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A Case Study of Load Scheduling For Home Energy Management with Integrated Renewable Energy

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ABSTRACT

Smart grids are very comprehensive systems where each sub-unit from generation to consumption should be considered separately. Home energy management systems and demand-side load management applications are also among the most important issues of smart grid systems. In this study, a smart home energy management model was developed in this concept, and energy management solutions were presented through an exemplary model. For this purpose, a home energy management algorithm was developed and simulated in the MATLAB Simulink environment by taking an apartment in Esenler, Istanbul as a reference. The smart home model discussed in this simulation study can generate its own electricity with renewable energy sources, store excess electrical energy in battery groups and also sell the surplus to the grid. This home model also enables end-users to control peak loads and schedule home appliances, especially during peak hours, following a demand-response program to consume energy more efficiently. Then, in order to see the electricity consumption results, electricity bill calculations were made according to both single and triple tariff pricing. The benefits of this model to the consumer and the grid were investigated, and also its effects on efficiency were examined. The results are given comparatively and the consumer's saving is depicted in figures.

***Keywords*—** Smart Grid, Home Energy Management, Renewable Energy Sources, Energy Efficiency, Load Scheduling

I. INTRODUCTION

With the increasing electricity consumption and rapidly developing technology, the demand for electric power has increased. Conventional electrical infrastructures are insufficient to meet this demand due to improper design, operating practices, and environmental factors. In today's world, smart grids have emerged as a solution of increasing demand. According to the European Commission, a smart grid is defined as a low-loss, high-quality, sustainable and safe electricity network that integrates the actions of all users connected to the system, where consumers generate and consume their own electrical energy" [1]. Therefore, this new grid lets customers and providers manage and generate power efficiently using renewable energy resources and smart pricing techniques.

Smart buildings have become essential components of the smart grid to optimize energy consumption, reduce costs, and enhance the reliability and effectiveness of the grid. According to the studies, 40% of the energy produced worldwide is consumed in buildings [2]. Smart grids and smart buildings with high-tech devices provide a two-way flow of energy with two-way communication systems to instantly control, monitor and respond to the grid movements. Thus energy efficiency of up to 20% in consumption can be achieved [3]. Smart sensors, smart metering infrastructures, intelligent home appliances, and Internet-of-Things (IoT) devices have been developed to control this building energy management [4]. Thus smart grids utilize information technology to transmit electrical energy effectively and reliably. Information communication technology also helps the grid collect data from various consumers [5-8]. Therefore, consumers can instantly monitor when and how much energy they consume and see how much they need to pay for it. Thus, energy efficiency from generation to consumer will be ensured while losses and leakages will be minimized [9]. A home energy management system is also included in this concept. The integration of IoT devices ensures maximum access to the information relative to each home energy management component [10]. Home energy management systems enable home appliance scheduling according to demand response programs enacted by energy providers [11-15]. This is usually achieved by turning devices on or off, reducing the overall demand, and considering the period of low electricity prices and higher power generation. The inclusion of energy-saving awareness as a demand response strategy in residences leads to end-user behavioral changes towards a more efficient usage of energy appliances promoting energy efficiency and reducing bills at consumption side [16].

Smart home energy management systems aim to improve the security and comfort of occupants' by employing information and communication technologies. In a smart home, devices need to communicate with each other to be able to exchange data. The management system components include sensors, measuring devices, smart controllers, infrastructure for communication, and a management controller. Communication protocols determine how these devices and sensors can mutually interconnect [17]. In addition to communication technologies, integrating energy storage systems, hybrid renewables, and power electronic devices into smart homes plays a significant role in managing home energy. Home energy storage systems offer an effective solution to the unpredictable nature of solar and wind power by supplying instant energy distribution or storage as needed to ensure a continuous and stable power supply. Home energy storage systems offer an effective solution to the unpredictable nature of solar and wind power to fulfill a continuous and stable energy need for critical loads in case of a grid outage. Thus, this storage system not only meets energy demand but also helps the grid operate reliably and economically [18-22].

In this study, a smart home model that generates its own electricity with renewable energy sources and sells the surplus stored energy to the grid is developed in a MATLAB/Simulink simulation environment. This home energy management system also consists of the electricity bill prediction, load scheduler and energy consumption monitor. The electrical loads at home were controlled by two-way communication between the home and network and energy efficiency was achieved by shifting large loads especially during peak hours with this model. A variable tariff pricing has been also taken into account and calculated the consumer's electricity bill to see that the cost of energy consumption was reduced based on this demand-response model. Finally, home energy management and energy efficiency analyses are conducted, and the results of the analyses are given comparatively with graphs in this study.

II. SMART HOME ENERGY MANAGEMENT SYSTEMS

Home energy management systems have an essential role in smart grids. A home energy management system is an energy system in which smart electric appliances are monitored, and the energy demand of the house is controlled by data exchange between the grid and home energy management systems. This management system will reduce peak loads by controlling the energy demand and enabling energy consumption awareness in consumer behavior. Furthermore, it is aimed to prevent the expensive and inefficient use of electric energy by ensuring that the peak loads are reduced. Although great efficiency will be achieved in the grid by controlling the loads used by consumers, the applicability of these systems depends on the active participation of the consumer in smart grid systems.

Demand response systems in smart grids provide control of peak loads in two ways; directly controlling loads or using variable tariff pricing. Controlling of loads includes managing consumer loads and meeting the demand response by sending control commands to smart homes equipped with advanced software and control technologies. Control of consumer loads is provided by smart meters and advanced building automation technologies. This way, it is possible to monitor and control the loads instantly. The variable tariff structure is an important energy efficiency method in changing the electricity consumption behavior of consumers and increasing energy efficiency. In addition, consumers will have significant savings with this method as their electricity bills will decrease. In this study, the electricity bill was calculated according to the variable tariff pricing and compared with a single tariff. Then the results of the comparison are shown in the graph.

III. SİMULATİON MODEL OF SMART HOME ENERGY MANAGEMENT

In this study, a smart home model which can generate its own electricity and sell the surplus to the grid was developed. Utilizing MATLAB® Simulink® environment, renewable energy resources consisting of solar panels and wind turbines, a battery group where the excess energy generated is stored, and an energy management system that monitors energy consumption data at hourly intervals were modeled. The simulation model consists of two stages: In the first stage, the wind turbine model and solar panel model were created, then consumer data were defined in Matlab/Simulink environment to create the smart home model. In the model, the customer can meet the house's electricity needs with the energy derived from the solar panel and wind turbine and sells the excess energy produced to the grid. The user's consumption data and the energy data obtained from the renewable energy sources were calculated monthly for a year. Then, electricity consumption was calculated, and the energy efficiency obtained by calculating the consumer's electricity bill is shown with graphics according to the situations usage of renewable energy sources. In the second part of the simulation model, a smart home model was created.

In this model, the smart grid monitors energy consumption at hourly intervals and sends a warning message to shift some loads if necessary. The power consumed by the devices in the house was also modeled. The devices in the home were grouped into two; the first group of loads, such as television, computer, and refrigerator are defined as critical loads and constitute loads that cannot be shifted by the stimulation coming from the grid. The second group of loads is non-critical loads that can be shifted until a later time, in line with the warning from the network. For these loads, consumers set a priority order according to their consumption habits. When they receive a consumption restriction message from the network, the use of loads can be shifted to another timeframe scheduled. The main goal here with the home energy management systems is to help reduce peak loads on the grid and ensure energy efficiency by restricting the use of large loads when necessary. Thus, the amount of power that the consumer wanted to use at certain time intervals was controlled in line with the

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demand of the grid, and the amount of power determined by the grid was tried to be captured. The loads to be shifted in this system must be approved for use from the energy management algorithm. Energy efficiency was achieved by preventing the peak loads in the grid, especially during peak hours, by controlling large loads that can be shifted. When we calculated the electricity bills of the consumers using this load shifting plan, it was seen that a considerable saving is achieved. Besides the single tariff calculation of electricity bills in Turkey, a triple billing system is implemented as scheduled. For this reason, the electricity bill calculation was made according to both single and triple tariff calculations in the electricity consumption analyses in this study. Then the results are given comparatively, and the consumer's saving is depicted in figures. An apartment in Esenler, Istanbul, was taken as a reference model in the simulation model [15].

A. Smart Home Energy Management Algorithm

In this study, an algorithm has been developed to model the smart home energy management system. Thanks to the algorithm, the consumers' energy consumption will be able to control, and it can be ensured that it was within the values determined by the grid. Thus, consumers will be able to keep their consumption within certain limits and reduce their electricity costs. In case the consumption exceeds the values determined by the grid, the loads will be shifted according to the scheduled order.

The algorithm given in Figure 2 can be explained as follows: The energy obtained from solar and wind energy is collected and subtracted from the load demanded by the consumer. If the result is positive, it is assumed that the generated power is above the consumption. In this case, the excess energy is used to charge the battery fully, and the remaining energy is sold to the grid. The simulation model describing the system's operation is given in Figure 1. If the total is negative, the demand power is considered to exceed the power generated. In this case, the battery's charge status is checked, and the power that the battery can supply is calculated by making sure that the battery charge does not fall below 30%. If the power that the battery can provide is greater than or equal to the power demanded by the consumer, the battery meets the entire demanded power. If the requested power is more than the battery can deliver, the battery will discharge to a minimum charge value of 30%, and the remaining power will be supplied from the grid. The flow chart diagram describing the system's operation is given in Figure 2.

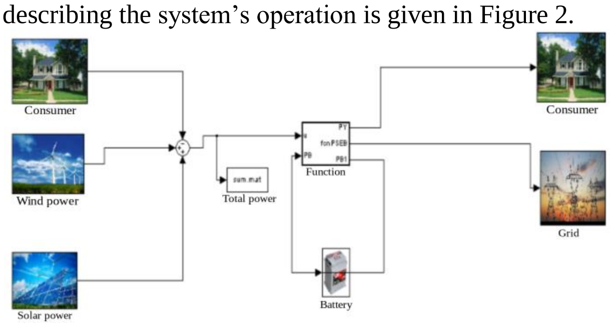

Figure 1: Smart home energy management simulation model

B. Selection of Solar Panels

Solar cell modules form a system with the inverter, battery group, and battery charge monitoring devices depending on the application. The energy obtained from the solar cell was stored in the battery groups in the system, and it was used as the stored energy, especially in the evening when we cannot get energy from the sun. Solar energy production was added to the model utilizing solar panels in the simulation model created.

The average daily electricity consumption of the house in the simulation model is 11 kW. Assuming that the sunshine duration in Turkey is an average of 6 hours, it will be sufficient to use a 2kW solar panel. To meet a power of 2kW, it is necessary to use at least 12 panels with a nominal output power of 175 W. Kyocera KC175 was considered suitable for selecting panels in the simulation model. It is known that this panel has a voltage of 23.6 Volts, MPP current is 7.42 Amps, and solar panel efficiency is 15%. Also, the Istanbul radiation data given in Figure 3 is taken as a basis for one-year solar radiation data to be used in the simulation.

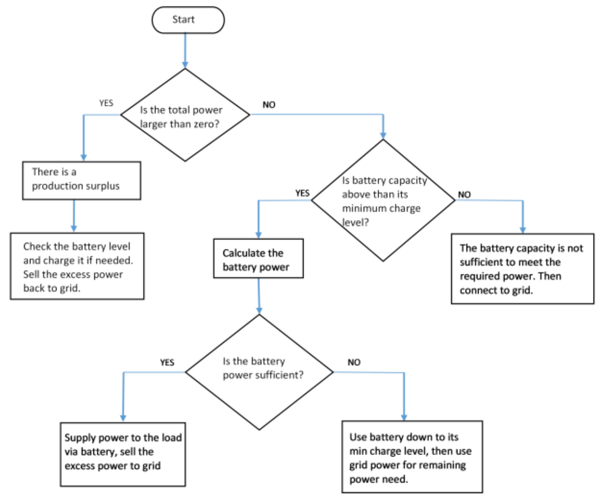

Figure 2: Smart home energy management algorithm

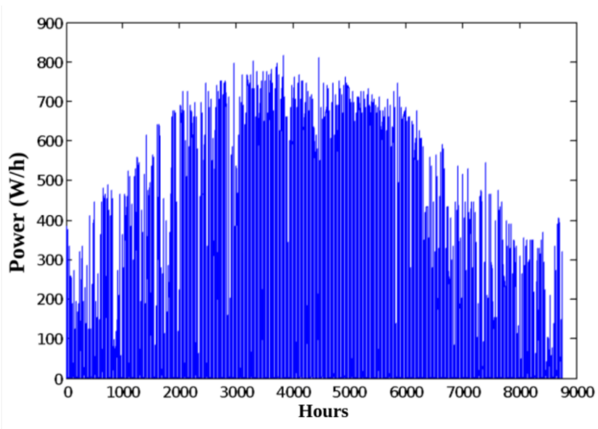

Figure 3: One-year solar radiation data

C. Battery Group Selection

Battery group selection was made to store the electrical energy obtained from renewable energy sources.

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Considering that the energy obtained from photovoltaic systems will also be stored, dry-type batteries are foreseen to be suitable. When a house with an average daily consumption of 11 kW was taken as a reference, the power of the battery group that can meet the energy need of this house for 2 days without any energy from the grid should be 22 kW. For this reason, it was found appropriate to select a 12V 1840 Ah battery group, and this amount of power could be met by connecting an 8-battery group of 230Ah in parallel.

D. Wind Turbine Selection

Wind energy is one of the most frequently used renewable energy sources. However, variable wind speed over time and limited energy storage capabilities are important challenges of wind energy. Also, the region's wind energy potential and energy needs should be considered to determine the wind turbines' power. In this study, a simulation model including wind energy was developed. In this simulation model, one-year wind data of Esenler, Istanbul region given in Figure 4 were taken as a basis. A Vestas 2.5kW wind turbine was chosen by considering the low wind speeds in the model.

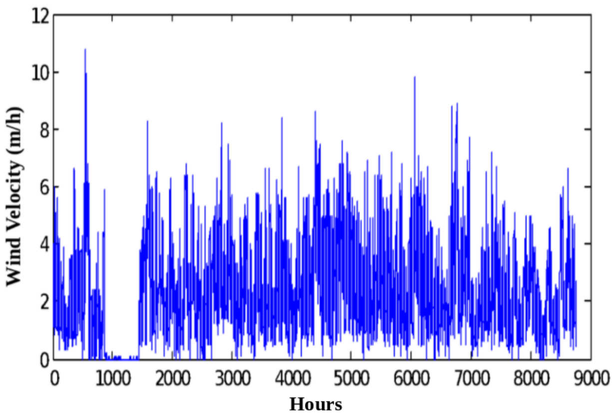

Figure 4: One-year wind data

E. Electricity Bill Calculation and Energy Efficiency

Once the renewable energy sources were selected, electricity billing calculations were made. In Turkey, besides the single tariff calculations, the triple tariff is also applied in electricity bills. For this reason, both tariff types were used in the simulation model. The bill was calculated on a single tariff of 0,59 cents/kWh without renewable energy resources in the first stage. In the second stage, the electricity bill was calculated according to the triple tariff system by dividing one day into certain periods. For example, between 22.00 and 6.00, which is the hour when the electricity demand in the grid is the lowest, 0.39 cents/kWh is charged as night tariff. 0.61 cents/kWh is charged as a day tariff from 6.00 to 17.00, and 0.90 cents/kWh is charged as a peak tariff between 17.00 and 22.00 [15]. The peak tariff is the most expensive because it is the busiest time zone of the grid.

In the simulation model, with the inclusion of renewable energy sources in the third stage, the consumer will meet his electricity needs and sell the surplus stored energy back to the grid. If the generated power and the power stored in the battery cannot meet the consumption, the required power will be supplied from the grid. The simulation results were taken for a one-year period, repeating separately for each month.

In Figure 5, the electricity bills were calculated by applying the single tariff, the triple tariff, and the triple tariff including renewable energy sources, and the results are shown comparatively. As seen in Figure 5, the monthly average electricity bill was reduced by approximately 20% in the case of using triple tariff, and %80 in the case of using triple tariff in which renewable energy sources were integrated (It should be noted that the installation costs of renewable energy sources are beyond the scope of this study.)

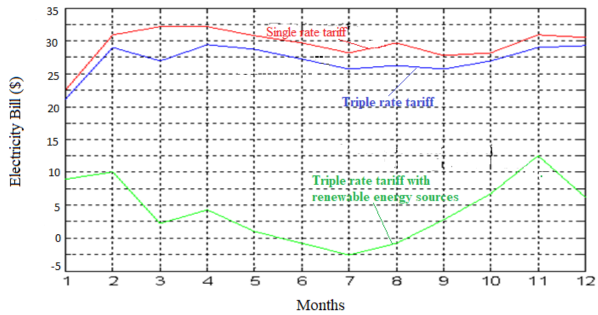

Figure 5: Comparative electricity bills by months (1$=12TL)

Table 1: Power demanded by months

	Power supplied by the grid (kW)	Power supplied by renewable sources (kW)	Power supplied by a battery (kW)	Demand Load (kW)
January	104.39	-75.05	34.5	214.39
February	132.54	-352.43	37.25	202.21
March	132.46	-68.86	39.41	240.74
April	129.24	-73.44	47.32	250.00
May	122.50	-74.93	43.31	240.74
June	103.54	-78.08	50.42	232.05
July	7.26	-8.26	93.56	227.47
August	104.59	-8.26	54.97	231.69
September	93.03	-68.14	55.15	216.32
October	237.24	-82.85	40.44	360.53
November	325.38	-43.34	17.44	386.16
December	178.85	-43.27	25.01	247.13
TOTAL	1671.01	-976.91	539.23	3049.42

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The data obtained from the simulation is seen in Table 1. The energy consumed for each month is located under the "Demand load" column. Excess energy from renewable energy sources has been used to charge the battery. In cases where the energy obtained from wind or solar energy is not sufficient to meet the consumption of the house, the energy stored in the battery is used. These values are shown in Table 1 in the "power supplied by the battery" column. In cases where the electricity generated by the smart home does not meet the electricity consumption of the house, the necessary electricity will be supplied from the grid.

In Figure 6, the monthly distribution of the electrical energy drawn from the grid is shown, when the energy produced by the smart home is insufficient. For example, the lowest value was seen in July, whereas the highest electrical energy was drawn from the grid in November. In addition, as expected, the energy consumed in July is supplied from both renewable energy sources and batteries, as seen in Figures 8 and 9.

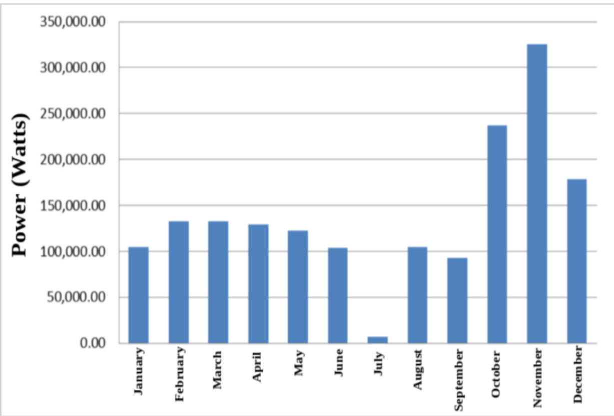

Figure 6: The amount of power supplied by the consumer from the grid for a year

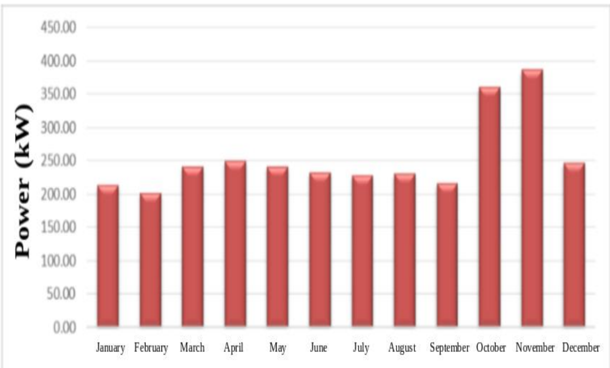

Figure 7: Consumption values of the consumer by month for a year

In the study, the consumption data of the consumer was monitored for a year, and the monthly consumption data is given in Figure 7. As can be seen from the chart, the highest consumption was in November to support the data in Figure 6. In Figure 8, consumption data provided from wind and solar energy sources for a year are shown. Finally, in Figure 9, the energy consumption data provided by the battery is given according to the months. When these two graphs are examined, considering the seasonal conditions, it is seen that the energy supplied from both the battery and the renewable energy sources is the highest in July.

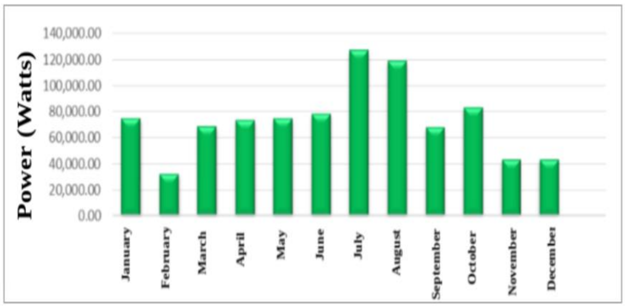

Figure 8: Energy consumption met by renewable energy sources for a year

In Figure 10, monthly energy consumption is given comparatively. The graph shows how much power the smart home needs is met from the grid and how much is from the battery and renewable energy sources by months. As can be seen from the graph, the energy supplied from the renewable energy sources and the battery is given as negative on the power axis as it is met by the energy produced by the smart house. On the other hand, the energy supplied from the grid is seen as positive on the power axis.

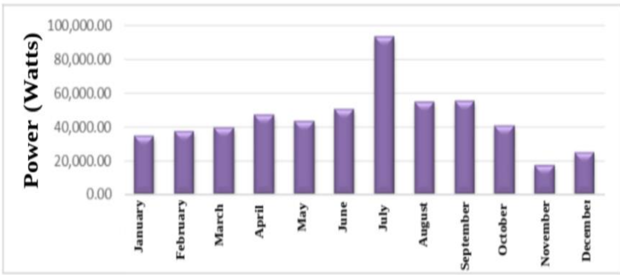

Figure 9: Energy consumption met by the battery for a year

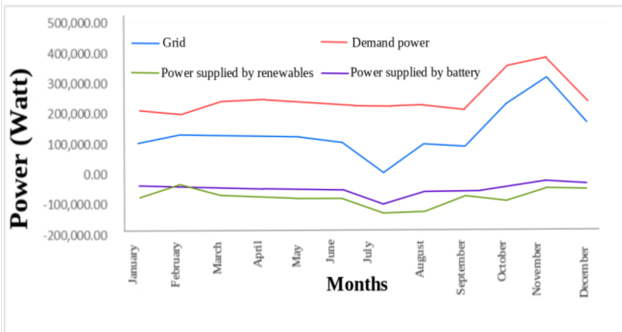

Figure 10: Comparing all the power amount consumed by the consumer by months for a year

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IV. SMART HOME LOAD CONTROL MANAGEMENT SYSTEM

At this stage of the study, another algorithm was created in MATLAB / Simulink environment for the smart home energy management system. In the model, hourly power consumption data of the household devices for a family of two were defined for simulations. Devices are divided into two groups: The first group loads are the essential loads, such as refrigerators, televisions, and computers. The second group loads are other loads like electric vehicles, washing machines, and dishwashers, which can be shifted for another time based on the grid's demand. The shiftable loads have been scheduled in order as electric vehicle charger, dishwasher, and washing machine.

In the simulation, to carry out the postponement process, the consumer should not exceed the consumption value of 2 kW in the peak hours between 17:00 and 22:00. The grid is the busiest at these hours, and the consumption pricing is the most expensive. As a result, the algorithm requests the information of the total consumption data demanded by the consumer every hour, and the energy management system compares the demanded power amount with the power quantities determined by the network. Suppose this value determined by the grid is exceeded. In that case, the charging process of the electric vehicle chosen in the first order is stopped and delayed, then the demand power to be consumed is recalculated. In case the calculated value exceeds the predetermined 2 kW value, the dishwasher in the second priority is stopped, and its operation is delayed, the demand is recalculated and compared with the demand of the network. The same process is repeated until the demanded power and the amount of power determined by the grid overlap. As a result of these, all demanded loads can be shifted. The demanded energy calculation is made again, and if the result is greater than the requested power, consumption is allowed by the grid as it is mandatory to use critical loads. This process is repeated every hour. In Figure 11, the home load management model's flow diagram that describes how these operations work is given [15].

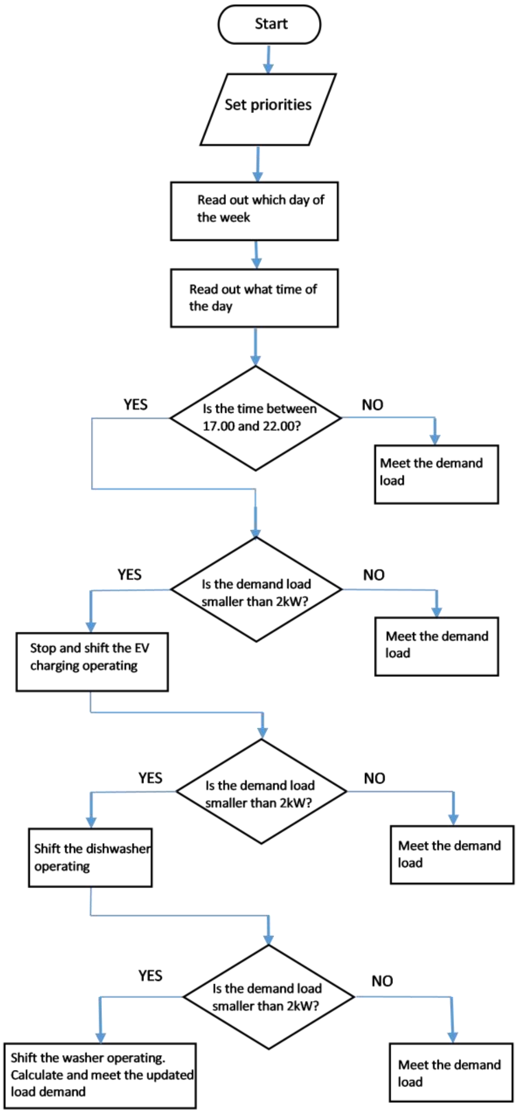

Figure 11: Smart home load management algorithm

In Figure 12, one-week comparative load-displacement results are given. As depicted in the graph, the lines expressed with the blue line are the smart house's daily normal electricity consumption graph. From data, it is seen that the user consumes more between the hours of 18:00 and 22:00, which we refer to as peak hours. Since these hour intervals are the peak consumption time in the grid, these are the highest pricing hours in the triple tariff billing system as well. For this reason, a consumption limit has been determined to balance the grid at peak hour intervals. If the amount of electricity that the consumer wants to use exceeds this limit, certain loads have been postponed to the night tariff, where the pricing is lower.

In Figure 12, red-colored curves contain the shifted consumption data. In this way, the consumption that peaks at a certain time interval have been slightly reduced. In Figure 13, one-month data is shown according to the grid model in which large loads are shifted to lower billing times. As seen from Figures 12

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and 13, shifting the large loads to the night tariff or day tariff, when electricity is cheaper, reduces the electricity bill by about %20 in this research. This load-shifting behavior has led to significant changes in household energy consumption patterns. Shifting home energy consumption to another time will also benefit the load balance of the grid.

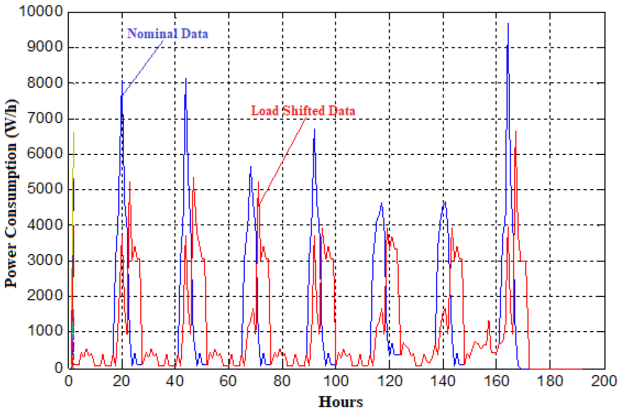

Figure 12: One week comparative load-displacement results

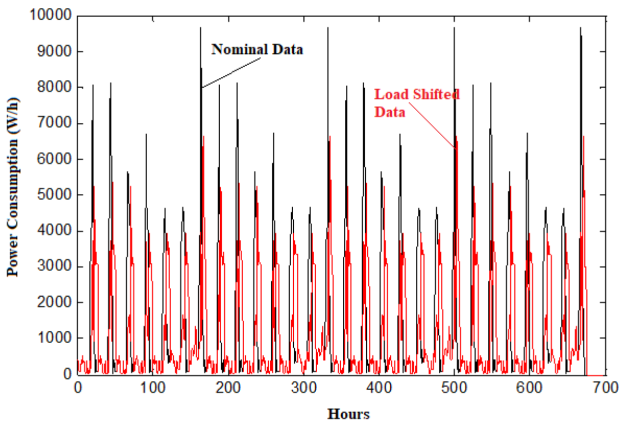

Figure 13: One month comparative load-shifting results

V. RESULTS AND RECOMMENDATİONS

In this study, a home energy management model was considered within the scope of a smart grid model, and a two-phase simulation model was developed. In the first stage, an energy efficiency smart home simulation model that produces its own electrical energy using solar and wind energy was designed. In this model created in MATLAB/Simulink environment, the consumer can store excess electrical energy in batteries and sell it to the grid. When the control and management models of the energy consumed in the house are examined, it is seen that the variable tariff pricing method is an effective energy efficiency method in changing the electricity consumption behavior of consumers and thus increasing energy efficiency. In this study, electricity bill calculations were done according to the variable tariff and single tariff structure systems. It was concluded that approximately 20% profit was obtained with the variable tariff based on the monthly average electricity bill. In the case of using the triple tariff in which renewable energy sources were integrated, the monthly average electricity bill was reduced by approximately 80%. The results for all three power consumption cases are analyzed and presented in graphs for comparison. It should be noted that the installation costs of renewable energy sources are beyond the scope of this simulation study.

In the second phase of the simulation model, a home energy management and control method in which the grid could communicate with the consumer and control the large loads in the home was carried out. For this purpose, an algorithm was created in the MATLAB/Simulink tool. According to the algorithm, the house loads are divided into two groups: non-shiftable loads and shiftable loads. The algorithm computes the power consumed and compares it with the power determined by the grid. If the determined limits are exceeded, the shiftable loads are interrupted according to the previously scheduled order and transferred to a later time. Thus it is ensured to stay within limits determined by the grid. As seen from the consumer electricity bill calculations, energy efficiency can be achieved by controlling energy consumption and determining the best time to shift or reduce loads taking into account user preferences in the house. Finally, it is concluded that the home energy management system with integrated renewable energy sources can reduce the cost of energy consumption in a reliable, affordable, and environmentally sustainable way. We hope that this work will promote the efforts towards a more efficient, user-friendly home energy management system for future smart grids.

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