

Article

Supply Side Management vs. Demand Side Management of a Residential Microgrid Equipped with an Electric Vehicle in a Dual Tariff Scheme

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Abstract: Fundamentally, two main methodologies are used to reduce the electric energy bill in residential, commercial, and even industrial applications. The first method is to act on the supply side by integrating alternative means of power generation, such as renewable energy generators, having a relatively low levelized cost of energy. Whereas, the second methodology focuses on the management of the load to minimize the overall paid cost for energy. Thus, this article highlights the importance of demand side management by comparing it to the supply side management having, as criteria, the total achieved savings on the overall annual energy bill of a residential microgrid supplied by two power sources and equipped with an electric vehicle. The optimization takes into consideration the cost of kWh that is paid by the prosumer based on an economical model having as inputs the outcomes of the energy model. The adopted energy model integrates, on the demand side, an intelligent energy management system acting on secondary loads, and on the supply side, a photovoltaic (PV) system with and without battery energy storage system (BESS). The outcome of this work shows that, under the right circumstances, demand side management can be as valuable as supply side control.

Keywords: energy; energy management; demand side management; plug-in vehicle; vehicle-to-grid (V2G); vehicle-to-home (V2H); home energy management system (HEMS)

1. Introduction

In many countries, especially developing countries, and for many applications of sensitive and strategic interest, such as isolated housing, telecommunication posts, border posts, etc., conventional electricity grid is not always available. The permanent availability of electricity is vital and conditions, to a very large extent, the quality of life of the inhabitants as well as the reliability of the installations and their permanent operation. In Lebanon, and for the past 30 years, the utility company was not able to provide continuous electrical supply to all grid connected consumers. The conventional solutions that are provided by the neighborhood-level diesel generators, driven by the need for fuel supply and maintenance, not only have disadvantages that are related to noise, pollution, and poor performance at partial load, but they also have a major economic disadvantage related to a higher cost of energy in most cases. Moreover, the technological solutions that are provided by conventional electrochemical storage are expensive, technically limited in power, and limited in capacity. Thus, since electricity is non-storable economically, electricity rates (i.e., the prices set by competing generators to electricity consumers) vary from month to month and they usually fluctuate by an order of magnitude between

low season and high season. However, in general, almost all consumers are currently charged some average price that is higher than the actual wholesale price at the time of consumption. On the other hand, the new technological solutions that are provided by hybrid systems, even if they are not yet economically competitive, offer high safety. Nevertheless, in view of the need for sustainable development, these solutions, with the support of public will, can be economically and energetically viable in the medium and long term. Still, these solutions require a laborious preliminary dimensioning that is based on in-depth knowledge of the site renewable energies potential upstream, a rigorous management of the electrical energy produced downstream and a know-how that only experience in the energy systems engineering will be able to ensure. Therefore, a new approach to reduce the average cost of the kWh that is paid by the consumer is to act on the load instead of the source. A demand side management algorithm, applied to time and energy shiftable loads, can be a solution. Meanwhile, partially or fully electrified light duty transportation, such as hybrid cars and electric vehicles, have gained greater interest [1]. Vehicle-to-grid (V2G) can help to address the challenges without dealing with the economic barrier associated with the initial cost of storage batteries by acting as a storage device. EVs can be considered as adjustable generators to minimize the consumer's energy bill. Several projects have been developed in the previous years with the same target. However, most of these projects focused on the integration of distributed renewable energy resources to minimize the microgrid's dependency on conventional power sources, such as the utility or diesel generators. This article tackles this issue from a new perspective. The interference will be on the load side instead of the source by acting on secondary loads, either time shiftable loads or power shiftable loads, in order to optimize the energy system and minimize the overall energy bill.

The work that was conducted in this article illustrates the combination of several strategies, such as a load scheduler, demand side management, vehicle-to-grid (V2G), and renewable energy power generation systems, with the aim of reducing the yearly electricity bill of a residential microgrid that is based on a dual tariff scheme. This article presents an innovative algorithm for load scheduling, which is based on appliances prioritization, and smart charging/discharging of EVs by integrating the end-user's anxiety factor. The main target of this article is to value the demand side management measures, presented by the proposed demand response algorithm, versus the conventional supply side measures that mainly rely on the integration of renewable energy sources with or without energy storage means. Consequently, the outcomes will be illustrated by comparing the values that were obtained from conventional supply side power generation measures with the results gained from the integration of new demand side measures. The main criteria for comparison will be the yearly electricity bill of the residential microgrid.

Accordingly, a good model to consider, for a dual electricity rate system, is the case of a Lebanese mid-scale residential microgrid that is equipped with a plug-in electric vehicle (PEV) where the microgrid is powered half of the time by the Utility and the second half by the neighborhood private diesel generator. This model also exists in several developing countries, such as Pakistan, Iraq, Syria, Nigeria, Yemen . . . etc., where the utility company, for a reason or another, is incapable of balancing the power supply with the demand load. The methodology that was adopted is divided into two main parts. The first part will focus on the optimization of the load management of the subject microgrid by acting on time shiftable appliances (i.e., dishwasher, washer and dryer . . . etc.) and power shiftable loads, such as the PEV. The optimization will take the cost of kWh to be paid by the consumer based on an economical model having as inputs the outcomes of the energy model into account. In the second part of the article, a photovoltaic (PV) system, without a battery energy storage system (BESS) at a first stage and with a BESS at a second stage, will be integrated in the microgrid to compare the impact of both methods, supply side, and demand side, on the residential microgrid's energy bill and assess the impact of the applied load management on the sizing of the PV system and BESS. The scale and profile of the considered residential model are assumed for illustration. Nevertheless, the proposed model can be modified and easily adapted to other case studies and even for dynamic rate structure applications, such as Real Time Pricing (RTP).

2. Related Works

An overview of similar research works conducted in the fields of residential demand side management, EV integration in residential microgrids, smart charging and discharging of EVs, residential appliances load scheduling, and Home Energy Management System (HEMS) is outlined in this section in order to highlight the contributions of this article.

2.1. Residential Demand Response Programs and HEMS

One of the most important challenges in the operation of any electrical grid is the power balance between the supply and demand. Power generation and load demand forecasting are key parameters for proper generation arrangement and power management [2]. Utilities have developed two mechanisms in order to maintain the balance of power supply and demand in a cost-effective way. The first mechanism is based on the integration of energy storage systems and the second mechanism is focusing on minimizing the peak load by encouraging the end-users to change their power usage behaviors with incentive benefits. The first mechanism is mainly limited by its high initial and operation costs. The second mechanism is very dependent on the capabilities and voluntaries of the end-users. Therefore, the demand side management programs should be carefully designed to incent the abilities of the end-users at power demand side. Demand Response and Demand Side Management are both terms that are used to describe programs developed to influence the electricity usage patterns of customers. Demand Response (DR) is a term that is used for programs that are designed to encourage end-users to make short-term reductions in energy demand in response to a price signal. Demand Side Management (DSM) programs promote higher energy efficiency from the end user's side. Demand Response (DR) programs are designed to respond to the prices and/or power availability on the market. It offers a variety of economic and operational profits to both electricity customers and grid operators [3].

In [4], Ozadowicz presents a review of demand side management concepts for prosumer microgrids based on Building Automation and Control Systems (BACS), Building Energy Management System (BEMS), and Home Energy Management Systems (HEMS), with the aim of improving the energy performance of households in the microgrid concept and introducing a new event-based active DSM concept with Technical Building Management (TBM) functions that are dedicated to building integrated prosumer microgrids with universal communication platform based on the BACS and IoT technologies. With a more specific approach, the work that is presented in paper [5] introduces an adaptive energy management framework enabling demand response programs for the UK residential sector. The proposed smart energy management system is based on three levels. The first level includes a day-ahead load shifting and scheduling time shiftable appliances based on the next day's market energy prices. The second level focuses on the balancing of supply and demand for the upcoming hour. Additionally, finally, the third level comprises the integration of different power sources, including a PV system with battery storage, with the aim of meeting the energy demand while minimizing the cost.

Thus, basically most of the proposed residential demand side management or demand response programs are based on load shifting and load scheduling while using a HEMS that controls the operation of time shiftable loads based on future market energy rates to minimize the end user's energy bill. When considering these aspects, the work conducted in [6] values the improvements achieved by introducing a dynamic HEMS in the Korean residential sector while proving that the HEMS can be a beneficial tool for both energy producers and energy consumers. Similarly, in [7] the authors propose a fuzzy logic based smart DSM strategy for the Australian residential use case. The proposed smart HEMS can significantly reduce the energy consumption, standby power loss and energy costs of the prosumer, while also preserving the comfort levels. In article [8], the authors propose a home energy scheduler that optimizes the stochastic scheduling of home appliances, in an RTP model, with a target of minimizing the cost of electricity. The suggested HEMS works according to three phases: real time monitoring (RTM), stochastic scheduling (STS), and real time control (RTC). During RTM, the HEMS obtains the operational status of each controllable appliance as well as the

electricity rate of the RTP model. In STS phase, the Markov decision process is used to optimize the operation of the controlled loads by predicting the proper limitation of appliances based on the stochastic behavior of cost of consumption. Finally, the controlled appliances are operated according to the determined schedule in the RTC phase. In paper [9], and in order to minimize the consumer's energy consumption in a Time of Use (ToU) scheme, the authors propose an Energy Scheduling and Distributed Storage (ESDS) algorithm. The authors divided the work into three scenarios in order to prove the efficiency of their algorithm. The first scenario offered the baseline case without Demand Side Management, whereas the demand side management was considered in the second scenario and the ESDS was introduced in the third scenario along with DSM. The obtained results showed that the proposed ESDS algorithm is capable of minimizing the Peak-to-Average ratio demand and achieving considerable energy and financial savings. Similarly, the work completed in paper [10] provides an optimization model for a microgrid while considering different combinations of distributed power generation systems, taking into considerations the environmental factors that impact these systems, and demand side management. The main target of the work is to reduce the energy bill of the microgrid without affecting the consumer's needs and comfort by applying a load scheduling strategy to meet the generation of the distributed systems.

2.2. Electrical Vehicles Integration in Residential Microgrids

For the last few years, the integration of electrical vehicles in microgrids has been gaining wide attention due to the increasing number of electric vehicles gradually entering the market. A general overview of the V2G technology along with the different methodologies that were used for different types of electric vehicles is presented in [11]. Moreover, several works have been conducted with the aim of optimizing the integration of electric vehicles within microgrids, and minimizing the consumer's electricity bill by creating hybrid systems that are based on different distributed energy resources.

From a demand side perspective, households' electricity consumption covers a considerable share, 20 to 30 percent, of the total consumption that qualifies for demand response programs. Based on this information, the work that was conducted in paper [12] provides several scenarios for smart grids electricity consumption optimization, while using sensors, actuators, smart meters, advanced tariff schemes, smart appliances, and electricity home control applications. The outcome of this work shows that sustainable development of power systems using smart grid technologies, such as smart metering, load scheduler, and sensors, can only be accomplished by acting on the peak demand.

On the other hand, several strategies and algorithms have been presented with the aim of managing the integration of electric vehicles within the microgrids and smart grids and limit their impact on the overall power demand of the end users. Within this context, the work conducted in [13] studies the viability of the V2G connection from a battery perspective. This study proves that a smart control algorithm is a must for any V2G connection to maximize the longevity of the battery. Such an algorithm will only allow access to the battery's stored energy that does not exceed its allowable depth of discharge and it does not jeopardize its lifespan. Similarly, the authors in [14] offer an in-depth review and analysis of the different electric vehicle charging strategies in the context of vehicle-to-home (V2H), vehicle-to-building (V2B), and vehicle-to-grid (V2G). As a result, it is shown that an optimal bidirectional electric vehicle recharging strategy relies on both the end user's profile and degradation of the battery, with special interest for the cases of V2H and V2B where renewable energy resources can be used to charge the EV during periods of high energy rates. Moreover, this paper highlights the concepts of energy aggregator and multi-agent-based as strategies that can be adopted in the future once the required global communication systems are available.

Paper [15] presents a comprehensive review and assessment of most of the different aspects of V2G and renewable energies within the microgrids. The first aspect targets the V2G connection as part of the Virtual Power Plant (VPP) phenomenon. The second addressed aspect is the interaction of the EV with the microgrid from a charging/discharging and smart metering perception. The third aspect defines the integration of the electric vehicle with different renewable energy power generation

systems. Finally, the paper evaluates the feasibility of the integration of EVs and renewable energy systems within microgrids.

Based on the aforementioned articles, it is obvious that different strategies, in the context of demand response and demand side, management with multiplex methods have been developed for different residential markets worldwide. However, all of these works have been conducted on microgrids in advanced electric markets, where utility power is always available, with advanced dynamic electric rate structures, such as Time of Use (TOU) or Real Time Pricing (RTP) schemes. Furthermore, some of these researches have considered integrating V2G along with renewable energy sources (RES) in their models. Nevertheless, this study considers the case of a residential microgrid in a developing country where the utility company is unable to meet the demand load and utility power is only available half of the time. Such a model presents two main singularities. The first particularity is revealed by the fact that, during power outage periods, the microgrid is powered from a neighborhood private diesel generator that charges higher rates than the utility company. Moreover, given that the utility power outages are unpredictable constitutes a second singularity to our proposed model. On the other hand, our proposed load scheduler presents the advantage of offering the end user an additional degree of flexibility by prioritizing the time shiftable load. Finally, this study highlights the impact of the integration of a demand response algorithm on the sizing of the PV system and BESS.

3. Modeling of the Residential Microgrid

The Lebanese residential microgrid, which was considered for this work, corresponds to one household occupied by four family members with an occupancy profile, as described in Figure 1. The house has an approximate area of 200 m², which is composed of three bedrooms, one living area, dining room, kitchen, and three toilets. It is assumed that the house is equipped with 3No air conditioning (AC) units of 12,000 BTUs each and 1No. AC unit with a capacity of 24,000 BTUs. Additionally, it is considered that the household is equipped with 2No electric water heater (EWH) tanks, one water lift pump, one dishwasher, one washer, and one dryer. The house is connected to the utility grid, via an energy meter, as the main electrical supply and connected to a diesel generator, also via an energy meter, for backup power in times of utility power outages. The diesel generator is considered to be owned by a neighborhood-level power producer and the supplied energy cost is different from the utility electric rate and defined by the distributor. The distributed energy resources considered are an off-grid photovoltaic (PV) system with medium size storage batteries and the battery of one PEV. The use of medium-capacity battery was considered to limit the cost and space required for installation as opposition to the use of high capacity battery energy storage system. Our model smart house will have a battery capacity of 7.2 kWh to cover the energy demand during the utility power outage. For the purpose of illustration, the PEV considered has a 30 kWh battery and a 6 kW charger. Moreover, the household is equipped with a home energy management system (HEMS) communicating with the energy meters, the time shiftable appliances, and the distributed energy resources. The considered residential microgrid scheme is shown in Figure 2. The HEMS is capable of detecting the availability of the different power sources (utility grid or diesel generator), assessing the energy generated by the PV system via a prediction model that is based on forecasted weather data, reading the PEV's battery and PV system storage batteries state of charge (SOC) and detecting the operation of the time shiftable loads via current sensing relays. The inputs for the HEMS are the kWh rates for the utility and diesel generator, the forecasted weather data, and the SOC of the storage batteries or PEV once plugged to the microgrid.

The work is divided into three scenarios. The first scenario only considers the implementation of the demand side management optimization algorithm, including the management of the PEV as a storage device. The second scenario shall include the results of the previous scenario combined with the power generated from the PV system and the last scenario will add to the previous ones the integration of the storage battery systems. The optimization will take the cost of kWh to be paid by the consumer based on an economical model having as inputs the outcomes of the energy model into

account. The economic study shall be based on an average utility electric rate equal to 0.10 \$/kWh and a diesel generator rate of 0.30 \$/kWh [16]. The microgrid is considered to be powered by the Utility half of the time and by the diesel generator in the second half, with an alternating cycle of four hours. In the second and third scenario, the impact of the load management on the sizing of the PV system and the BESS shall be evaluated as the final outcome of this work.

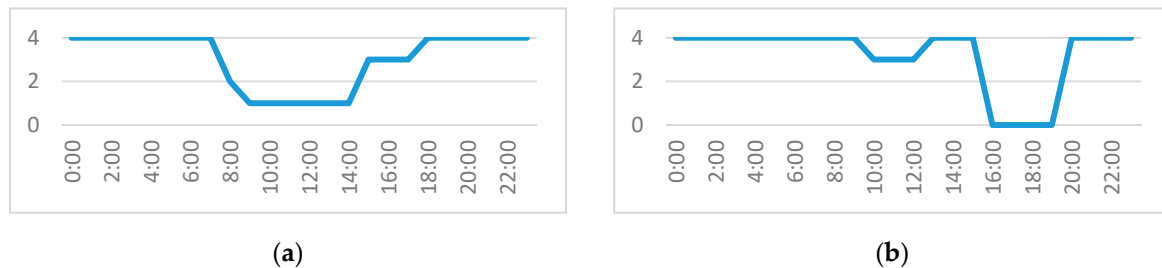


Figure 1. (a) Weekday occupancy profile; and, (b) Weekend occupancy profile.

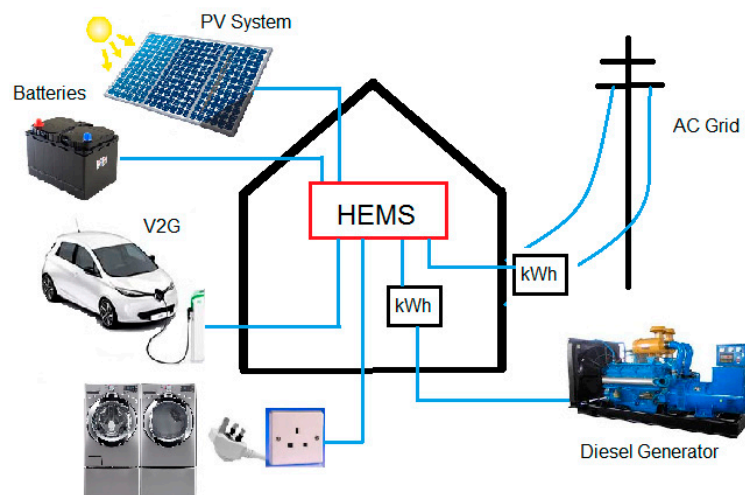


Figure 2. Residential microgrid scheme.

4. Scenario 1: Load Management

Nowadays, most electricity consumers do not acknowledge the differences in electricity prices, and simply act as flat rates price takers, simply because they have no incentives to adjust their electricity consumption patterns [17]. In the Lebanese case, and due to the deficiency in the power supply from the utility which can reach up to 12 h per day, and the different energy cost paid for the diesel generator back up power, the model can be considered to be a special case of dynamic rate structure that is similar to the double tariff structure [18]. Therefore, through applying a demand response (DR) program, consumers can optimize their energy consumptions and minimize their electricity bill. DR can be considered as one of smart grid's main components, which has the potential to help power markets set efficient energy prices, mitigate market power, improve economic efficiency, and increase security [19]. A demand response program will notify the consumers of an opportunity to reduce the costs by limiting the demand in periods when the household is powered by the source with the highest kWh rate. To achieve that, a comprehensive appliance classification is essential for understanding distinct spatial and temporal operation characteristics of appliances and design their corresponding control strategies. For this purpose, we have divided the appliances included in our case study into four categories, as detailed in Table 1. Fixed/Critical Loads are equipment whose power consumption and usage cannot be controlled (i.e., Refrigeration, lighting, TV etc.). Time Shiftable loads are loads that can only be shifted in time and operate on their own power consumption patterns (i.e., washing machine, dishwasher) [20,21]. Power Shiftable loads are the appliances that have a prescribed energy

requirement, depending upon the usage of customer (i.e., PEV). Comfort Based loads are the devices that are used to control a physical variable that influences the user's comfort (i.e., HVAC). In this work, the Electric Water Heater (EWH) is considered to be a time shiftable load, since it is considered that a well-insulated water tank can preserve hot water for 24 h.

Table 1. Residential appliances classification.

Fixed/Critical Loads			Comfort Based Loads	Power Shiftable Loads
Fridge	Lighting	Other Appliances	HVAC	Electric Vehicle
Time Shiftable Loads				
EWH		Washer	Dryer	Dishwasher

4.1. Demand Response Algorithm

The proposed DR algorithm will only be acting on the time shiftable loads. To shift the load of appliances, these appliances have to be scheduled. The proposed scheduler's target is to reduce the overall cost of electricity used to run the appliances. For calculation purposes, it is assumed that a given ahead fixed utility and generator electricity tariffs (i.e., USD per kWh) are provided. We consider a simple scenario where the tasks do not depend on each other. To optimally schedule a task given the prices, it is sufficient to try each feasible start time in turn, evaluate its total cost, and select the one with the lowest total cost. In our case, the procedure is very simple, since we only have two fixed rates and the time applied for each rate is directly related to the presence or absence of the utility power.

The total energy cost formula is given by:

$$\sum_{t \in T} (j_t \cdot \gamma_U \cdot E_{U,t} + (1 - j_t) \cdot \gamma_G \cdot E_{G,t}) \quad (1)$$

$$\begin{cases} j_t = 1 & \text{if Utility power is available} \\ j_t = 0 & \text{Else} \end{cases}$$

γ_G : Generator Energy rate \$/kWh

γ_U : Utility Energy rate \$/kWh

$E_{G,t}$: Energy registered at Generator kWh meter

$E_{U,t}$: Energy registered at the Utility kWh meter

Therefore, the objective of the DR algorithm is to minimize the total electricity bill, which can be formulated, as follows:

$$\text{Min} \sum_{t \in T} (\gamma_G \cdot E_{G,t} + \gamma_U \cdot E_{U,t}) \quad (2)$$

In our case, it is assumed that γ_G is greater than γ_U and it is considered as constant. Thus, the formula can be simplified to the following:

$$\text{Min} \sum_{t \in T} (E_{G,t}) \quad (3)$$

All time shiftable loads operating during this period shall be shifted to the utility power in order to minimize the total energy consumed when the generator powers the household. The HEMS will detect the operation of any time shiftable load via installed current sensing relays. If the available power source is the preferable one (the source with the lowest energy cost), the appliance will continue to operate as scheduled. Otherwise, the HEMS will stop the operation of the time shiftable appliance and will store it in a matrix $TSL_{m,n}$. Once the preferable power source is available again, the time shifted appliances will be re-operated. Two levels of priority are set in order to organize the operation of shifted loads. The first level of priority is the day. This level of priority is defined to make sure that

all shifted appliances will be re-operated in the same day. The second level of priority is set by the user and it reflects the importance of the appliance on the quality of life of the inhabitants. Moreover, a cycle duration is pre-assigned for each appliance; therefore, once re-operated the HEMS will allocate a sufficient time for operation. Another set criterion for the re-operation of the time shiftable appliances is to make sure not to exceed the maximum permissible power defined by the electric network. Thus, the HEMS will measure the actual load on the time t of re-operation and based upon this will define the number of re-scheduled appliances that can be simultaneously operated. The power limitation formula is defined, as follows:

$$\sum_{l \in L} P_{l,t} + \sum_{n \in N} TSL_{1,n} \leq P_{Max} \quad (4)$$

$TSL_{m,n}$: Time Shiftable Load Matrix

$m \in \{1, 2, 3\} \rightarrow 1$ for Load Power, 2 for Priority L1 and 3 for Priority L2

$n \in N$: set of time shifted loads

$l \in L$: set of all loads

$t \in T$: set of time intervals

$P_{l,t}$: Power of load l at time t

P_{max} : Microgrid max. Permissible Power

We decided to test the developed DR algorithm on four typical weeks each in every season due to the absence of a detailed hourly load profile showing the operation of each appliance or system (i.e., Lighting, HVAC and fridge . . . etc.) all over the year (autumn, winter, spring, and summer). An hourly load profile has been developed for each week with detailed hourly operation for each appliance and system. The developed load profile has a resolution t of one hour. For more in depth results, the model can be easily amended to have a resolution of 30 min or even 15 min. Moreover, the model has for input an hourly profile for the utility outages based on the real case found in Lebanon (outside Beirut district). Table 2 details the considered shiftable loads along with their power consumptions, cycles, and priorities.

Table 2. Residential appliances classification.

Appliance	Power (kW)	Priority L2	Cycle (Hours)
Electric Water Heater #1	2	1	3
Electric Water Heater #12	2	2	3
Water Pump	0.75	3	1
Washer	1.4	4	1
Dryer	1.3	5	1
Dishwasher	1.1	6	2

The hourly load profile is given via a matrix $L_{i,t}$ where i is the type of the load (i.e., 1 for fridge, 2 for lighting, 3 for other appliances, 4 for HVAC, 5 for EWH#1, 6 for EWH#2, 7 for Water pump, 8 for washer, 9 for dryer, and 10 for dishwasher) and t is the time resolution. It is also assumed that, in the case an appliance has already started its cycle and a utility electrical outage occurs, the appliance will resume its cycle when the backup generator power is available.

The DR algorithm will go through the load matrix $L_{i,t}$ starting by checking the operation of any time shiftable appliance for each time resolution t . In the case that an appliance is operated during a high energy rate period, it will be stopped and saved in the time shiftable loads matrix $TSL_{m,n}$, allocating the load a day priority and an appliance priority. This process can be summarized, as detailed in Algorithm 1 and the logic diagram shown in Figure 3.

Algorithm 1: Demand Response Optimization of Time Shiftable Loads

- 1: Initiate algorithm at time t
- 2: **if** power source with lower energy rate is available **then**
- 3: Check if time-shiftable loads are stored in the TSL matrix
- 4: **if** TSL is not empty **then**
- 5: Re-operation of time shifted loads
- 6: **else**
- 7: no action
- 8: **end if**
- 9: **else**
- 10: Check if a time shiftable appliance is operational: $(1 - j_i) \cdot L_{i,t} > 0$; $i \in \{5, 6, 7, 8, 9, 10\}$
- 11: Store the load in the TSL matrix: $TSL_{1,n} = L_{i,t}$
- 12: Stop the load: $L_{i,t} = 0$
- 13: Assign time shifted load priority level I: $TSL_{2,n} = \text{Round}(\frac{t}{24} + 0.5)$
- 14: Assign time shifted load priority level II: $TSL_{3,n} = PR_i$
- 15: Rearrange the time shifted loads stored in TSL by order of priority
- 16: **end if**
- 17: Re-do the same procedure for $t = t + 1$

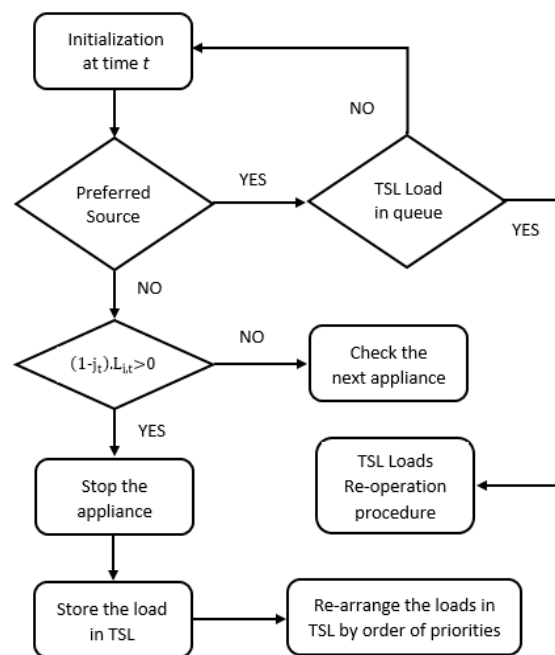


Figure 3. Demand Response Logic Diagram.

4.2. PEV Charging and Discharging

The formulation of the PEV charging/discharging coordination is based on multi-objectives optimization. The goals of the optimization are to minimize the charging cost and minimize the energy consumed from the generators, by using the PEV batteries as source of energy, in order to minimize the household total energy bill. The usage of a plug-in electric vehicle in V2G process in order to optimize the energy consumption or to shave peaks is different from other used techniques (i.e., usage of renewable energy resources) for its dependence on batteries. Battery life is significantly influenced by the number of cycles, depth of discharge, charge/discharge rates, and other factors [22]. On the other hand, the PEV user's constraints can constitute major challenges. Electric vehicles users generally require a complete charging of the batteries, in the shortest possible time, for the purpose of maximizing the vehicle's autonomy. Therefore, battery life and charging time are both considered

as major restraints to any V2G configuration. An optimization between the user’s need of a quick recharge time and the contribution to the energy regulation of the microgrid, as required by the energy manager, is a must [1].

We have defined three factors: SOC_{max}^* the maximum state of charge set by the user, SOC_{min}^* the minimum state of charge set by the user, and DT the user set daily trip energy in order to respond to these constraints. To ensure the safety and increase the life of the battery, SOC_{min}^* cannot be lower than SOC_{min} (The minimum state of charge set by the battery manufacturer). The factor SOC_{max}^* is related to the EV range anxiety. The range anxiety is defined as the fear that a vehicle has insufficient range to reach its destination and would thus stand the vehicle’s occupants [23]. The charging and discharging strategy is shown in Figure 4.

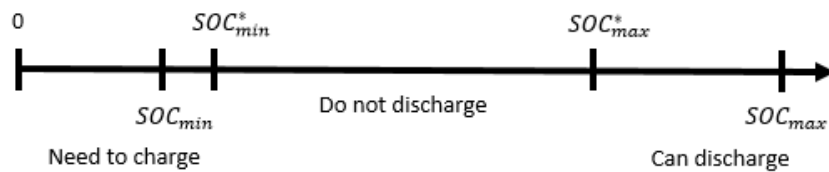


Figure 4. Plug-in electric vehicle (PEV) battery charging and discharging strategy.

The three factors are interconnected based on the following formulas:

$$SOC_{max}^* - DT \geq SOC_{min}^* \tag{5}$$

$$SOC_{min}^* \leq SOC_t \leq SOC_{max}^* \tag{6}$$

$$SOC_t = E_t / E_{max} \times 100 \tag{7}$$

The PEV will not charge and discharge at the same time. Thus, the charging and discharging process can be defined with the following system:

$$\begin{cases} p_t^C = k \cdot P_t^C \\ p_t^D = (1 - k) \cdot P_t^D \end{cases} \tag{8}$$

$$\begin{cases} k = 1 & \text{if } SOC_t - SOC_{min}^* < 0 \\ & \text{or } SOC_{max}^* - SOC_t > 0 \\ k = 0 & \text{Else} \end{cases} \tag{9}$$

Equation (12) describes the constraints on the power of the PEV involved in the V2G process. The PEV power cannot exceed the maximum value of the charge power P_t^C , from the microgrid to the PEV. Additionally, the PEV power at time t (p_t) cannot exceed the maximum discharge power P_t^D , from the PEV to the microgrid. Moreover, at any time of discharge, p_t cannot exceed the total microgrid demand power L_t^T . These constraints limit the value of p_t to be less than the PEV’s maximum service capability.

$$\begin{cases} p_t \leq P_t^C \\ p_t \leq P_t^D \\ p_t \leq L_t^T \end{cases} \tag{10}$$

Equation (11) provides the charging and discharging constraints.

$$\begin{cases} 0 \leq C_t^C \leq C_{max}^C \\ 0 \leq C_t^D \leq C_{max}^D \end{cases} \tag{11}$$

where C_t^C and C_t^D are, respectively, the charge and discharge ratios and C_{max}^C and C_{max}^D are, respectively, the maximum available charge and discharge ratios.

The electric quantity constraints are given by the following equations:

$$Q_{e_{min}} \leq Q_{e_t} \leq Q_{e_{max}} \quad (12)$$

$$Q_{e_{min}} = (1 - DoD_{max}) \cdot B \quad (13)$$

$$Q_{e_{max}} = B \quad (14)$$

where DoD_{max} is the battery maximum depth of discharge and B is the battery capacity.

At any time t , the electric quantity equation can be written:

$$Q_{e_t} = SOC_t \cdot Q_{e_{t-1}} + \left(\eta_C \cdot P_t^C - \frac{P_t^D}{\eta_D} \right) \Delta t \quad (15)$$

where η_C and η_D are, respectively, the battery charging and discharging efficiencies.

It is necessary to minimize the energy used for charging the battery when the household is powered from the generators in order to minimize the electric bill resulting from the PEV battery charging (time with the higher energy rate). In order to achieve that, we decided to limit the charging level, in periods of utility power outages, to the anxiety level SOC_{max}^* . In periods when the utility power is available, the electrical vehicle will be charged to SOC_{max} . The above criteria can be summarized by the following equations:

$$\begin{cases} \Delta Q_t^{max} = (SOC_{max} - SOC_{min}) \cdot B \\ 0 \leq \Delta Q_t^C \leq (SOC_{max} - SOC_t) \cdot B \rightarrow \text{if Utility} \\ 0 \leq \Delta Q_t^C \leq (SOC_{max}^* - SOC_t) \cdot B \rightarrow \text{if Generator} \\ 0 \leq \Delta Q_t^D \leq (SOC_t - SOC_{min}^*) \cdot B \end{cases} \quad (16)$$

where ΔQ_t^{max} , ΔQ_t^C , and ΔQ_t^D are, respectively, the maximum available capacity, the available charge capacity, and the available discharge capacity.

The energy management when the PEV is plugged to the microgrid depends on the available energy from the PEV battery. This energy can be estimated or communicated by the HEMS. Two cases can be distinguished. In both cases, the PEV battery has to be charged to fulfil the user's daily trip. The first case of charging is considered when the utility power is available. In this case, the HEMS will keep the PEV battery charging until the maximum state of charge of the battery is achieved. In the second case, the period of utility power outage, the HEMS will only charge the PEV battery to the anxiety level that is defined by the user. This measure allows for minimizing the electric bill for charging the electric vehicle. The PEV battery charging algorithm is detailed in Algorithm 2 and the logic diagram is given in Figure 5.

On the other hand, the additional energy stored in the PEV battery, as given by Equation (19), will be used to fully or partially shave the microgrid demand load in periods of utility power outage in order to optimize the household energy management. If the energy stored in the PEV is less than the demand load energy ($E_{V2G} < E_{Home}$), all of the permitted PEV battery power, as defined in Equation (12), is injected in the grid and the missing power will be provided by the generators. Otherwise, the priority is given to the PEV battery and the generators power is null.

$$(SOC_t - SOC_{max}^*) \cdot Q_e \quad (17)$$

$$P_{Home} = P_{V2G} + P_{Gen} \quad (18)$$

Algorithm 2: Optimization of the Charging and Discharging of a PEV

- 1: Initiate algorithm at time t
- 2: **if** PEV battery is lower than the upper charging level set by the user **then**
- 3: Initiate the charging process
- 4: **if** the preferred power source is available **then**
- 5: Charge the battery to the maximum charging level (SOC_{max}) set by the Manufacturer
- 6: **else**
- 7: Charge the battery to the maximum charging level (SOC_{max}^*) set by the User
- 8: **end if**
- 9: **else**
- 10: Initiate the discharging process
- 11: **if** the preferred power source is available **then**
- 12: Charge the battery to the maximum charging level set by the Manufacturer
- 13: **else**
- 14: Use the extra stored energy to supply the microgrid
- 15: **end if**
- 16: **end if**
- 17: Re-do the same procedure for $t = t + 1$

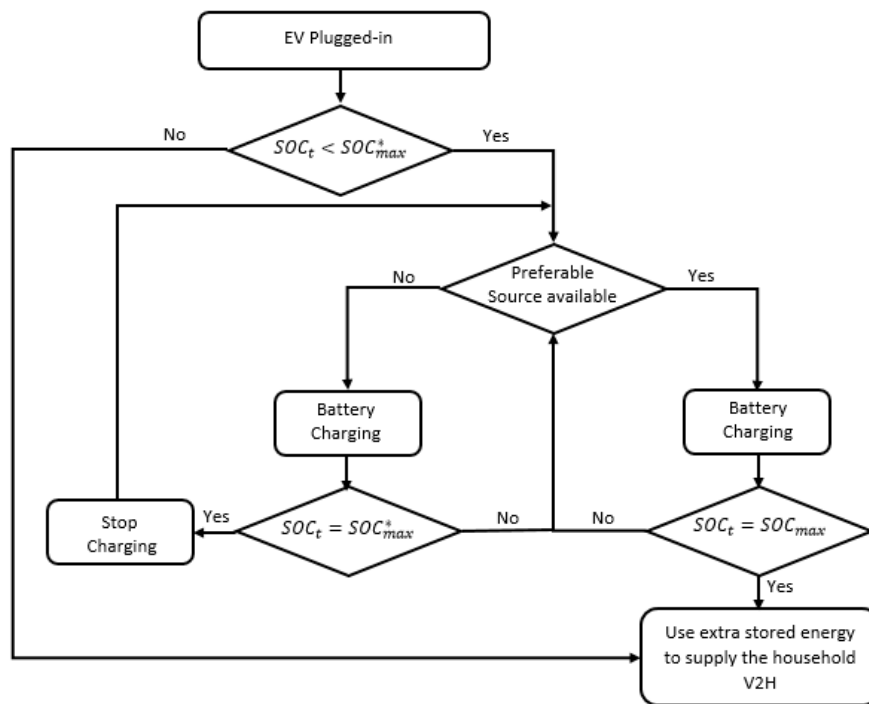


Figure 5. Scenario 1 logic diagram.

The energy cost for charging the PEV battery is given by Equation (19). Additionally, the saved energy cost when the PEV battery is injecting power to the microgrid is given by Equation (20).

$$\sum_{t \in T} (j_t \cdot \gamma_U \cdot E_{U,t}^C + (1 - j_t) \cdot \gamma_G \cdot E_{G,t}^C) \quad (19)$$

$$\sum_{t \in T} ((1 - j_t) \cdot \gamma_G \cdot E_{V2G,t}^D) \quad (20)$$

We applied the algorithm to four seasonal weeks based on the load profiles developed here above in order to validate the functionality of the developed demand response and PEV charging and

discharging algorithms, as detailed here above. The weekly savings are calculated by comparing the baseline load profile weekly total energy cost (TEC) to the optimized load profile weekly total energy cost. Obtained results are shown in Table 3.

$$Savings(t) = (BEC(t) - OEC(t)) \times Energy\ Cost(t) \quad (21)$$

$$Total\ Savings = \sum_{t \in T} Savings(t) \quad (22)$$

Table 3. Scenario 1 weekly savings.

Week	Baseline Energy Cost	Optimized Energy Cost	Savings	%
Summer	\$102.04	\$82.94	\$19.01	18.72
Winter	\$74.46	\$56.35	\$18.11	24.32
Spring	\$69.01	\$53.35	\$15.66	22.70
Autumn	\$64.17	\$47.41	\$16.76	26.12

5. Scenario 2: Load Management with PV

In this scenario, along the demand response algorithm and the PEV charging/discharging algorithm detailed in scenario 1, a photovoltaic source is integrated. In this scenario, the home batteries shall not be considered. In this case, the home energy management system HEMS integrates three functions: a demand response load manager, a smart charging/discharging control for the plug-in electric vehicle, and a local energy management. Photovoltaic panels will only provide electrical power to the residential microgrid during the day with a power peak around the midday. Nonetheless, several production variations may occur due to weather variations. Based on the weather forecasting and historic database of PV power, an afore-estimated PV power profile (\hat{P}_{PV}) can be utilized. It is essential to develop an appropriate calibrated model, make some assumptions about operation, and define the proper metrics and performance indicators to thoroughly investigate the interactions between the different components of the residential microgrid. During normal operation, electric power, which is needed to meet the AC load, is provided by combining the power delivered by the PV system via the inverter, the PEV battery's power whenever its state of charge allows, the utility power whenever is available, and the private neighborhood diesel generator in periods of utility outage. Figure 6 summarizes the above power combination.

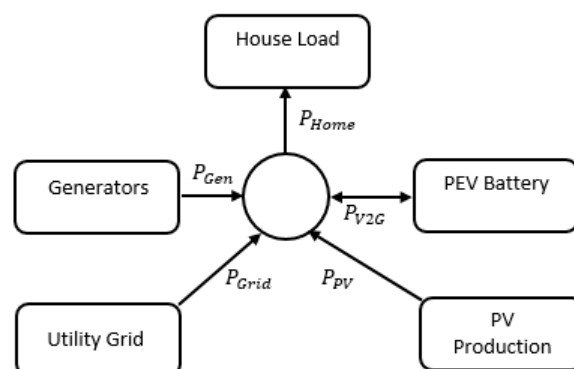


Figure 6. Power distribution with PEV and PV connected.

At any instant in time, the energy flows depend on the building AC loads, the available source of energy (utility or diesel generator), the solar PV power, and the state of charge of the PEV battery, as shown below:

- Mode 1: If solar PV AC power is greater than or equal to the building AC load, the utility power is available and the PEV battery state of charge is less than SOC_{max} , the power provided by the utility meter will be zero and the building AC loads will be met by the solar PV AC power from the inverter, with any excess power available being used for PEV battery charging.

$$P_{Home} + P_{G2V} = P_{PV} \quad (23)$$

- Mode 2: If solar PV AC power is greater than or equal to the building AC load, the utility power is available and the PEV battery state of charge is equal to SOC_{max} or the PEV is not connected to the microgrid, the power that is provided by the utility meter will be zero and the building AC loads will be met by the solar PV AC power from the inverter, with the excess power being provided by the PV will be wasted.

$$P_{Home} = P_{PV} \quad (24)$$

- Mode 3: If solar PV AC power is less than the building AC load, the utility power is available and the PEV battery state of charge is less than SOC_{max} , the additional power that is required to meet the load will be provided via the utility meter and the PEV battery will be charged while using the utility power.

$$P_{Home} + P_{G2V} = P_{Grid} + P_{PV} \quad (25)$$

- Mode 4: If solar PV AC power is less than the building AC load, the utility power is available and the PEV battery state of charge is equal to SOC_{max} , the additional power required to meet the load will be provided via the utility meter.

$$P_{Home} = P_{Grid} + P_{PV} \quad (26)$$

- Mode 5: If solar PV AC power is greater than or equal to the building AC load, the utility power is not available and the PEV battery state of charge is less than SOC_{max} , the power provided by the generator will be zero and the building AC loads will be met by the solar PV AC power from the inverter with any excess power available will be used for PEV battery charging (same as Equation (23)).
- Mode 6: If solar PV AC power is greater than or equal to the building AC load, the utility power is not available and the PEV battery state of charge is equal to SOC_{max} or the PEV is not connected to the microgrid, the power that is provided by the generator will be zero and the building AC loads will be met by the solar PV AC power from the inverter, without the need to discharge the store energy in the PEV battery (same as Equation (24)).
- Mode 7: If solar PV AC power is less than the building AC load, the utility power is not available and the PEV battery state of charge is less than SOC_{max}^* , the additional power required to meet the load will be provided by the generator and the PEV battery will be charged to reach SOC_{max}^* .

$$P_{Home} + P_{G2V} = P_{Gen} + P_{PV} \quad (27)$$

- Mode 8: If solar PV AC power is less than the building AC load, the utility power is not available and the PEV battery state of charge is above SOC_{max}^* , the additional energy that is stored in the PEV will be used to power the load and, if additional load is still required, the additional power that is required to meet the load will be provided via the generator

$$P_{Home} = P_{Gen} + P_{PV} + P_{V2G} \quad (28)$$

We first established a new baseline introducing the PV system to our case study residential microgrid model in order to validate the savings achieved with the proposed algorithm detailed here above (Algorithm 3). Thus, we compared the total energy cost of the baseline model, including a PEV,

with a PV system to the same model after integration of the proposed optimization algorithm. The new baseline model power formula, at a time integral t , is given by Equation (29). Table 4 details the results obtained in scenario 2.

$$P_{Home,t} + P_{V2G,t} = (1 - j_t)P_{Gen,t} + j_t \cdot P_{U,t} + P_{PV,t} \quad (29)$$

Table 4. Scenario 2 weekly savings.

Week	Baseline Energy Cost with PV	Optimized Energy Cost	Savings	%
Summer	\$78.63	\$64.65	\$13.98	17.78
Winter	\$57.95	\$45.80	\$12.15	20.97
Spring	\$51.69	\$44.75	\$6.93	13.42
Autumn	\$50.74	\$40.22	\$10.52	20.73

The impact of the PV system integration on the microgrid can be valued by comparing the baseline of scenario 1 to the baseline of scenario 2. The integration of the PV system alone, while not taking the control of time shiftable and power shiftable loads into consideration, added an average of 22.8% of savings. These savings, as demonstrated, are practically equal to the 22.9% average savings that are achieved in scenario 1 (as per results shown in Table 3) through the implementation of a smart HEMS acting on time shiftable and power shiftable loads. The combination of the smart HEMS with the PV system introduced an additional average of 18.2% to the total savings (as per the results shown in Table 4.). Thus, the results that were obtained in this simulation show that the combination of the HEMS with the PV system achieved an average of 36.9% of savings on the residential microgrid's annual electricity bill.

The total weekly wasted PV energy is another factor that is important to monitor, as a result of scenario 2 simulation. The wasted PV energy is defined as the difference between the maximum power that could have been generated by the PV system when operating at its maximum power point within a time frame t , and the actual generated power within the same time frame. Figure 7 shows a comparison of the wasted PV energy between the baseline model and the optimized model. It shows that, after implementation of Algorithm 3 to the baseline model, the wasted PV energy increased. This increase is due to the fact that the utility power outage occurs in midday every other day, which coincides with the prime time of the PV power generation. Additionally, since, if the generated PV power is not sufficient to operate the time shifted appliances, these appliances are shifted to the period with utility power supply, thus the wasted energy from the PV system, after implementation of Algorithm 3, has increased.

Therefore, we decided to investigate the case where a smaller PV system is installed with optimization while using the algorithm of scenario 3, and to compare the obtained results to the savings that were obtained from a larger PV system without optimization. Figure 8 shows a comparison between the achieved savings from the baseline model with the integration of the PV system without optimization and the same baseline model with a PV system half the size of the initial one with optimization, respectively, for the summer and spring weeks. The results that are shown in Figure 8 reflect the importance of the demand side management, including the demand response and the optimization of the charging and discharging of the PEV battery, over the implementation of renewable energy-based solutions. In our case, for the summer week, the savings that are achieved with a smaller size PV system with load management are 34% larger than the savings achieved with the implementation of a larger scale PV system without load management.

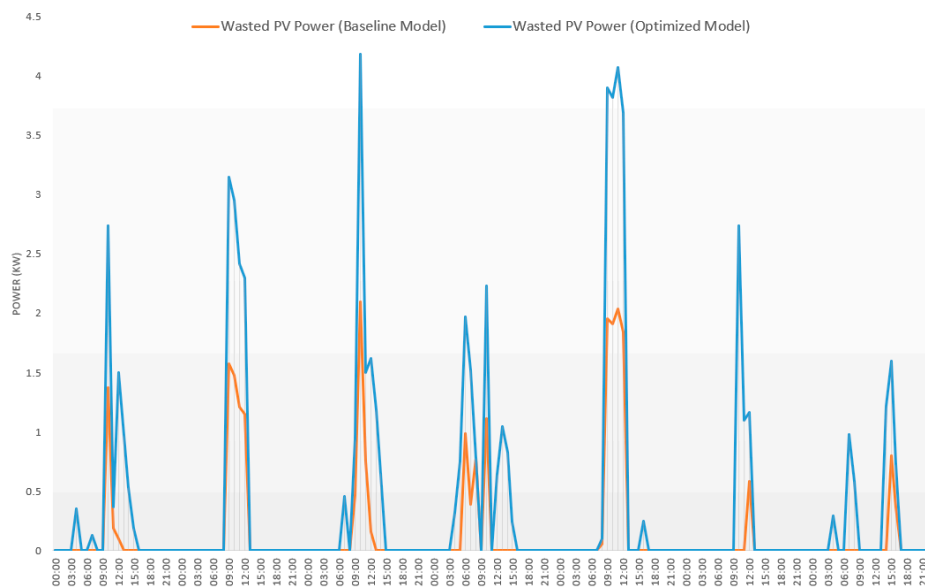
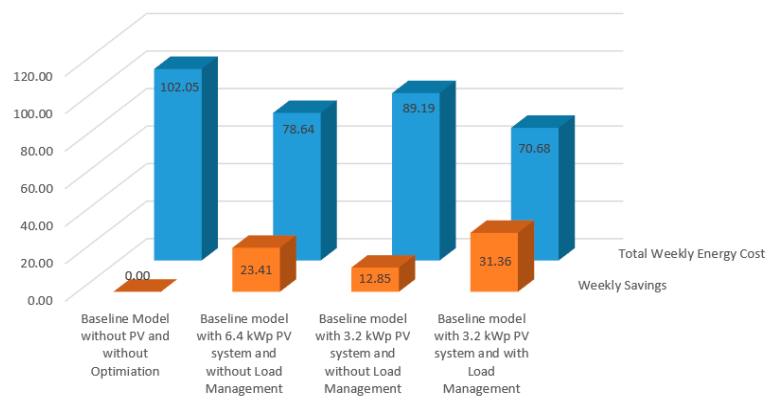
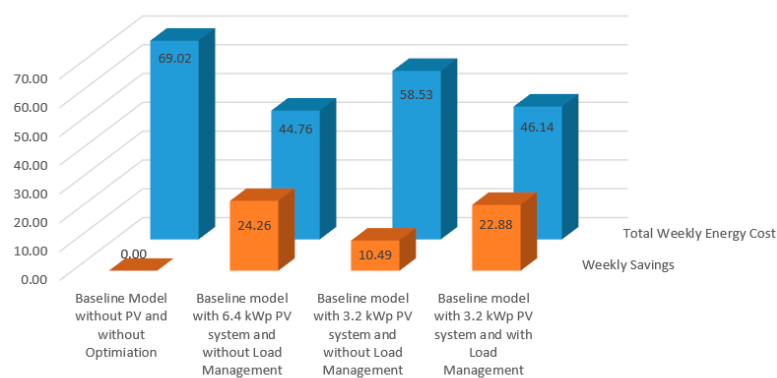


Figure 7. Summer week wasted grid photovoltaic (PV) energy comparison between the baseline load model and optimized load model.



(a)



(b)

Figure 8. (a) Summer week—Savings after reduction of the PV System size; (b) Spring week—Savings after reduction of the PV System size.

6. Scenario 3: Load Management + PEV + PV + BESS

The simulation results that were conducted in scenario 2 showed that the PV system is not always generating at its maximum power point. We defined the wasted PV power as the difference between the maximum power that could have been generated by the PV system within a time frame t and the actual generated power within the same time frame. Thus, we decided to integrate in the third scenario a battery energy storage system BESS to recover the wasted energy, store it, and benefit from it in periods when the microgrid is supplied by a high energy rate power source. In this scenario, the PV system will be associated with a storage system that includes a set of batteries acting as a long-term storage device and the battery of the PEV that acts as a dynamic power regulator when the electric vehicle is plugged-in and its state of charge allows it. In this configuration, the excess energy that is generated from the PV system will be mainly stored in the home BESS, since the PEV is rarely plugged-in to the microgrid during the day. The main concern with the BESS is to set a minimum charging and discharging cycle for the batteries every day. The depth of discharge of the batteries will be maintained between 30% and 80% during normal operation to increase the batteries' life time. For scenario 3, Figure 9 shows the power distribution of the microgrid.

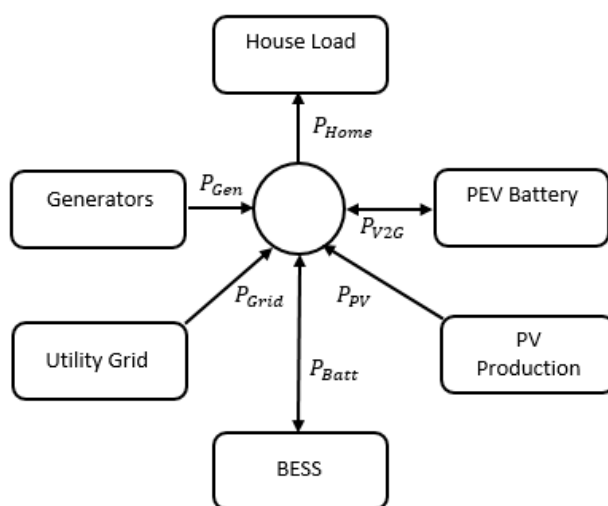


Figure 9. Power distribution with PEV, PV, and battery energy storage system (BESS) connected.

During the day, the priority will be given to the PV system and the utility, or the private diesel generators in periods of utility power outage, in the case that the PEV is not plugged to the microgrid, and when the PV system is generating power. The utility or private diesel generators will only cover, in this case, the additional power that is required by the load. In case that the power generated by the PV system is greater than the microgrid's required load, the excess energy will be stored in the BESS. In case the PEV is plugged to the microgrid, it shall act as load or source based on its state of charge and the available power source (utility or private generator), as detailed in scenario 2. The energy management during the night time depends on the available energy from the BESS and the PEV battery. This stored energy will be controlled and communicated to the microgrid by the HEMS. The main criterion that controls the flow of energy from the BESS and the PEV battery to the microgrid is that the batteries of the BESS should be discharged to the maximum possible condition, that is, the minimum acceptable state of charge SOC_{min}^{Batt} is not exceeded, in order to be ready for charging the next day and the PEV battery should be charged to SOC_{max}^* to cover the required energy for the next day trip planned by the end-user. In this scenario, we combined the BESS charging and discharging algorithm with the previously detailed algorithms for the PV power management (Algorithm 3), PEV battery charging and discharging algorithm (Algorithm 2), and the demand response for time shiftable loads (Algorithm 1). The combination of these four algorithms shall be considered as Algorithm 4. In order to evaluate the savings that were achieved by Algorithm 4, we established a new baseline model by

integrating a 7.2 kWh BESS to the baseline model with the 6.4 kWp PV system. The BESS is composed of 6No. Lead Acid batteries, 12 V 100 Ah each. It is assumed that the BESS is half charged at the beginning of the simulation and the minimum acceptable state of charge $SOC_{min}^{Batt} = 2.16$ kWh (30% of the maximum BESS capacity). The charger capacity is 1kWh with a charging efficiency $\eta_C^{Batt} = 0.88$ and a discharging efficiency from the BESS to the microgrid equal to $\eta_D^{Batt} = 0.88$. After applying Algorithm 4 to the baseline model, including a 6.4 kWp PV system and a 7.2 kWh BESS, the new weekly energy costs and savings are shown in Table 5.

Table 5. Scenario 3 weekly savings.

Week	Baseline with PV + BESS Energy Cost	Optimized Energy Cost	Savings	%
Summer	\$74.40	\$58.02	\$16.38	22.01
Winter	\$54.07	\$42.23	\$11.83	21.88
Spring	\$48.03	\$42.14	\$5.89	12.26
Autumn	\$46.13	\$37.12	\$9.01	19.53

The comparison of the baseline electricity cost of scenarios 2 and 3 shows that the integration of the BESS only contributed to an average of 7.06% of additional savings. Additionally, the addition of the BESS to the optimized microgrid, including the HEMS and PV system, only contributed to an increase of 7.9% of the savings. Hence, the obtained results clearly show that the supplementary savings gained from adding the BESS to the microgrid are comparatively low, especially during spring and autumn periods. These savings are not enough to justify the relatively high investment and operational cost of battery energy storage solutions. Not to forget that such storage systems usually require a considerable storage space, which is a curtailment to residential applications.

Moreover, a comparison between the three methodologies was performed. The comparison between the three scenarios and their weighting was conducted based on the savings that were achieved in each scenario in order to provide a general assessment for the presented work. Table 6 shows a summary of the savings achieved with the different scenarios. Nevertheless, a comparison between the weekly energy bills of the residential microgrid with and without the PEV showed an increase of the residential microgrid energy bill by 60% that was caused by the energy needed to charge the PEV.

Table 6. Different scenarios weekly savings summary table.

Week	Baseline + PEV Energy Cost	Scenario 1 Savings	Scenario 2 Savings	Scenario 3 Savings
Summer	\$102.04	\$19.01	\$37.39	\$44.02
Winter	\$74.46	\$18.11	\$28.66	\$32.23
Spring	\$69.01	\$15.66	\$24.26	\$26.87
Autumn	\$64.17	\$16.76	\$23.95	\$27.05

As shown in Table 6, the total achieved savings after implementation of the different measures ranged from 29% to 43% of the baseline energy cost. Among these savings, 43% to 62% of the savings were achieved by just interfering on the load side, with a minimal investment that only included the installation of HEMS. The savings added by the integration of a PV system are less than the savings achieved by the load management (scenario 1) and were between 26% and 41%. The savings achieved by the addition of a BESS were not that remarkable and ranged between 10% and 15%. Additionally, as demonstrated in Section 4, the integration of the load management, which includes time shifting of time shiftable loads and optimization of the charging and discharging of the PEV battery, allows for minimizing the size of the PV system without affecting the achieved savings. Nevertheless, this idea requires further investigations and a certain algorithm should be established to define the optimal size of the PV system after implementation of the demand side management.

7. Conclusions

The energy management of houses and isolated sites has strong relevance in future power systems, mainly in the microgrids and smart-grids context. Load management and demand response are considered as key elements of the smart grids [24] and they play a key role in reducing the yearly electric bill of residential microgrids. Nevertheless, a successful demand response program requires both the DR enable technologies and the right adaptation to the available model. For more than a decade, the Lebanese residential sector has been paying a considerable electric bill. This article proposes an algorithm for the improvement of a Lebanese residential microgrid that was equipped with a plug-in electric vehicle, a photovoltaic system, and a battery energy storage system, by reducing the overall yearly electric bill. The proposed model operates in a double tariff scheme where conventional utility power is not available all the time. Even though the case of a Lebanese residential microgrid is considered, the proposed model can be extrapolated to other countries and use cases where the utility company is incapable of balancing the power supply with the demand load for a reason or another.

Thus, this article can be considered as a visionary perspective for the Lebanese residential microgrids. The results that were obtained in scenario 1 show that the implementation of demand side load management, especially when managing the PEV as both a load and a storage device, can achieve considerable savings to the overall electric energy bills comparable to the savings that were achieved with the installation of a PV system with BESS. Nevertheless, the size of the capital needed for the implementation of a demand side load management system is negligible as compared to the capital that is required for the installation of a PV system with BESS, especially if we do not include the price of the PEV, since we consider that the PEV will become a fundamental element of all future microgrids. Moreover, the results of scenario 2 showed that the implementation of the demand side load management allows for minimizing the size of the required PV system, and thus minimizing the required investment, without affecting the overall achieved savings on the residential microgrid electric energy bill. On the other hand, the results of scenario 3 demonstrate that the addition of the BESS, in that case, can have minimal impact on the overall savings, thus confirming that the huge investment required for the BESS can be spared.

The proposed algorithms can be a test-bed to evaluate various microgrids models, renewable energies technologies and policies. Additionally, the proposed improvements of the Lebanese residential microgrid can be considered as an integration of advanced technologies applied to a basic electric model, which provides potential for extrapolating this work to similar sensitive and strategic interest, such as isolated housing, telecommunication posts, border posts, etc., where a conventional electricity grid is not always available. This study can be extended in the following aspects. (1) The real value of the study embeds in the fact that the developed model can readily be modified and adapted for other case studies, and even for dynamic rate structure applications, such as Real Time Pricing (RTP) or Time Of Use (TOU). (2) Small power generation units, such as small turbines and solar panels, and electricity storage facilities, such as, batteries and compressed air energy storage, can be incorporated. (3) An algorithm can be developed to calculate the optimal size of the PV system and BESS after integration of the load management system. (4) We recommend conducting a comprehensive cost-benefit analysis that explores technology investment, deployment, and lifecycle costs against projected savings, including a detailed sensitivity analysis, in order to evaluate the impact of the various independent variables on the output of the developed model.

Author Contributions: A.I., H.I. and M.G. conceptualized the research and defined the objective of the study; A.A. and H.I. set the methodology; A.A. developed the model, wrote the code and did the simulations; A.I., H.I. and M.G. analyzed the results; and all the authors contributed to the writing of the manuscript.

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