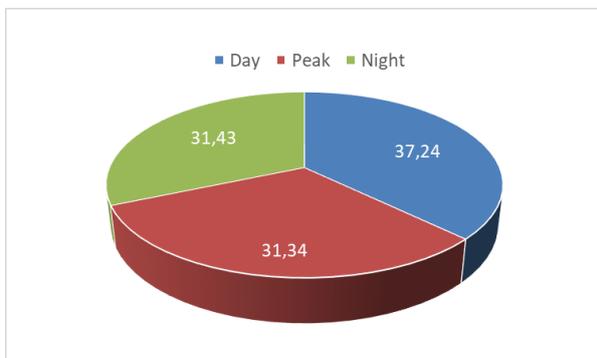**4.4. Impact of Time-Based Load Shifting Scenarios on Energy Costs**

Time-based load shifting is a strategy aimed at reducing energy costs by shifting electricity consumption from high-cost hours to lower-cost periods. In three-time tariffs, energy usage is increased during off-peak nighttime or daytime periods to avoid high prices during peak hours. Significant savings can be achieved by operating high-energy-consuming appliances, such as electric vehicle chargers, water heaters, and household appliances, during lower-cost hours. Managing electricity consumption based on time is a critical strategy for both reducing energy costs and maintaining grid balance. In this section, four different load-shifting scenarios were applied by considering electricity tariff variations at different times of the day. The household



**Figure 17.** Distribution of total annual energy consumption by daytime, peak, and nighttime tariffs

consumption profile was taken into account, and energy usage was shifted to lower-cost time intervals. Based on real data analysis, the impact of load-shifting strategies on electricity bills was assessed, potential cost savings were calculated, and optimal scenarios were determined. A three-time tariff system charges electricity consumption at different rates depending on the time of the day. This tariff model typically includes three-time intervals: peak, daytime, and nighttime, with different unit prices for each period. In Turkey, for households consuming more than 5,000 kWh annually, the three-time tariff system provides cost savings. However, for the household examined in this study, with an annual energy consumption of 4,306 kWh, the total energy cost was calculated as approximately $273 per year under the single-time tariff. If the three-time tariff had been applied, the cost would have been around $362, resulting in a 32.28% increase in energy expenses. Therefore, for households with relatively lower electricity consumption, the single-time tariff model remains the preferred option in Turkey due to cost advantages. However, in cases requiring high energy consumption, such as electric vehicle charging, switching to a three-time tariff system can lead to significant cost savings. Table 4 presents the current electricity pricing rates for Single-Time and Three-Time Tariffs applicable to residential users in Turkey.

**Table 4.** Energy pricing for single and three-time tariffs (residential) [41].

| Tariff Type | Energy Amount | Low Tier Charge ($/100 kWh) | High Tier Charge ($/100 kWh) | Day Charge ($/100 kWh) | Peak Charge ($/100 kWh) | Night Charge ($/100 kWh) |
|---|---|---|---|---|---|---|
| Single Time (Low Voltage Residential) | 0-220 kWh | 5,67 | - | - | - | - |
| | >220 kWh | - | 8,35 | - | - | - |
| Three Time (Low Voltage Residential) | 100 kWh | - | - | 8,63 | 12,65 | 5,39 |

Billing for the household was conducted using the single-time tariff throughout one year. In the single-time tariff, the pricing structure applies a low-tier rate of $5.67 per 100 kWh for consumption up to 220 kWh, while a high-tier rate of $8.35 per 100 kWh is applied for consumption exceeding 220 kWh. In contrast, the three-time tariff applies different rates for each time period. The daytime rate is $8.63 per 100 kWh, the peak rate is $12.65 per 100 kWh, and the nighttime rate is $5.39 per 100 kWh.
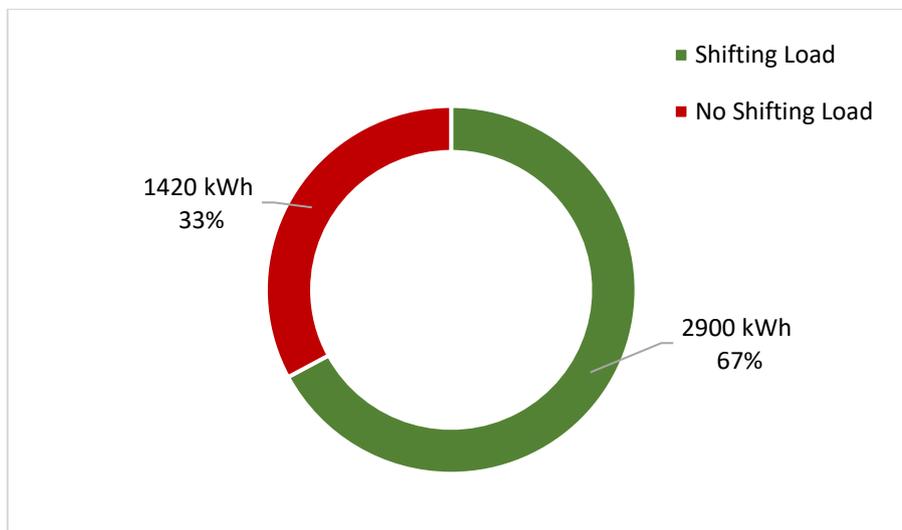


**Figure 18.** Shiftable load ratios of annual household energy consumption

Figure 18 presents the load shifting ratios based on the household's total annual energy consumption and load types. The analysis indicates that a significant portion (67%) of total energy consumption can be shifted to time periods with more economical tariffs through load shifting strategies.
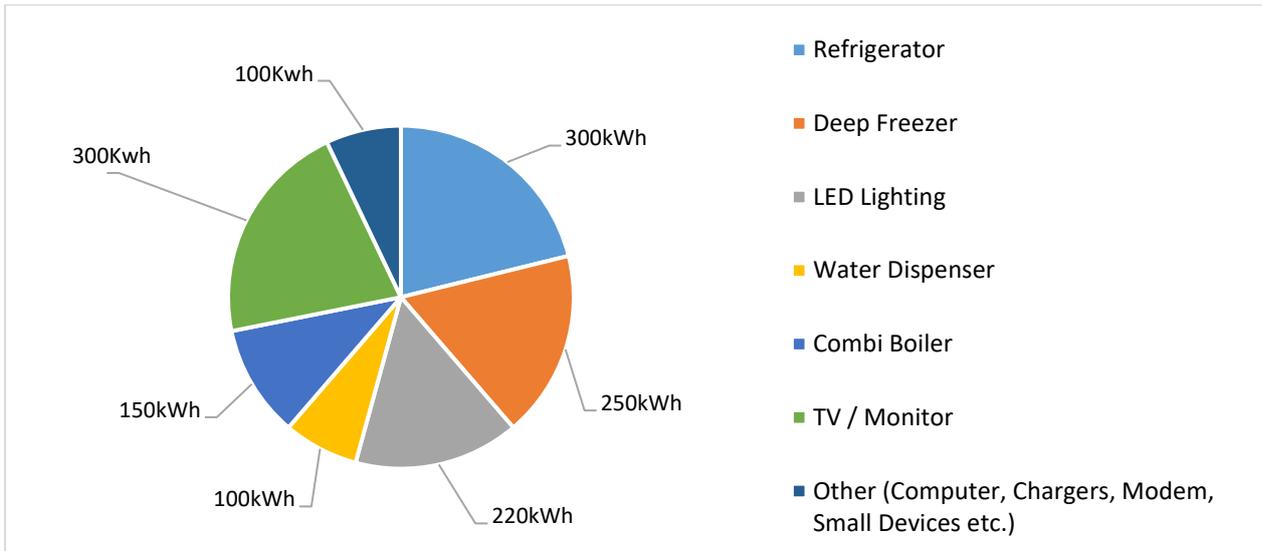
**Figure 19.** Annual energy consumption of non-shiftable loads

The pie chart in Figure 19 illustrates the annual energy consumption of non-shiftable loads in the household. The chart presents the energy usage distribution of appliances such as refrigerators, deep freezers, LED lighting, water dispensers, and similar devices. Since these loads require continuous operation, they cannot be shifted based on time-of-use tariffs. However, their energy consumption can be reduced by improving energy efficiency or limiting usage durations where possible.
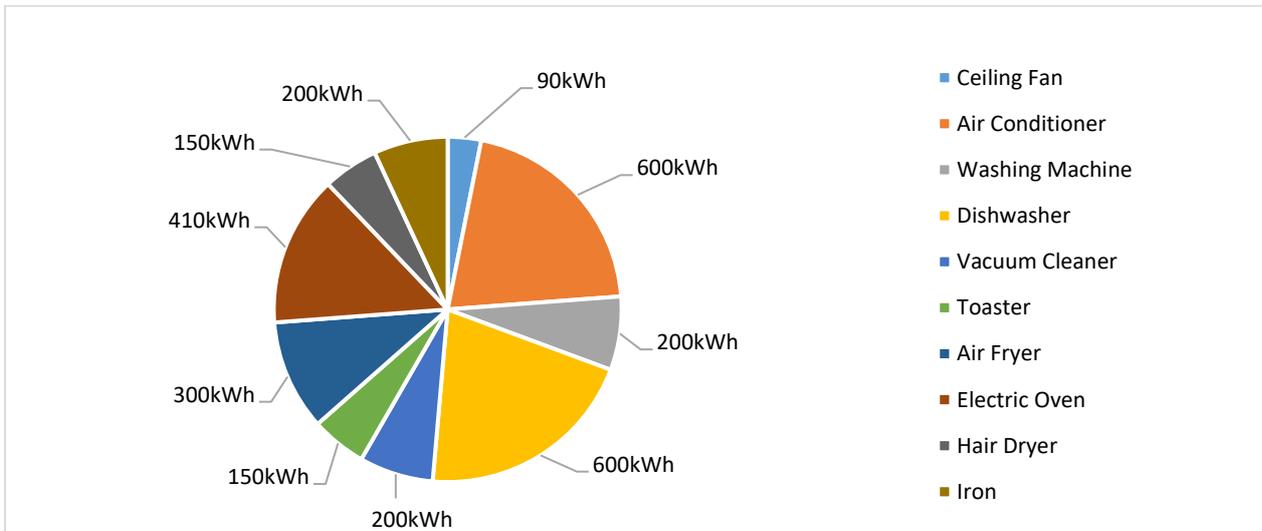


**Figure 20.** Annual energy consumption of shiftable loads

Figure 20 presents the annual energy consumption of shiftable loads in the household. Since these devices have flexible usage hours, they can be shifted to lower-cost time periods, providing a cost advantage. Appliances such as dishwashers, washing machines, air conditioners, and electric ovens can be programmed using timers, allowing them to operate during economical tariff hours. Additionally, devices like air fryer, toaster, and iron can be optimized based on user habits. Considering the annual household energy consumption, hourly daily averages, and the shiftable load ratio presented in Figure 18, four time-based load-shifting scenarios were applied:

- Shifting from Peak Hours to Nighttime
- Shifting from Peak Hours to Daytime
- Shifting from Daytime to Nighttime
- Shifting from Peak and Daytime to Nighttime

Shifting from Peak Hours to Nighttime is a strategy that aims to transfer energy consumption during peak hours (typically 17:00 - 22:00) to the lower-cost nighttime period (22:00 - 06:00). This approach helps avoid high tariff rates, resulting in cost savings. Shifting from Peak Hours to Daytime involves transferring energy consumption from peak hours to the generally lower-cost

daytime period (06:00 - 17:00). This method is particularly useful when shifting to nighttime is not feasible, providing an alternative way to reduce costs by avoiding peak tariffs. Shifting from Daytime to Nighttime moves energy consumption during daytime hours to the lower-cost nighttime period. This method is especially effective for loads with flexible scheduling, such as washing machines and electric vehicle charging, allowing for significant savings. Shifting from Peak and Daytime to Nighttime transfers consumption from both peak and daytime periods to the lowest-cost nighttime

tariff. Designed to achieve maximum cost savings, this strategy is particularly applicable to highly flexible loads, leading to substantial reductions in energy expenses.

The primary objective of these scenarios is to optimize total costs by shifting consumption to lower-cost time periods. Within the three-time tariff system applied to the household, load shifting ratios of 25%, 50%, and 75% were implemented, and the effects of these different shifting scenarios on electricity bills were analyzed.
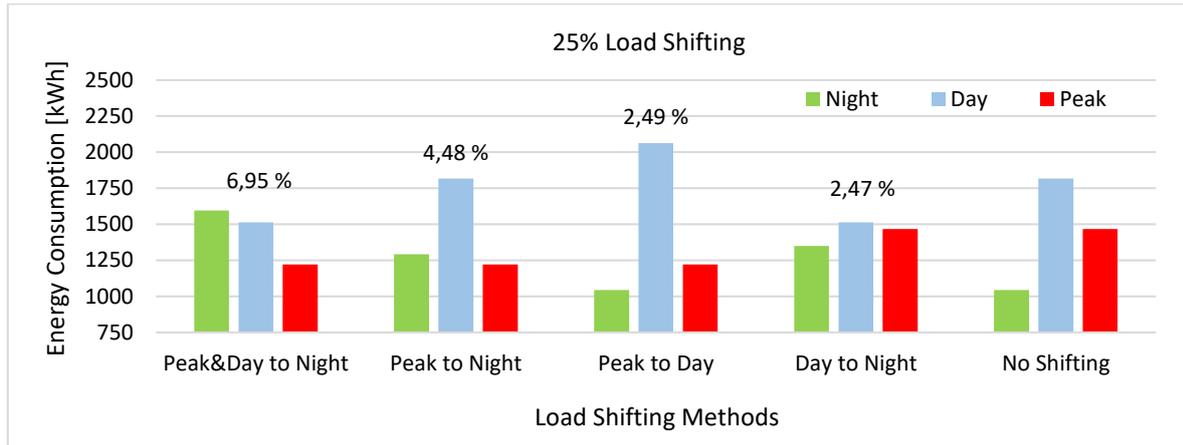


**Figure 21.** Impact of 25% load shifting on bill savings for different load shifting strategies

The impact of a 25% load shifting ratio on the energy consumption profile and the corresponding bill savings rates is presented on Figure 21. The percentages 6.95%, 4.48%, 2.49%, and 2.47% displayed on the graph represent the bill savings achieved for each load shifting scenario.

Among the strategies, the "Peak & Day to Night" method provides the highest savings, while the "Peak to Day" method results in the lowest savings rate. These findings indicate that shifting consumption to the lower-cost nighttime tariff offers significant economic benefits.
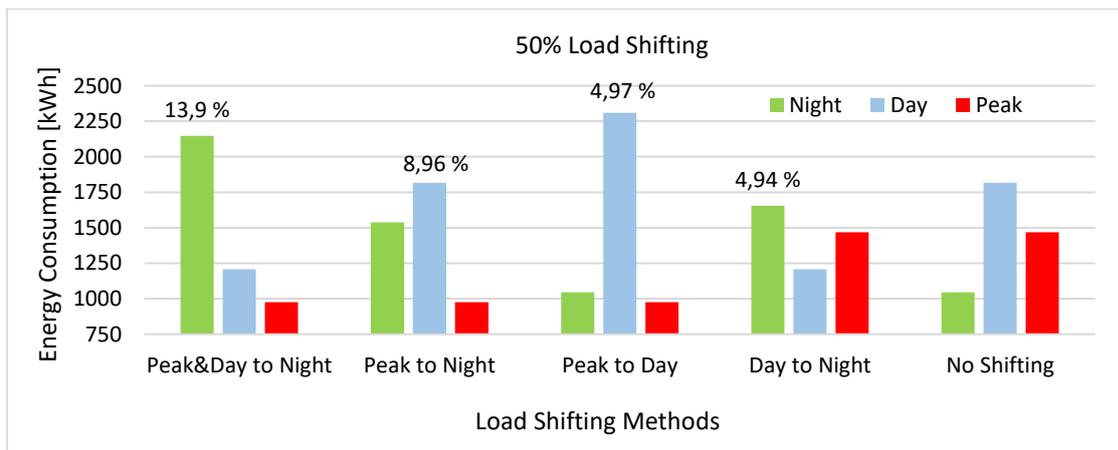


**Figure 22.** Impact of 50% load shifting on bill savings for different load shifting strategies

Figure 22 illustrates the impact of a 50% load shifting ratio on energy consumption and the corresponding savings rates. The highest savings rate, 13.9%, was achieved using the "Peak & Day to Night" strategy. The "Peak to Night" (8.96%) and "Day to Night" (4.94%)

scenarios also provided notable cost advantages. However, the "Peak to Day" method resulted in the lowest savings rate of 4.97%. These findings highlight that shifting consumption to nighttime hours is a key strategy for reducing energy costs.
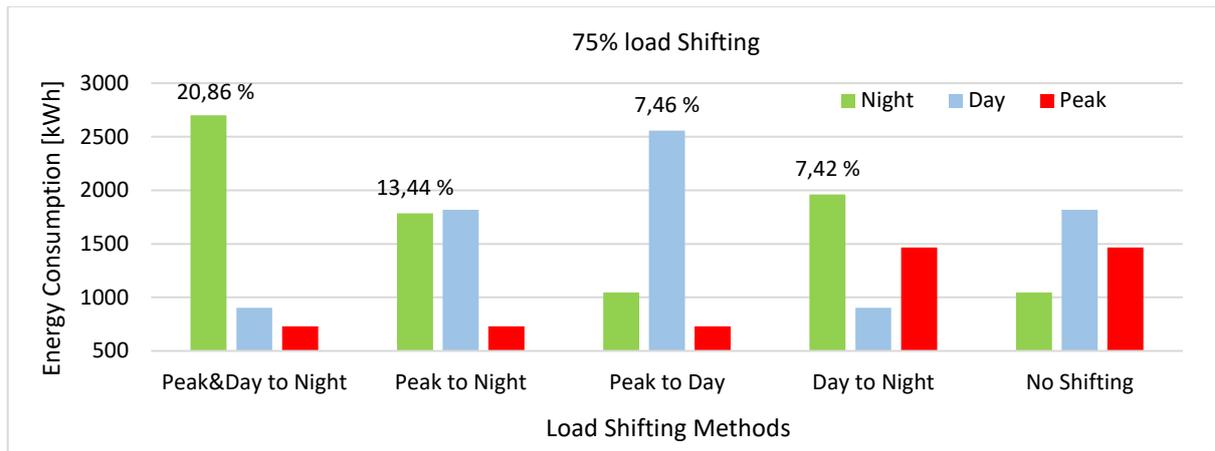
**Figure 23.** Impact of 75% load shifting on bill savings for different load shifting strategies

Figure 23 illustrates the impact of a 75% load shifting ratio on energy consumption and the corresponding savings rates. The "Peak & Day to Night" strategy provides the highest cost savings, achieving a 20.86% reduction in energy expenses. The "Peak to Night" method results in a 13.44% savings, while the "Day to Night" strategy offers a more limited reduction of 7.42%. The "Peak to Day" method provides the lowest cost advantage, with a savings rate of 7.46%. The results for different load shifting ratios and strategies demonstrate that shifting consumption from peak and daytime hours to nighttime yields the greatest savings, with bill reductions of up to 20.86%. Meanwhile, shifting only from peak to nighttime results in 13.44% savings. These findings confirm that load shifting strategies play a critical role in reducing energy costs and highlight the importance of maximizing the benefits of nighttime tariffs.

## 5. Conclusion

This study focused on the development of a low-cost IoT-based SEMS to optimize energy consumption and reduce costs in smart homes. SEMS transmits real-time energy consumption data to the Blynk 2.0 platform, providing long-term analysis capabilities. Comparisons with a commercial Kohler measurement device confirmed that the system achieves an accuracy rate of 99.98%. Additionally, SEMS is capable of evaluating power quality components, analyzing voltage variations and frequency fluctuations. The study examined daily, weekly, and seasonal energy consumption patterns and analyzed consumption variations. Four different load-shifting scenarios were evaluated, demonstrating that redirecting high-cost peak-hour consumption to lower-cost nighttime tariffs can lead to cost savings of up to 20.86%. The impact of electricity tariffs on consumers was also analyzed, revealing that while three-time tariffs may introduce additional costs depending on consumption habits, they can offer significant advantages for high-energy-demand systems. The proposed system

stands out compared to commercial measurement devices due to its ability to record data at higher frequencies and analyze not only consumption trends but also grid voltage stability and power quality. While commercial meters typically log hourly average consumption, SEMS performs measurements at five-second intervals, enabling the detection of sudden voltage fluctuations and frequency variations. Furthermore, its real-time notification mechanism allows users to be informed about power quality issues, promoting more conscious energy management. This study provides a foundation for future low-cost solutions in smart grids, demand management systems, and energy optimization. The integration of SEMS with advanced energy management features such as consumption forecasting, automated load shifting, and dynamic tariff management is envisioned. Additionally, the system's integration with renewable energy sources will support the effective management of variable generation sources, such as solar and wind energy. In conclusion, the developed SEMS offers an effective solution in smart energy management, with high-accuracy data recording, low-cost implementation, and a scalable system architecture. The widespread adoption of such systems will contribute to lower energy costs for individual consumers and better load balancing for grid operators, making a significant impact on sustainable energy management.

**Author's Contributions**

**Mehmet Taştan:** Drafted and wrote the manuscript, performed the experiment and result analysis

**Ethics**

There are no ethical issues after the publication of this manuscript.

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