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Demand Side Management Techniques for Home Energy Management Systems for Smart Cities

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Abstract: In this paper, three distinct distributed energy resources (DERs) modules have been built based on demand side management (DSM), and their use in power management of dwelling in future smart cities has been investigated. The investigated modules for DERs system are: incorporation of load shedding, reduction of grid penetration with renewable energy systems (RES), and implementation of home energy management systems (HEMS). The suggested approaches offer new potential for improving demand side efficiency and helping to minimize energy demand during peak hours. The main aim of this work was to investigate and explore how a specific DSM strategy for DER may assist in reducing energy usage while increasing efficiency by utilizing new developing technology. The Electrical Power System Analysis (ETAP) software was used to model and assess the integration of distributed generation, such as RES, in order to use local power storage. An energy management system has been used to evaluate a PV system with an individual household load, which proved beneficial when evaluating its potential to generate about 20–25% of the total domestic load. In this study, we have investigated how smart home appliances' energy consumption may be minimized and explained why a management system is required to optimally utilize a PV system. Furthermore, the effect of integration of wind turbines to power networks to reduce the load on the main power grid has also been studied. The study revealed that smart grids improve energy efficiency, security, and management whilst creating environmental awareness for consumers with regards to power usage.

Keywords: demand side management; home energy management; distributed energy resources; ETAP; smart cities; PV system

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1. Introduction

Nowadays, there is an increasing electricity demand and an increasing cost of the raw materials. One essential challenge within the energy sector is how to consistently improve energy efficiency. DSM has been identified as one of the main strategies to be supported in order to increase the reliability and secure operation of electricity [1,2]. This strategy generally aims to overcome problems such as high energy costs, environmental issues, network reliability issues, and reduced energy supplies.

DSM strategies that focus on changing consumer demand for electricity include new financial incentives and education supporting changes in human behaviour. DSM strategies also focus on the integration of RES to produce clean energy whilst achieving environmental goals. These DSM approaches are most effective in the long term. There are also many other ways of reducing energy demand in the short term. For example, energy efficient lighting fixtures can be used, as well as power scheduling systems for appliances to avoid peak demand hours or replacement of old appliances with energy-efficient ones. In recent years, the growth in the electric vehicle market has caused a substantial increase in energy demand for homes because of the high-power consumption of electric vehicle charging, which has made peak load management more important in reducing grid penetration. It is a well-known fact that photovoltaic and wind generating stations has a significant impact on the stability, flexibility, and adequacy of power system. That is regarding utilities companies trying to reduce these intermittence electricity generation sources.

Two of the most effective load management strategies, in relation to the efficiency of domestic, commercial, and industrial loads, are the integration of renewables and load scheduling. These two strategies are particularly useful for reducing peak demand and are proposed in this work. When these strategies are used with the correct technologies, they can be fully utilized and produce significant results.

First, it is necessary to consider the cost of high energy demand. Research shows that more active participation in the market on the demand side could have significant benefits. Moshari and Hussain [3,4] examined the direct effects on high energy costs and consumer behaviour from newly emerging smart grids. Spot pricing is a mechanism that matches the supply of power with the amount used by consumers in real time. Spot prices therefore determine when generators are turned on or off at any given time. The study partly discussed consumer behaviour in relation to this, identifying low elasticity of demand [5–9]. The majority of consumers were therefore not worried by spot prices. Demand responses did not fall in correlation with this, leading to higher price spikes on the centralised market [10–12]. However, if DSM techniques are executed correctly and consumer behaviour is considered, (e.g., providing smart meters) demand benefits more, price spikes can be reduced, and the environment benefits significantly.

Bernow and Safdarian [13,14] discussed the environmental benefits of DSM, specifically analyzing DSM methods, which can minimize unwanted environmental effects. DSM strategies have the potential to reduce the need for electricity generation whilst creating more opportunities for renewable energy, thereby reducing waste disposal needs associated with, for example, power plants, fuel handling, and air pollution. Later in this report, the use of renewables for DSM will be considered, as well as its capability for peak power consumption shaving, and how this can benefit grid penetration.

Different techniques and technologies are used to protect the DSM system, as discussed in [15,16]. Technologies such as these are highly effective tools when managing energy aggregation for buildings. These technologies enable customer market participation, energy savings, and the integration of more clean energy sources [17–19]. Currently, when using these technologies together, they are all connected, and the data is passed through a Home Energy Management System (HEMS). A HEMS allows a user to monitor appliance activity and power consumption whilst being able to remotely control the on and off times of appliances, as described in [20–22]. Furthermore, the user can specify which appliances are flexible regarding operating times and which appliances must be always on. This is one of three main uses of a HEMS.

DSM consists of a set of techniques that represents an innovative approach for energy consumption of households and other electric utilities. The lack of regulation and consensus on HEMS evaluation procedures makes reproducibility and comparability exceptionally difficult. The Christoph and Saeed Hosseini [23,24] points out HEMS evaluation criterion; however, there is no compromise regarding what metrics should be used to present DSM in energy management systems. The research work was carried out to overcome the unsolved research issues related to HEMS. This contribution presents a significant improvement in HEMS as a result of the successful integration of DER with DSM techniques. A DER is a small unit of electricity generation that operates locally and is connected to a larger power grid at the distribution level, whereas RES sources are basic sources that are used to generate electricity.

This paper analyses the energy management of DERs at a residential level, in buildings such as homes. Smart homes may also use renewable energy generation in the form of, for example, solar panels on the roof or local energy storage. With smart energy management systems, emerging technologies can provide new and effective DSM strategies. In general, DSM strategies are categorized into energy-efficient strategies and demand response (DR) strategies. The primary goal was to observe how specific DSM strategies, i.e., energy-efficient strategies, are minimizing energy consumption while maximizing efficiency, using new emerging technologies and proposed modules. A software called ETAP [25] was used to experiment with the integration of distributed generation such as RES to utilize local power storage, providing flexibility to consumers. The rest of the paper is organized as follows. Sections 2 and 3 explain the state-of-the-art trends, and the fundamentals and configuration of the HEMS model with DERs, respectively. Furthermore, mathematical formulations of both the solar and wind generation are presented. In Section 4, the results and analysis of the proposed methodology in the case of the UK are investigated and discussed, and finally, Section 5 concludes the paper.

2. Related Work

Recently, several HEMS have been presented. Their common goals in these studies are the minimization of electricity cost, reduction of greenhouse gas and carbon emissions, reduction of peak to average ratio and peak load demand, and enhancement in the efficiency of power system. The appliances' scheduling issue has been explained as an optimization problem by numerous classical and heuristics techniques. In this regard, some recent scientific researches are included below.

The authors of [26] highlighted the significance of energy planning and management for smart cities (SC). In this study, they also provided an overview of SC energy system planning and optimization. The four areas of the energy system for SC are discussed in detail: generation, storage, transit, and end user. Although an energy storage system (ESS) is incorporated to assist household load during grid failures, scheduling the usage appliances or moving load, the application of an ESS in response to dynamic pricing in the energy market has not been investigated. According to the authors of [27], there are several approaches to integrate RESs and the distributed generation (DG) into the smart grid (SG), and the notion of SCs has been thoroughly discussed. The hurdles of incorporating DG into the existing network have been identified. Furthermore, at low and medium voltages, the impact of DG on voltage control and stability was also examined. There is also an in-depth discussion of the influence of DG on power system stability, power quality, and voltage sag owing to the failure of dispersed sources. As a result, they also examined the influence of the use of DGs as well as RESs on power system stability and quality. A major oversight has been the failure to consider the incorporation of ESSs into the residential sector and their function within DSM initiatives.

The authors of [28] provide an overview of current demand response (DR) and HEMS developments in the residential sector. They have also highlighted the value of HEMS in terms of load shifting and curtailment. Current optimization approaches, such as model predictive control, mathematical optimization, and heuristic algorithms have also been elaborated in their study. Furthermore, the effects of device heterogeneity, vagueness in predicting, computing limitations, and temporal considerations on optimization algorithm design were also explored. However, neither the user comfort (UC) nor the waiting time for appliances have been addressed. In reference [29], a concise overview of the recent developments in HEMS research and development has been provided. DR, AS, DSM, and single- or multiple-goal improvement in HEMS are explored. A discussion has not been held on the applicability of RESs and ESSs into residential sectors and their influence on electricity bills.

Lee et al. [30] described a REMS based on linear programming (LP) for lowering power costs by charging the ESS from the utility during off-peak hours and discharging it during peak hours. No consideration was given to the incorporation of RESs into the residential sector. To transfer shiftable appliances from peak to off-peak hours, the authors of [31] suggested an ILP-based HEMS with integrated RES. There was no consideration for UC or ESS integration, however. Scheduling household appliances for power cost reduction or pattern optimization is discussed in [32]. For the domestic appliances and the RES, MILP is utilized as a scheduling tool. A home-based RES not only cuts electricity costs, but it also generates income by selling excess energy to the utility. Although RES with HEMS is beneficial to both utilities and consumers, single or small household customers may find it difficult to install RES in their home.

3. Proposed System Models

To overcome the shortcomings of the previously proposed HEMSs, this paper describes an enhanced home energy management system. The proposed system not only facilitates the integration of DERs at residential and distribution levels, but also reduces the prosumer's electricity bill. For this purpose, ETAP models were developed and simulated. The simulations were accomplished following the proposed DREs system modules as mentioned in the abstract. This section illustrates the analyzed system configurations, model of various components, and household load and to test various DSM strategies in relation to the integration of renewables in a power network, single line diagrams were created. Furthermore, load scheduling was considered, as well as possible effective approaches used by HEMSs.

3.1. System Configurations

Four different system designs of electricity system of home energy with various combinations of PV and wind were considered. These models were created on ETAP and contain parameters such as those found in power networks today. The single line diagrams show generation, transmission, and distribution of power to various loads. This section discusses the various components making up the ETAP models.

Model 1: AC generation → AC transmission → AC distribution to cluster of domestic loads (Lump loads).
Model 2: AC generation → AC transmission → AC distribution to cluster of domestic loads (Lump loads) and single separate domestic load (static loads).
Model 3: AC generation → AC transmission → AC distribution to various domestic loads. One isolated domestic load directly connected to PV array.
Model 4: AC generation → AC transmission → AC distribution to cluster of domestic loads. Wind power connected to 11KV bus bar.

When implementing the single line diagrams in ETAP, the following are considered:

3.2. Load Types

When creating the single line diagrams, the first thing to consider is the type of load that needs to be powered, and what the incoming power source will be. The type of load used in ETAP is the lump load. The lump load is a mix between a static and inductive load. This therefore varies based on the defined percentage for the type of load.

Determining the average domestic load is problematic, given that power consumption differs considerably in different circumstances. Power consumption is determined by many factors including type and size of property, and the number of people in the home. The domestic loads implemented in the model are consequently based on data collected by the Office of Gas and Electricity Markets, which is a non-ministerial government department based in the UK. The data are reliable as the department is recognized by a national regulatory authority. Data on typical domestic power consumption in the UK is collected once every two years as shown Table 1. The power usage averages were calculated based on the different profiles of customers using the median. The data shown in Table 1 is taken from the Office of Gas and Electricity Markets (OFGEM) [33], which is a non-ministerial government department based in the UK. In 2020, the average annual electricity consumption for a UK residential utility customer was 3760 kilowatt hours (kWh), an average of about 334 kWh per month. Domestic load consists of lights, and home electric appliances as mentioned in Table 1. Most of the domestic loads are connected for only some hours during a day. For example, lighting load is connected for few hours during nighttime [33].

Table 1. Typical UK average domestic load values [33].

	Profile Usage Tier	kWh	Total
Gas	Low	8000	
	Medium	12,000	
	High	17,000	
Electricity profile 1	Low	1800	9800
	Medium	2900	14,900
	High	4300	21,300
Electricity profile 2	Low	2400	10,400
	Medium	4200	16,200
	High	7100	24,100

3.3. Profile Usage Tiers

For the sake of simulating domestic loads with peak and off-peak rates, electricity profile 2 was used for simulations as the data is based on economy 7 m. Table 1 shows the UK average domestic load values while Table 2 shows the peak and off-peak consumption split as a percentage for economy 7 m, as well as the difference in power cost when using electricity during peak and off-peak hours. Below are profile usage tiers for domestic loads. Economy 7 m refers to the meter type that usually goes with an Economy 7 electricity tariff. It works with Economy 7 m to provide a different price per kWh based on one's time of use.

1. Low—small apartment for one or two residents.
2. Medium—semi-detached home with a family of three to four residents.
3. High—detached home with five to six residents.

Table 2. Peak and off-peak time power consumption split GB, economy 7 m.

Consumption Split for Great Britain	
Peak hours during daytime usage	58%
Off-peak hours during night-time usage	42%

3.4. Theoretical Domestic Load

To assess the effectiveness of solar panels linked directly to a single dwelling for load peak shaving and load shifting appliances, a theoretical domestic load is built and simulated in ETAP. Data related to the power consumption of various appliances based on their operating times has been compiled in Table 3 and based on data selection from [20,34].

A HEMS has been used to construct a modified schedule for the identical appliances used in Table 3. A static load is used to mimic a constant steady load when developing the model in ETAP. To see how load shifting is an effective approach for satisfying the economy 7 power consumption split stated in Table 2, a load consumption simulation for both schedules is designed. In the testing part, load consumption graphs and load flow experiments on ETAP models are examined.

Table 3. Normal appliance schedule.

Load Types	Appliances	Schedule	Power (W)
Shiftable	Computer	1–10 a.m.	320
	Dishwasher	10–12 p.m.	2000
	Washing machine	10–12 p.m.	2000
	Water heater	12–9 p.m.	4000
	Electric car	2–9 p.m.	3000
	TV	9–10 p.m.	
	Tumble dryer	10–12 a.m.	2000
Non shiftable	Fridge	12 a.m.–12 a.m.	1040
	Freezer	12 a.m.–12 a.m.	800
	Lights	12 a.m.–12 a.m.	1200

Calculation of the tabulated power consumption values for the individual appliances in Table 3 are based on the specification of typical products available online. It is worth to note that some appliances may not necessarily be consuming the same amount of power throughout the day constantly. Therefore, the duty cycle of the appliance must be taken into account when calculating the power consumption.

The process carried out by the HEMS when an economy 7 m is used in a smart home connected to a photovoltaic system is depicted in a Flowchart, as shown in Figure 1. As previously stated, the HEMS allows the user to input load types for appliances, and the system monitors and records power consumption of specific appliances over the operating times based on normal use. The user can confirm appropriate time slots for specific appliance use, and the system will create new time slots while taking peak consumption hours into account. Assuming the load shift is configured, the system examines the current energy price. If this price is too expensive owing to high peak energy consumption hours, grid electricity will be utilized. Renewable energy, on the other hand, will be used if it is stored and the time is during low peak hours (at night).

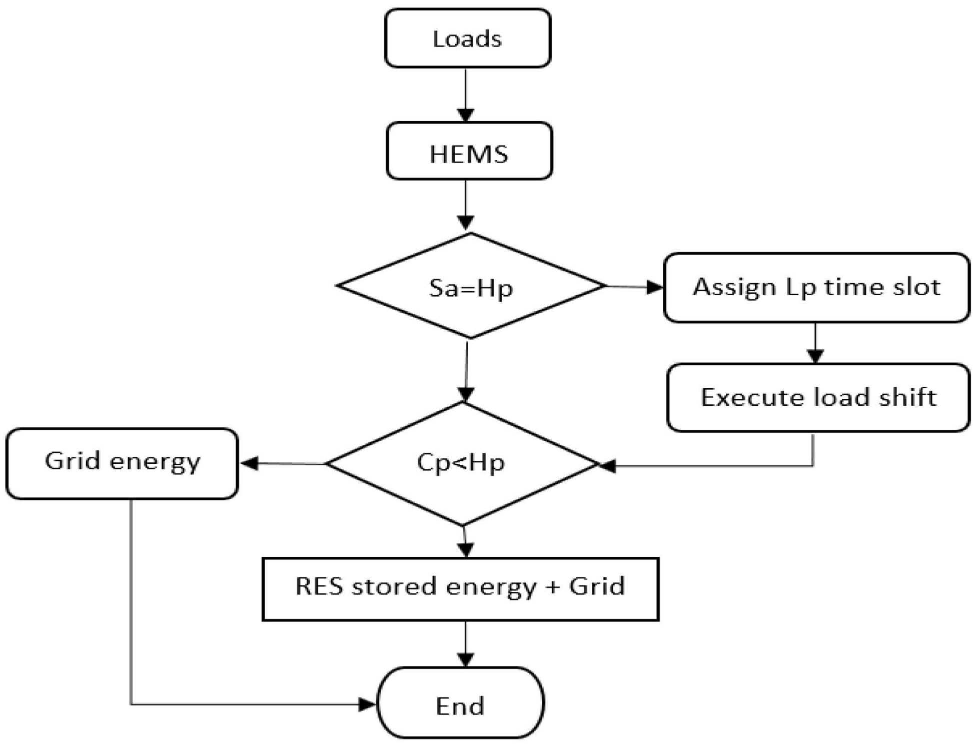

Figure 1. Flowchart of home energy management systems. Sa = Specified shiftable loads, Hp = High peak hours, Cp = Current energy price, Lp = Low peak hours.

3.5. Renewable Energy Integration

Grid penetration must be reduced to satisfy increased electricity demand. The HEMS depicted in Figure 1 will be crucial in determining how energy consumption varies for a single home load. It will also show when the best times are to use the RES, such as a PV system connected directly to a home. The RESs will turn on and off at times determined by demand response methods (economy 7 m on and off-peak times) proposed in the ETAP models' domestic load implementation. By offering suppliers more control, these renewable energy systems, when combined with demand response technologies and a HEMS, will drastically minimize grid penetration. Furthermore, because of the improved control provided by a HEMS appliance schedule, the stored renewable energy can be used to influence homeowner behavior. The HEMS, for example, will optimize load scheduling and track solar power generation. If the maximum energy was generated between 9 a.m. and 4 p.m., and peak energy use is around 6 p.m., the storage would be used around 6 p.m. Based on the economy-7-m usage split provided in Table 2, this would also lower energy bills.

In Table 3, an electric car is also included in the load profile. When charging the electric vehicle, any residual power that was not delivered during peak consumption at 6 p.m. can be merged with grid electricity. If the e-car is scheduled to charge at 6 p.m., the HEMS can reschedule it to off-peak times. For example, based on the load consumption split for off-peak hours, in the early hours of the morning when energy prices are lower. These benefit both the supply and the consumers by lowering grid penetration and energy bills.

Despite the fact that this type of smart home system is not currently being adopted by a large number of consumers, both utility providers and the UK government are currently supporting the development of these systems, which means that they will undoubtedly contribute significantly to smart grids and the future of energy management systems with RES. This technique will be tested utilizing the RES listed below.

3.6. Solar Energy System

To ensure desired functionality, a PV array must first be constructed and then added to ETAP with the appropriate specifications. A single line diagram is designed to accommodate an ideal test to be carried out for a PV system designed and tested for an individual house in which the appliance loads are proposed in Table 3. Table 4 tabulates the characteristic parameters such as: quantity, power, usual operation times, and wattage consumption of various loads.

Table 4. Load assessment.

Load Types	Quantity	Load (W)	Total Load (W) =Quantity × Watts	No. of Hours per Day	Total Kilo-Watts-Hrs (kWh) =Total Load × No. of Hrs/Day
Compact Fluorescent lights	10	15	150	8	1200
TV	1	130	130	1	130
Computer	1	80	80	4	320
Fridge	1	130	130	24	1040
Freezer	1	100	100	24	1000
Total			590		3690

Between the PV array and the existing system, an inverter is also required, so that solar energy can be utilized by the consumer by inverting it from DC to AC. In addition, the inverter is used to connect to the internet in order to access the HEMS. For this very purpose, a string inverter is utilized in this arrangement. Because the total energy usage of the appliances indicated in Table 4 is 3690 Wh per day, great attention should be taken while choosing an inverter to ensure that it is not undersized. The selected inverter for the given load should be at least 30% oversized. For example, for the total load of 592 W for the appliances in Table 4, the inverter should have the specification of 767 W = 590 + 590 × 30% or above then this depending on the standard inverter available in the marked.

To ensure proper performance in grid-connected systems, the inverter input rating must match the PV array rating. The voltages in the system must then be determined. The backup battery bank that powers the standalone system is referred to as the system voltage. The fact that load changes can alter system voltages and it should be considered while choosing the DC system voltage. Due to this, a system voltage should increase with an increasing load. If a household uses small load appliances, for example, a 12 V system would be used on the other hand when the loads are heavy, a 48 V system should be used. However, an intermediate DC system voltage will be proposed in this system. A deep cycle battery is the type of battery utilized in the PV system. This battery only uses a small amount of energy and recharges quickly every day. To assure capacity on days when there is less sunlight, the battery should be oversized as well. Along with incorporating inverter losses, the battery size is computed depending on the inverter output and its efficiency. For example, for the total load (3690 Wh/day) of the household appliances in Table 4, for an inverter with 85% efficiency, the requirement for the battery can be calculated as:

$$\text{Battery capacity} = \frac{3690\ \text{Wh, day}}{0.85} = 4341.18\ \text{Wh/day} \tag{1}$$

$$\text{Battery rating} \ = \frac{4341.18\ \text{Wh, day}}{24\ \text{V}} = 180.88\ \text{Ah, 24 V} \tag{2}$$

where the standalone PV system is unable to provide power due to inclement weather, a battery backup should be available to provide power during the night. As, owing to practical considerations, lead acid batteries are used with a 50% depth of discharge, the battery capacity can be calculated as:

$$\frac{180.88\ \text{Ah}}{0.5} = 361.812\ \text{Ah/day},\ 24\ \text{V} \tag{3}$$

Furthermore, for 4 days of battery backup plan, the battery capacity can be approximated to be 361.812 Ah × 4 days ≈ 1460 Ah, 24 V. PV module size is determined by the PV module's power output capability, location, and electricity demand. For this design, we are assuming 4–6 kWh/m^2. For a case with a battery efficiency of 80%, the requirement for the solar panel can be calculated to meet the load condition as:

$$\text{Battery capacity} = \frac{4341.76}{0.8} = 5427.2\ \text{Wh/day} \tag{4}$$

Solar panels required to meet load conditions:

$$\text{Solar panel rating} = \frac{5427.2}{\text{solar radiation}(4.5)} = 1206.04\ \text{Wp} \ \approx\ 1200\ \text{Wp} \tag{5}$$

The parameters of the PV panel, array, and inverter are entered into ETAP, which is then linked directly to a 0.4 kV bus and tested. The most optimal power generation is evaluated, and it is taken into account that solar irradiance is dependent on the coordinates set on ETAP for location, thus generation may fall short of ideal conditions at times. Parameters, on the other hand, can be easily changed to provide a more suitable PV system. By setting the system's coordinates to the United Kingdom, under normal weather circumstances, 3.6 kW and 4 kW have been obtained.

3.7. Wind Turbine Generator

In order to investigate the effectiveness of wind turbine on reducing grid penetration on bigger scale with a cluster of loads, in ETAP, a wind turbines model has also been integrated. Wind turbines have already been examined in terms of how they work and how effective they are as a renewable energy source. Step down transformer and Wind Turbine Generator (WTG) are used as model components to implement the system in ETAP. To begin, the WTG's rated real power is set to 2 MW, the voltage is set to 15 kV, and the power factor is set to 90%. ETAP creates the aerodynamics power coefficients, locked rotor, and grounding parameters automatically. This data are acquired from ETAP samples that are pre-determined depending on the variables mentioned. The average wind speed in meters per second is a crucial WTG variable that must be selected carefully, and, in this arrangement, the speed is set to 15 m/s. When installing wind turbines, the power curve, which establishes the link between wind speed (m/s) and the electrical power generated, is critical since it indicates whether the system is running properly. Four models were developed in ETAP to test various DSM techniques, as illustrated in Figures 2–5, respectively.

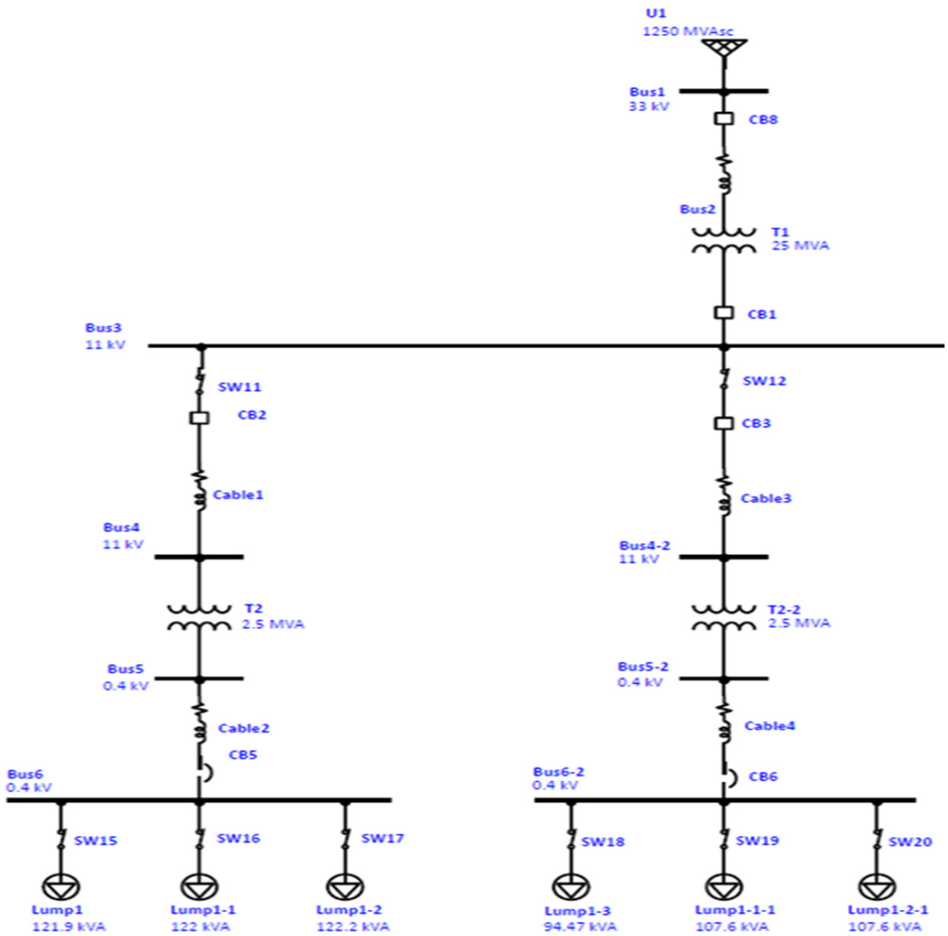

Figure 2. Model with low electricity generation.

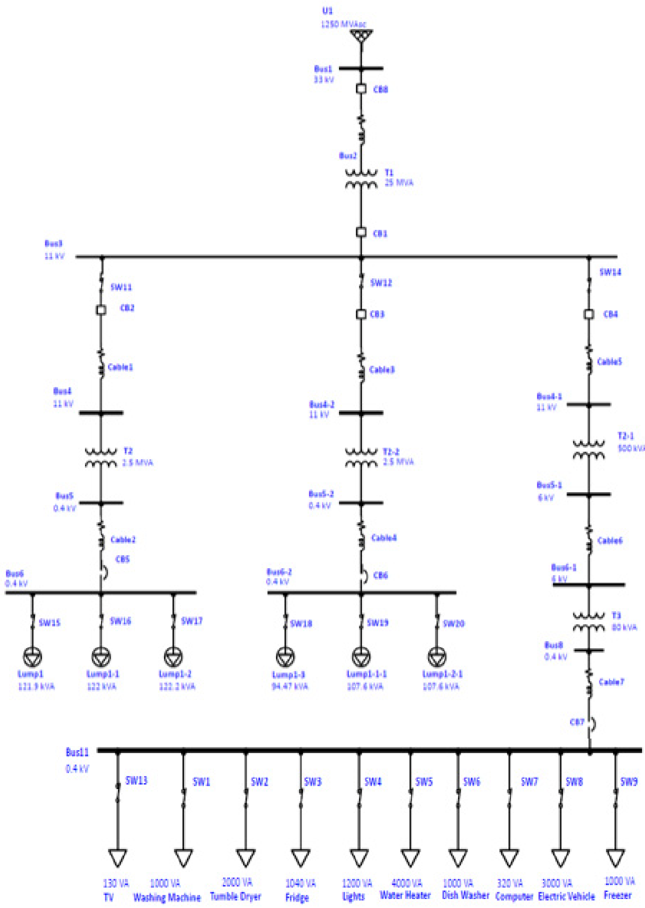

Figure 3. Reducing grid penetration with RES.

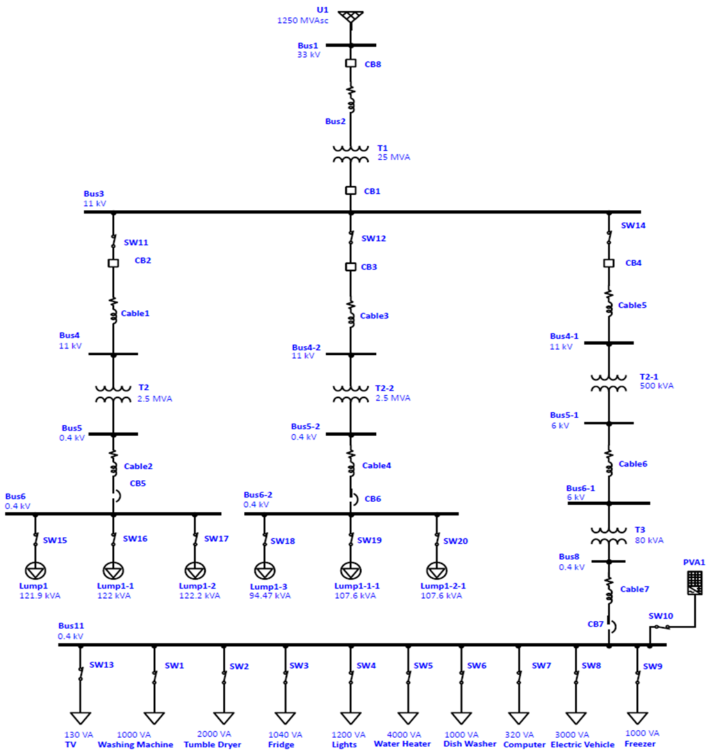

Figure 4. HEMS and renewable energy systems, i.e., solar.

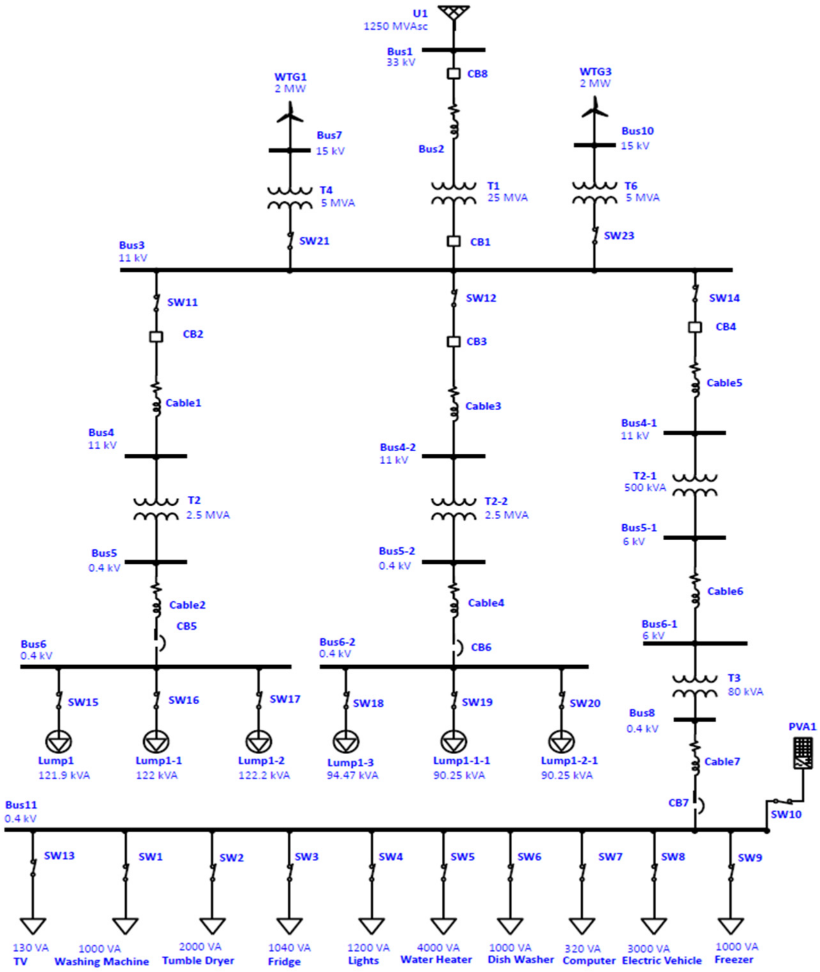

Figure 5. HEMS and mixed RESs (solar and wind).

4. Results and Analysis

The models created were analysed using various DSM strategies, as shown in Figures 2–5. These tests provided an understanding of how effective large-scale energy management systems such as smart grids and even smaller systems such as HEMSs can be in reducing power consumption without compromising on customer satisfaction and negative environmental effects. The Adaptive Newton Raphson method for load flow analysis was used on ETAP models as a numerical solution for each system. ETAP enables computation of precise steady state voltages and phase angles. Furthermore, it is used because it can find reactive and real powers flowing into all transformers and lines of models created. This analysis can therefore help with the design of the system with respect to system currents and voltages. With these values known RES are integrated in the network where they are needed most, as a DSM strategy.

On ETAP models, the Adaptive Newton Raphson method load flow analysis was employed as a numerical solution for each system. ETAP makes it possible to calculate precise steady-state voltages and phase angles. ETAP can also detect reactive and actual powers flowing via all transformers and lines of the models. As a result, this study can assist in the design of the system in terms of currents and voltages. As a DSM approach, these values can be used to integrate known RES into the network where they are most needed.

4.1. Load Shedding

Figures 2 and 3 are put to the test with load shedding conditions, and they include clusters of diverse home loads. Electrical power stations may not have enough capacity to provide all active loads in the network in some cases. If this happens, the system will become unbalanced, resulting in large blackouts. To avoid this, the supplier can urge customers to cut their power use at specified periods or turn off specific parts of the electrical network.

By using ETAP, load shedding is tested using single throw switches and load flow analysis. This would determine the network's minimal power shed requirements for each individual subsystem. In addition, this would choose a certain load combination to meet the system's requirements. In the model below, as shown in Figures 6 and 7, however, a switch has been opened to cut power at one portion of the network and more power has been delivered to the loads with a higher priority. These high priority loads are domestic in the model, but in reality, they can be utilized to keep hospitals, jails, and other critical loads in the distribution network powered up. In emergency scenarios, ETAP can also construct load schedules for an operator to reduce power consumption. Load schedules include features such as load priority levels, load groups, and other things. It is also simple to switch or change the schedule. The analyses of models in Figures 1 and 2 are shown in Figures 6 and 7.

In Figure 6, the analysis shows that the power grid is producing less power than required by the loads. The power at the 400 V bus is not within ±5%. In this situation, assuming a load has a higher priority over another, then one line can be switched off to supply enough power required by another. In Figure 6, red busses mean power requirement is not met, which is problematic switch open to cut-off power for load shedding. At this point, it is clearly seen that the power at the 400 V bus 6 is high enough to be operated and bus 6-2 is no longer powered. For further analysis, intelligent load scheduling can also be used as part of load preservation analysis. This creates load schedules for an operator in emergency situations for power reduction purposes. Load schedules consist of load priority levels, load groups, and addition to these schedules can also be easily switched.

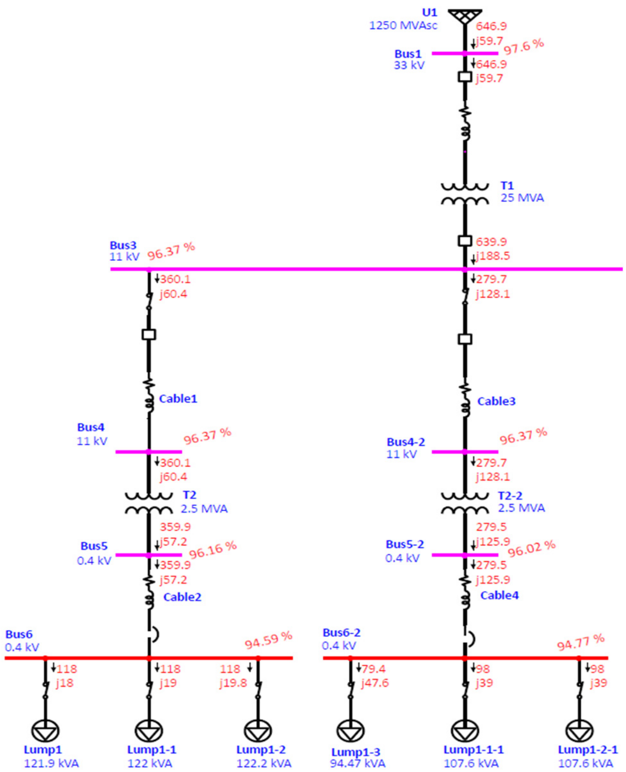

Figure 6. Load flow simulation results of model presented in Figure 2.

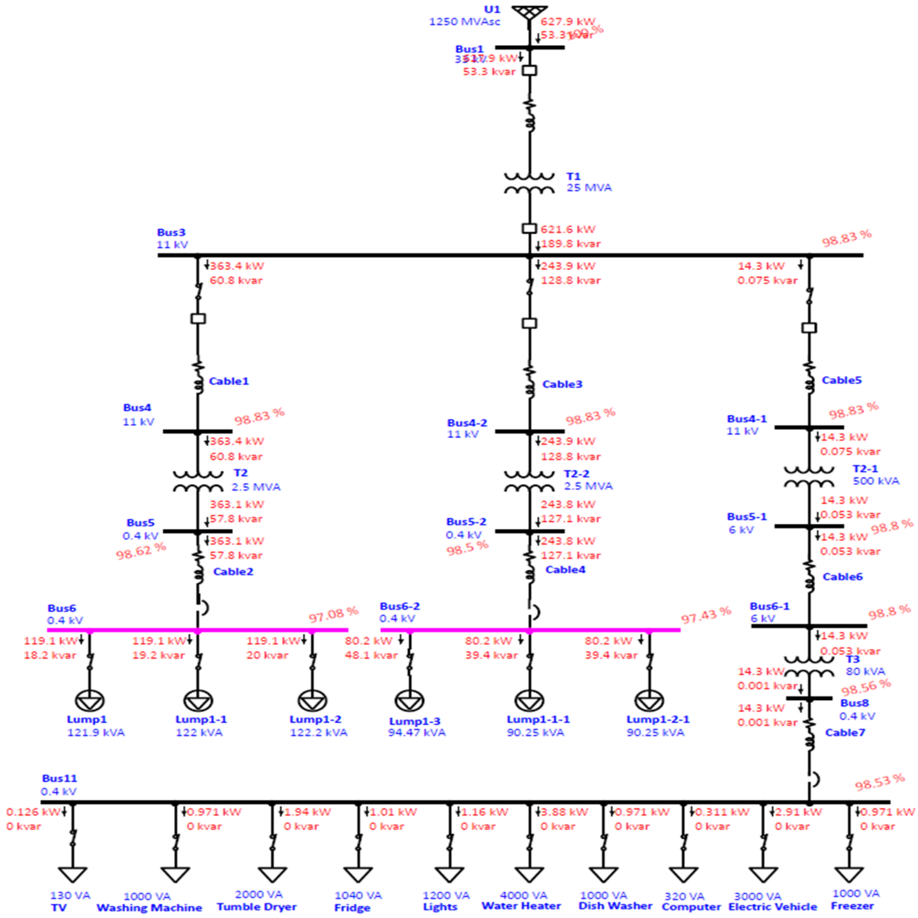

Figure 7. Simulation results of model presented in Figure 3.

4.2. Reducing Grid Penetration with RES

To see how RES can help to reduce grid penetration, the built renewable systems are merged with the model system below in Figures 8 and 9. Nonrenewable power generation, transmission, and distribution to various household loads are all included in this model. The system's household loads are divided into sections. Bus 6 and 6-2 carry clusters of household loads that were previously examined in Table 1 (load profile 2, 15 medium on bus 6-2, and 15 high on bus 6). A 400 V bus bar for one individual dwelling with Table 3 static loads is linked to the third line connected to cable 5. One of the significant impacts due to the DERs is the reverse power flow (RPF). In our case, PV generated during daytime is higher than home load consumption, thus RPF can be observed. The consequences are evident in the power system with voltage peaks. Therefore, based on the amount of RPF, we can propose reverse power relay to protect the system voltage fluctuation and reverse power in the network by disconnecting the DERs from the distribution network under fault conditions.

4.3. HEMS and Renewable Energy Systems

The PV array (PVA1) connected to the individual residence is shown in the load flow study below (Bus11), as shown in Figures 8 and 9. PVA1 generates 3.7 kW according to this data, indicating that the system is performing as intended. When the bus bars are pink, it means that the power on that bus is approaching its optimal level. These, however, are likely to fluctuate depending on the quantity of power generated and load changes caused by appliance use. On bus11, a PV system is tested with a single dwelling. The results of corresponding power consumption are shown in Figure 10.

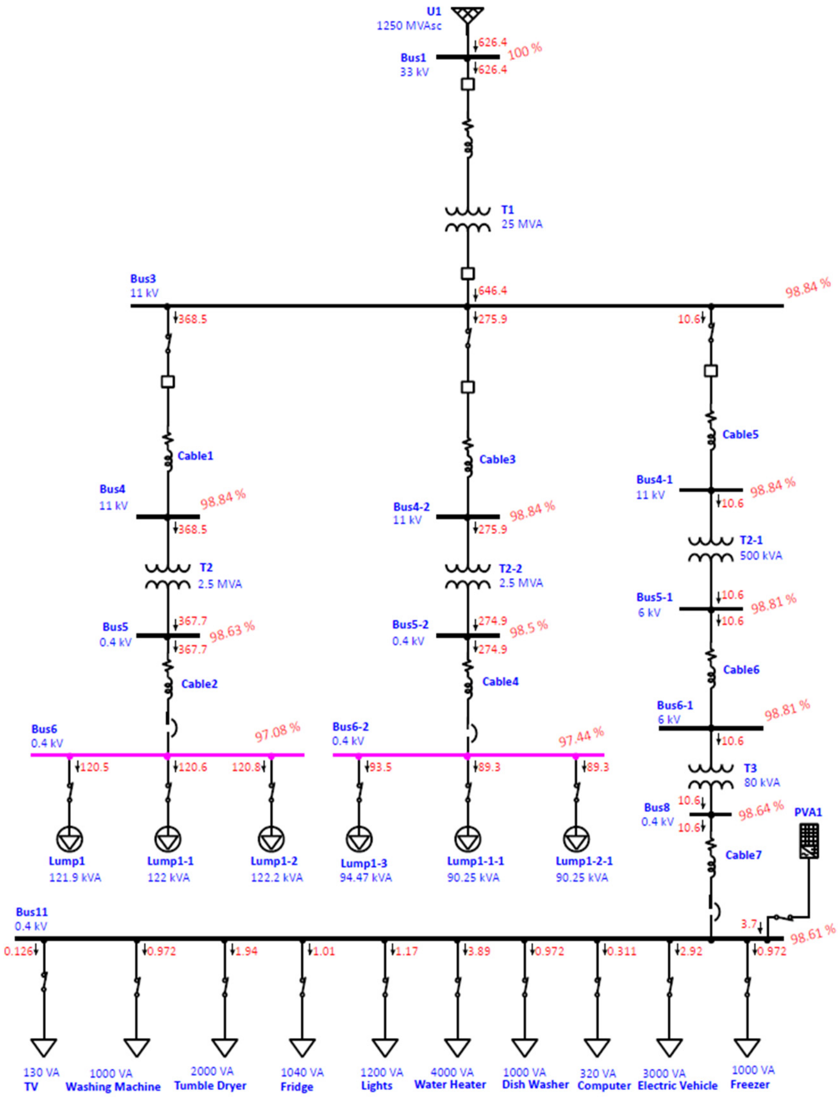

Figure 8. Simulation results of model presented in Figure 4.

Assuming the domestic load created on bus 11 is using an economy 7 m, a HEMS can be a particularly useful energy management tool. In Figure 11, the orange line shows the appliance power usage when the economy 7-m power cost times are not considered. Meanwhile, the blue line does consider this, and the scheduling of appliances has been used. The scheduled appliance plot therefore shows a power consumption curve more spread out throughout the 24 h, while considering appropriate operating times. This load scheduling technique is most commonly used for peak load reduction in buildings, as previously mentioned.

Figure 12 shows the same load shifted appliance schedule power consumption. The blue curve includes the PV system created in ETAP. When the PV system is utilised at optimal times or even during specific appliance operations, peaks in the power consumption graph are significantly reduced due to peak shaving (between 20:00:00 and 23:00:00). With this PV system, the consumer can actively participate in power system operations.

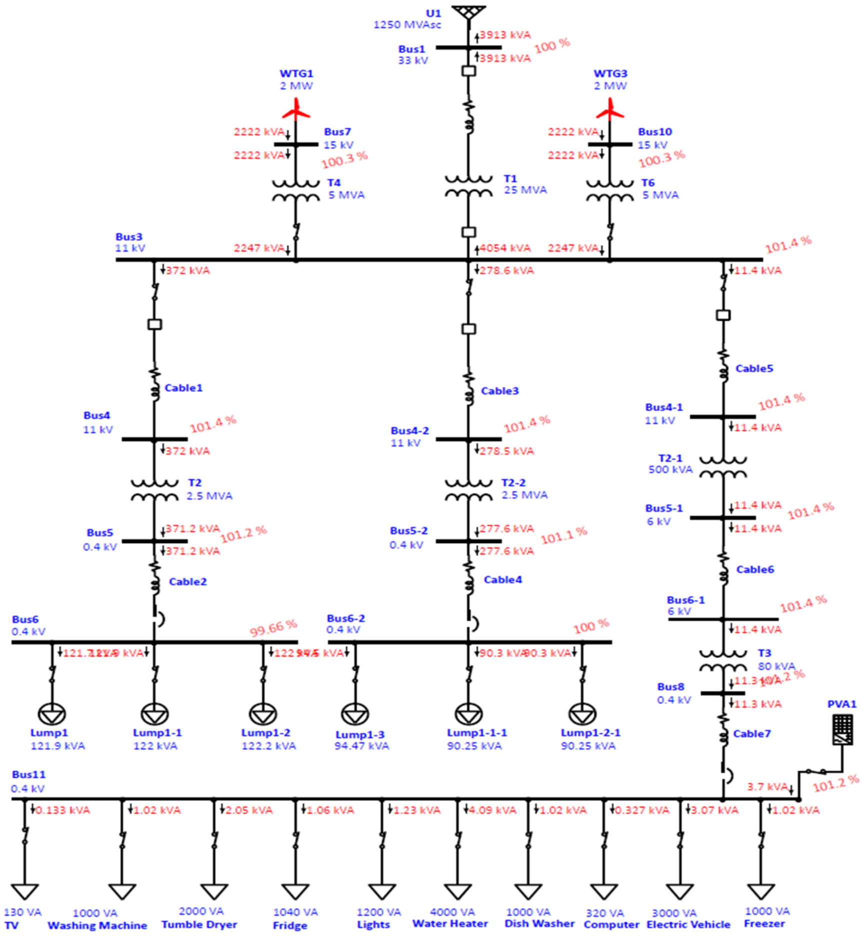

Figure 9. Simulation results of model presented in Figure 5.

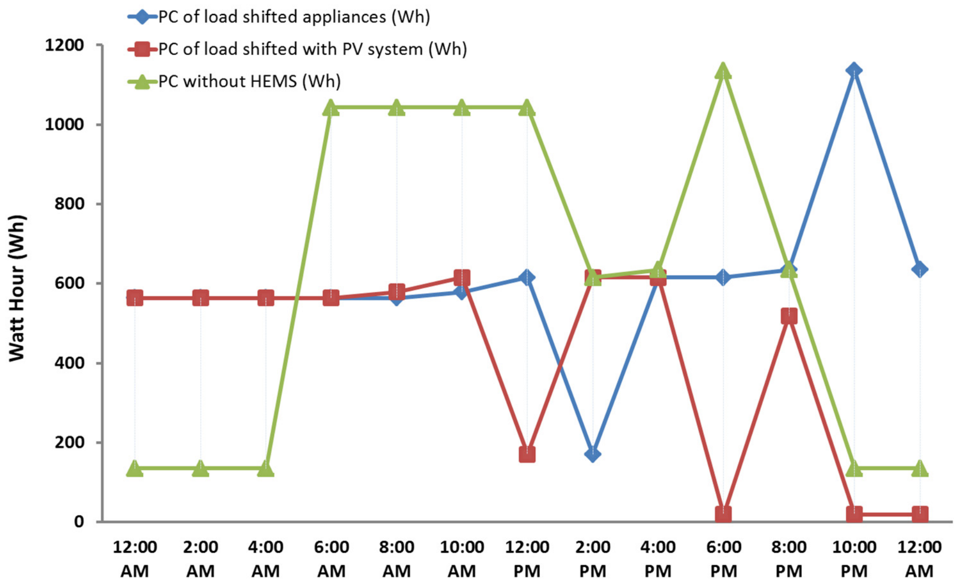

Figure 10. Comparisons of 24-h power consumption profile for different scenarios.

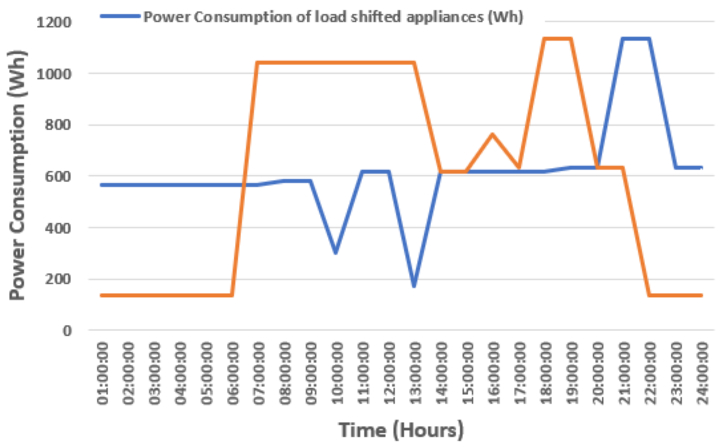

Figure 11. 24-h winter power consumption graph for load shifted with and without an HEMS.

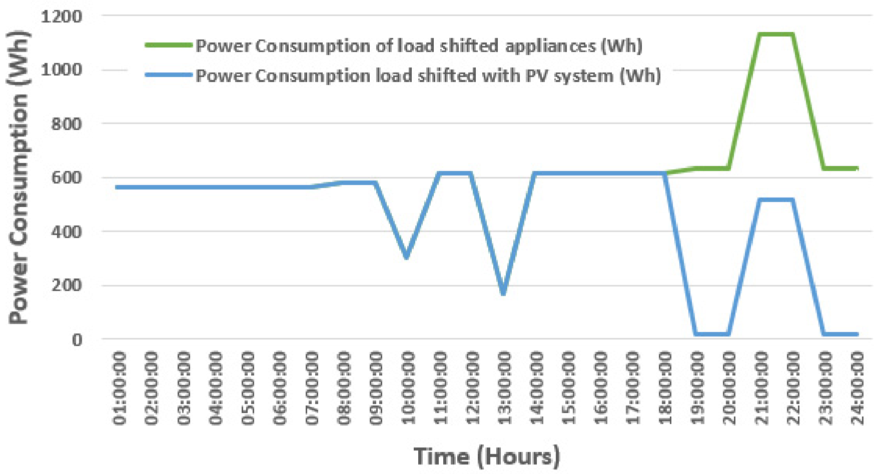

Figure 12. The 24-h winter power consumption profile for load shifted appliance with and without a PV system.

From the load flow analysis, the operating voltages at the buses were taken as shown in Table 5. When conducting loads flow studies in ETAP, depending on the operating voltages of the buses, the bus is highlighted in a certain colour to show whether it is functioning correctly or otherwise. In Figures 7 and 8, both bus6 and bus6-2 are pink. The colour pink in ETAP is automatically set to indicate that the bus is close to facing a problem. This is important when considering that the loads connected are medium and high-power consumption clusters of domestic loads with varying energy usage. In order to reduce the need of higher non-renewable generation from the grid, more renewable energy sources can be utilised to increase power at these buses. For example, solar panels can be implemented on a larger scale, or realistically wind power can be utilised due to the very high supply of wind resources in the UK. If these are available, the HEMS system can create schedules to reduce power consumption.

The load flow analysis of Figure 9 shows the various active powers when two wind turbines are being utilised. The wind turbines are both separately generating 2 MW prior to being stepped down to 1995 kW at the 11 kV bus3. With both turbines active, the buses all operate at 100% or very close to 100%, which is why no bus is highlighted in pink or red. Therefore, assuming the current loads require more power during winter, a sufficient amount of power can be supplied when utilizing these wind turbines.

Table 6 contains the operating voltages as a percentage of the specified buses when the grid voltage magnitude is increased from 90–100%. As previously seen, any bus will be made pink if between the range of 95–97.9% from the nominal voltage. From the load flow analysis data recorded, it can be seen that the grid is required to operate at lowest, 95.5% in order to power the loads during a low power consumption season (summer when heaters are less likely to be used). Furthermore, Figure 11 shows the trend of the data recorded in Table 6. The graph shows that the wind turbines make a significant difference in reducing grid penetration, since the loads can be sufficiently powered with much less non-renewable energy.

Table 5. Bus operating voltages from load flow analysis of Figure 7.

Bus ID	Nominal Voltage (kV)	Operating Voltage (%)
Bus1	33	100
Bus3	11	98.84
Bus6	0.4	97.08
Bus6-2	0.4	97.44
Bus11	0.4	98.61

Table 6. Load flow analysis of model-4 (wind power).

	Grid Operating Voltage			
Grid Operating Voltage (%)	Medium Voltage Bus3: 11 kV	Low Voltage Bus6: 400 V	Low Voltage Bus6-2: 400 V	Low Voltage Bus11: 400 V
90	91.42	89.57	89.64	91.22
90.5	91.52	90.07	90.45	91.72
91	92.42	90.58	90.95	92.21
91.5	92.91	91.09	91.46	92.71
92	93.41	91.59	91.96	93.21
92.5	93.91	92.1	92.47	93.71
93	94.41	92.61	92.97	94.2
93.5	94.91	93.11	93.48	94.7
94	95.41	93.62	93.98	95.2
94.5	95.91	94.12	94.48	95.7
95	96.41	94.63	94.99	96.19
95.5	96.91	95.13	95.49	96.69
96	97.41	95.63	95.99	97.19
96.5	97.9	96.14	96.5	97.68
97	98.4	96.64	97	98.18
97.5	98.9	97.15	97.5	98.67
98	99.4	97.65	98	99.17
98.5	99.9	98.15	98.51	99.67
99	100.4	98.66	99.01	100.2
99.5	100.9	99.16	99.51	100.7
100	101.4	99.66	100	101.4

5. Conclusions

A HEMS was analysed and tested to observe the effectiveness of smart energy management systems at the residential level. The proposed model for the HEMS operation is based on existing scheduling techniques that create a schedule with a trade-off between customer comfort and energy consumption minimization. The proposed schedule is based on a demand response strategy using an economy 7 m. Renewables were also integrated into the models to correctly deal with the distribution of aggregation and control of DERs.

The PV array system tested proved very useful when considering its capability to generate around 20–25% of the full domestic load, based on operating voltage limitations. These observations prove that voltage remains regulated with purposed DSM techniques. In combining both renewable and non-renewable energy resources, the results proved that high priority loads can remain powered during emergencies. This applies when a lower generation than needed takes place at the power grid. Using ETAP, load flow analysis of various systems was carried out to help establish how much power can be generated by renewable systems designed for the specific loads. This approach was also used to reduce grid penetration when clusters of loads were considered. Two wind turbines were integrated to the power network to generate more electricity and proved very useful for balancing the system when the load increased. The data show that, when utilizing the wind turbines, the main power grid only required an operating voltage magnitude of around 95% to power the chosen loads. In addition, key emerging technologies for smart grids were considered to address an ageing infrastructure. The tests carried out showed that smart grids provide higher energy efficiency and management whilst creating environmental awareness for consumers with regards to power usage. Above all, they allow for a greater level of control and security within the power network. In future work, energy management algorithms and advanced forecasting techniques can also be used to create new load schedules for the HEMS and new distributed energy resources can also be integrated into more complex power networks.

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Abbreviations

DER	Distributed energy resources
DSM	Demand side management
RES	Renewable energy sources
HEMS	Home energy management system
ETAP	Electrical power system analysis
PV	Photovoltaics
AS	Appliance scheduling
SC	Smart cities
DG	Distributed generation
SG	Smart grid
ESS	Energy storage system
DR	Demand response
LP	Linear programming
UC	User comfort
AC	Alternating current
DC	Direct current

WTG	Wind turbine generator
MW	Mega watt
RPF	Reverse power flow
Sa	Specified shiftable loads
Hp	High peak hours
Cp	Current energy price
Lp	Low peak hours

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