Design of an Energy Management Algorithm for a Hybrid System of PV, Batteries, EDL and Diesel

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***Abstract*— An energy management system (EMS) is an important tool for the control of power flow in a multi-source power system. In this report, an energy management algorithm is developed for a hybrid Photovoltaic-Battery-Grid-Diesel system, considering cost and pollution minimization. Residential load data has been firstly collected, followed by finding the electric power produced by the solar energy system, and modeling the unreliable electricity grid. The algorithm prioritizes photovoltaic (PV) energy, followed by the grid, when available, and the batteries, and use a diesel generator as a last resort. Simulations for a summer and winter day validate the logic of the energy management system, and aggregate results for the entire year show that most of the energy is met by the PV and battery systems.**

Keywords*— *Energy management system – algorithm – Photovoltaic – Battery – Grid – Diesel – load data

I. Introduction

Lebanon has a long history of energy mismanagement. Corruption and lack of investments have prevented the national company, EDL, from continuously providing power to its inhabitants. After the economic collapse of 2019, EDL has only been able to secure 2 to 4 hours of power a day [1]. With the rising price of crude oil, economical alternatives have been needed for the population. One of these alternatives appears to photovoltaic (PV) solar energy. Some sources claim that the import of photovoltaic panels alone, without the batteries and auxiliary components, has been multiplied by a factor of 5 between 2020 and 2021 [2]. In the context of residential installations, where land is limited, PV panels need to be accompanied by an energy storage system, typically a battery, that will help mitigate the intermittency of the solar resource and provide satisfactory power to the load. The power supply system will include EDL for its current cheap prices, and a diesel generator for backup. This diversity in resources entails an energy management system to efficiently control the power flow of the hybrid energy system taking into consideration meeting the full energy demand with minimal cost.

II. Problem Formulation

A. Project definition

The aim of this work is to design an energy management system to meet the load demand at the least cost through controlling the use of the different energy sources. The system to be controlled is a hybrid system consisting of PV panels, battery storage system, the utility grid, and a backup diesel generator.

Figure 1 shows a configuration of our sources for our energy management system. The key component, the solar panels, will deliver energy from sunrise to sunset and will, most of the time during that period, provide excess power. The load will therefore be met. To limit losses and minimize the use of diesel, the excess energy produced will be stored in batteries that discharge when the load is not met by both EDL and PV.

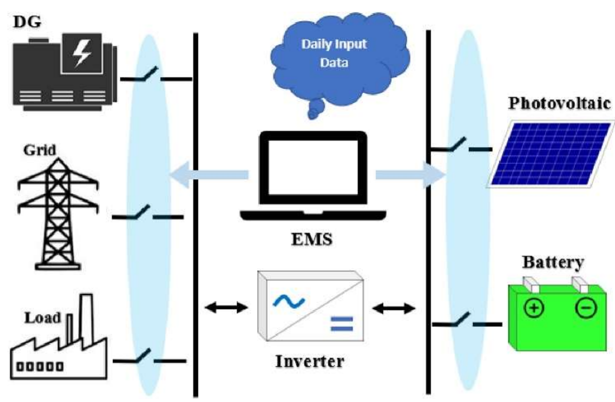

Figure 1. System components. (Chedid et Al.)

B. Project Requirements

Temperature and irradiance at our location were needed to calculate the power generated by our PV system. Then battery specifications were collected to model our energy storage system. As for EDL, since it is intermittent and does not have a preset schedule, an EDL availability datasheet was created using Python. Finally, the algorithm was simulated using MATLAB.

III. LITERATURE REVIEW

The energy management system uses a smart algorithm in order to control the power flow of the system. Several hybrid energy management algorithms are found in the literature that achieve cost minimization and maximum reliability of the system.

In [3], a detailed survey of the literature is presented on Behind the Meter (BTM) energy management systems (EMS). The literature covers the technological aspect of EMS like power systems and energy storage, the economical aspect that targets minimizing consumption by utilizing optimization and scheduling techniques, and the social aspect that comprises recent social science studies on human behavior towards more efficient use of energy independently of any technological modification. [4] proposes an energy management system for a hybrid energy microgrid consisting of PV and wind sources, a battery storage system, and the utility grid. The system is modeled through equations describing the power provided and/or consumed by each source during periods of high and low renewable energy generation. A conventional power management algorithm is included, where the priority in energy dispatch is given to PV and wind, followed by the battery, and ending with the grid. A similar system is discussed in [5], with the grid replaced by a wind turbine, while a dump load is also added. During periods of excess power generation, if the battery is fully charged, the surplus of energy is fed to the dump load. On the other hand, if a deficiency exists, the microturbine acts as a backup when the battery cannot generate the needed power.

A new architecture is introduced in [6] for a system made up of a photovoltaic field, a wind turbine based on an asynchronous speed doubly fed synchronous generator, and a battery storage system. The system ensures maximum utilization of the power generated by the renewable sources by using a multisource system supervisor. The hybrid renewable energy system is complemented by the grid and a diesel generator for the case of Lebanon in [7], where a Maximum Power Point Tracking (MPPT) controller and a fuzzy logic controller are utilized for the solar and wind sources respectively. A transformer and an inverter are used to connect the two renewable sources and battery to the other non-renewable sources. The energy source of the consumer at a given time in this energy management system is decided by several parameters such as the availability of grid energy, the cost of different sources, the charging level of the battery, and the availability of solar/wind power.

An improvement to the basic algorithms previously introduced include optimizing the power flow through optimization techniques introduced in [4], [8], [9], and [10]. A novel algorithm is introduced in [4] that coordinates the power always drawn from the battery and grid through the insertion of a contribution factor. The renewable sources remain first in priority, but after that, the contribution factor decides the proportion of consumption of the remaining two resources. This factor is chosen to be a function of the electricity tariff, which varies over the day, and an optimization problem is established where the optimal value of the contribution factor minimizes the electricity tariff whilst resulting in the least possible battery degradation.

An advanced EMS is introduced in [8] for a system of solar panels, a lead-acid battery, a fuel cell stack, and an electrolyzer. The surplus of energy is stored in the battery and as hydrogen produced by the electrolyzer. It is shown that the average cost of supplying power from the battery is less than from the fuel cell under a certain power threshold value. Therefore, the implemented algorithm gives priority for battery discharge when the needed power is below the threshold and for the fuel cell otherwise. The EMS also disconnects non-critical loads in case of extra load consumption and power deficiency. The results show a reduction in the Fuel Cell On-Off switch cycle and an absence of a deep discharge of the battery.

The proposed energy management algorithm for the hybrid PV-Wind-Tidal-Battery islanded DC microgrid in [9] minimizes the operation cost of the microgrid under the constraints of energy demand/supply balance. The results verify maximum utilization of the renewable energy sources and improvements in the battery lifetime. While the above energy management systems focus on single-source energy supply at a certain time, [7] introduces a multi-source energy mixing scheme for a solar-wind-battery-grid system. A particle swarm optimization (PSO) algorithm is designed to control a Time Rate Multi-Pulse Width Modulation (TRM-PWM) energy mixer and ensure the operation in anti-islanding mode. The algorithm finds the most cost-efficient mixture of the different electricity sources at each hour of the day which meets the demand profile of a house.

The operation of the energy management system is further enhanced when applied in for smart grids. [11] investigates the use of a multi-agent approach to reduce the consumer's bills and the system's reliance on the national grid. Four agents are introduced: a grid agent to coordinate the feeding and supply of electricity from the grid, a storage agent in a centralized battery to control energy storage, a prosumer agent to manage the trading of energy produced, and a consumption agent to control the power dispatch in smart homes. Considering the energy availability, the price, and the consumption, two algorithms were designed to control the different agents of the system

[12] proposes demand response systems in energy management systems aggregators as a potential technique. It is indicated that current trends in power systems will lead us to load follows supply strategies in energy management systems, adapting to renewable energy power systems. The survey also suggests that robust, low cost and secure communication infrastructures and protocols will be necessary for the exchange of data, which will be utilized by adaptive optimization algorithms. A case study in [3] discusses the integration of a smart farm - smart grid system, where the smart farm is a network of sensors and actuators connected via ZigBee to a decision support system with a database, which communicates with the smart grid to make decisions for energy usage.

Finally, a MATLAB program to simulate an EMS operation over a year is presented in [13], where the algorithm controls power flow and calculates hourly energy consumed/generated by every component of the hybrid power supply system over a year. The goal is calculating the cost of electricity over year of operation.

IV. Methodology

Before designing the energy management algorithm, data was collected for the residential load demand, on the hourly solar irradiance of the location of this load to construct the energy production profile given by the photovoltaic panels used, and modeled the specifications of the battery storage needed for our design. After that, we simulated the power shortage of Électricité du Liban (EDL), and added a backup diesel generator. The core of our work consisted of creating datasheets and algorithms to set the priorities between different energy sources on MATLAB.

The following tasks were performed:

• Collection of data and specifications for the load, the storage system, and the solar irradiance

• Creation a datasheet for the EDL energy availability

• Decision on the priorities of energy dispatch and establishment an algorithm flowchart.

• Translation of this flowchart into a working algorithm

• Simulation of algorithm on MATLAB

V. Load Characteristics

The load is a small residential house, and contains minute-by-minute data across 4 years [14]. After preprocessing the data using Python, the load characteristics found in Table 1 are obtained.

Table 1. Load metrics.

Total Energy Consumption (MWh)	11.3
Maximum Hourly Power (kW)	7.9
Minimum Hourly Power (kW)	0.2
Average Hourly Power (kW)	1.3

As seen in Figure 2, the average consumption ranges between 360 and 2200 W. The afternoon is the time of day

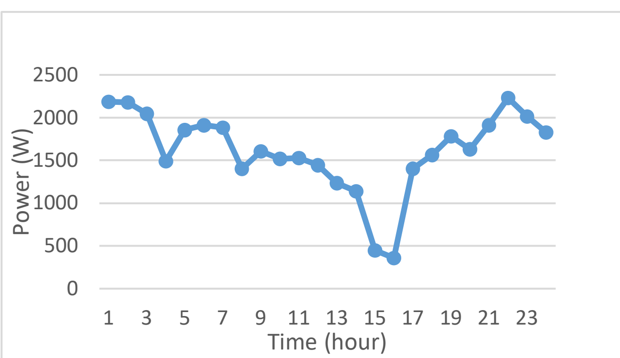

Figure 2. Average load profile.

when on average, the power consumed is the lowest. At that time, the PV panels (PVPs) are usually able to deliver all the power needed by the load and the difference between the energy produced and consumed should be stored to minimize the costs and maximize the efficiencies. On contrary, between 8 PM and 3 AM, the load consumes the most energy and PVPs are not available. The energy management system we are designing should aim to properly distribute the energy produced to peak hours while relying mostly on PVPs and EDL as well as minimizing the use of the diesel generator.

VI. Resources

A. EDL Utility Grid

The electricity sector in Lebanon has never fully recovered from the Civil War that ended in 1990. Power shortages happen daily. Currently, the public electricity provider, EDL, is only providing 2 to 4 hours of electricity a day on average. Based on this information, and due to the absence of a regular power schedule, we created an EDL availability datasheet using Python, with a recurrence of 1 hour of power followed by a power outage duration, modeled as a random variable normally distributed around 9 hours with a standard deviation of 3 hours. Figure 3 depicts the model over 3 days. When available, EDL has the capacity to fully satisfy the residential load, regardless of the power consumed. With the current inflation, and since the electricity is still subsidized at the old prices, EDL can be considered as a very cheap energy source. However, we should not consider this source as the main component of our system but rather as a complement to charge batteries and as a supply to the load only when the PVP's generated energy is not enough.

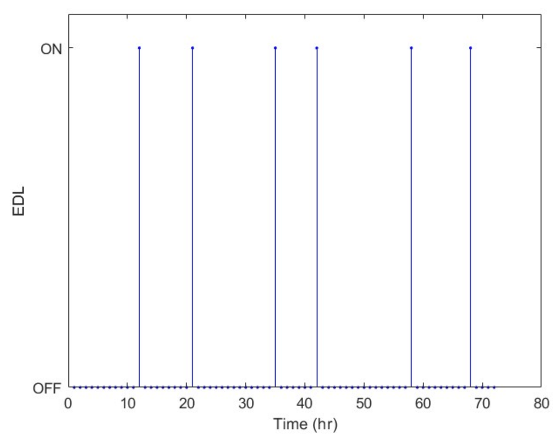

Figure 3. EDL model for 3 days.

B. Solar Resource

Data for the solar resource was retrieved from NASA's POWER Data Access Viewer [15], from which estimates for "All Sky Surface Shortwave Downward Irradiance" in Watt per meter squared were available as time series data, in comma separated values (.csv) format. These data are hourly values for every hour of year 2020 at the (arbitrary) location of the AUB campus (33.9009, 35.4811). Figure 4 below illustrates the data on a specific day, August 8th 2020.

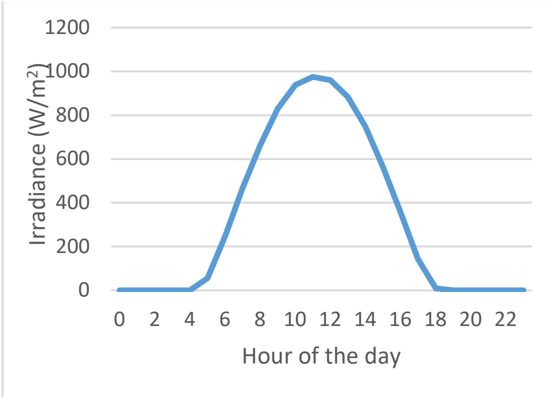

Figure 4. Variation of solar irradiance on a summer day.

However, the values are at horizontal surface and photovoltaic panels are usually installed at a certain angle (typically equal to latitude), which entails the need to calculate the radiation at the tilted panels. The model used for these calculations is an Anisotropic Sky Model, called HDKR model. A MATLAB code was developed for this purpose, it takes day, time and irradiance measurement, in addition to solar zenith angle which greatly reduces computations (also provided by the NASA dataset) and returns irradiance on the tilted angle. The calculations assume the given location and tilt set at latitude angle as explained earlier.

In Figure 5, a plot illustrates the calculated irradiance using the HDKR model. Notably, the available irradiance on a tilted panel is bigger according to this estimation, which could be interpreted by the fact that the model accounts for ground reflected as well as circumsolar and horizontal brightening components of irradiance, which add to the estimated value.

The electric power produced can then be found through considering the area of the panels and their efficiency. Finally, the values of electric power consumption are corrected for the corresponding cell temperature through the concept of Nominal Operating Cell Temperature (NOCT).

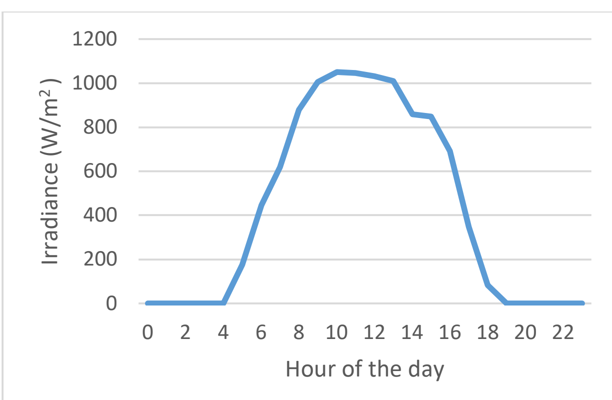

Figure 5. Estimation of solar irradiance on a tilted surface.

C. Battery Storage System

The battery storage system has a terminal voltage of 12V and nominal capacity of 2000Ah or 24kWh. Some other parameters are summarized in the following Table 1:

Table 2. Battery characteristics.

Minimum Charging/discharging time	10 hours
Maximum power of Battery	2.4 kW
Maximum state of charge	90%
Minimum state of charge	30%
Charging/discharging efficiency	90%
Battery inverter efficiency	94%

The batteries on a full charge are allowed to fully charge/discharge in 10 hours, resulting in a maximum power input/output of 2.4 kW. However, to preserve battery health, the state of charge (SOC) is maintained between 30 and 90%. Furthermore, charging and discharging of battery have an efficiency of 90%; if a certain amount of energy is used to charge the batteries, only 90% is stored, and the rest is wasted. Similarly, if a battery is discharged by a certain amount of energy, 90% of that energy is usable, and the rest is wasted as well. In addition to these losses, conversion from AC to DC and vice versa are 94% efficient. These efficiencies are implemented in the code to model practical systems with practical limitations. In addition, the maximum discharge rate of the battery per hour is taken to be 10% of the total nominal battery capacity.

Other considerations that are omitted for simplicity are battery self-discharging factor, a modeling of the imperfection of energy storage and loss of energy over time, and aging coefficient to model battery degradation over time. These are small factors that may not be very significant at the scale of the simulation, single household over one year.

D. Diesel Generator

As a backup when no other energy source is available, a diesel generator is used to fulfill the load demand. Diesel generators are expensive since the cost of operation is dependent on the prices of fuels, and are an important source of pollution; therefore, we chose to not prioritize it over any other energy source at our disposal. However, diesel generators have two advantages: they can be quickly used whenever they are needed, and their size can be designed to meet the maximum demand of the load. For our load, the maximum hourly power needed is 7.9 kW. Hence, our energy system should include a diesel generator that should be able to provide this amount of power to prevent any potential outage. An 8-kW generator is chosen for that purpose.

VII. Energy Management Algorithm

The developed power management algorithm is based on the most economic power flow. The priority is given for the electric power generated from PV, followed by EDL, the batteries, and the diesel generator respectively. PV power is always favored in order to capture the most out of the *free* irradiance. EDL is second cheapest and when present can supply unlimited power, but it is only available for very short periods. As a result, two modes are explored by the energy management system: when EDL is on and when it is off.

A. *EDL Off*

This is the most common case given the limited presence of EDL. PV is used to supply as much as possible of the load demand and to charge the batteries in case of a surplus. If PV fails to meet the load demand, batteries will supply the extra demand unless they reach their minimum state of charge. If the latter occurs, diesel generators are turned on to meet the remaining demand.

B. *EDL On*

In this mode, PV as in the previous mode would supply the load and batteries with their maximum capacity. If PV fails to achieve any of the two objectives, EDL will provide the extra energy. Consequently, the load demand is met, and the batteries are fully charged from PV and EDL, without the need for any diesel supply.

The general architecture of the algorithm is shown in Figure 6.

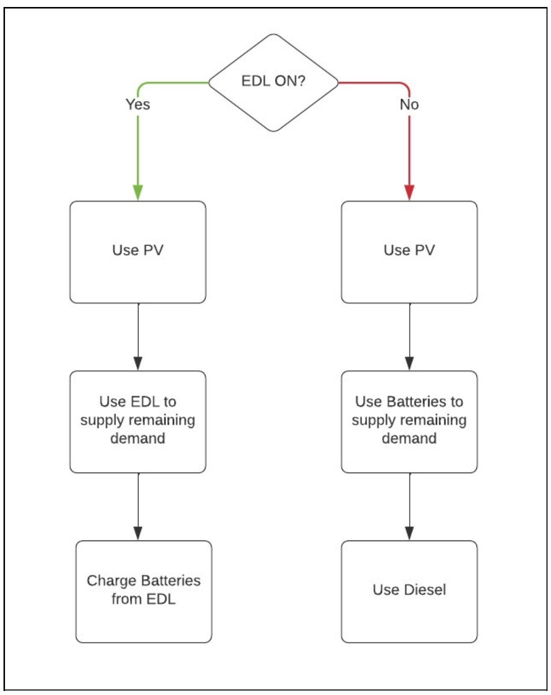

Figure 6. Rules-based power flow approach flow chart.

VIII. SIMULATION & RESULTS

The algorithm is simulated in MATLAB over an entire year. Figure 7 (a) shows the results for a summer day. As expected, PV can meet the demand throughout the day. The batteries, which were fully charged at midnight when EDL was available and by PV during the day, complemented PV and the grid that supplied energy during the morning and night. Fig 7 (b) displays the battery's state of charge, which was kept at a very high level during that day. As illustrated, there was no use of diesel generators during that day.

The energy flow during a winter day is described in Fig 8 (a). PV power during that day was lower and shorter in duration than on the summer day. EDL was available at 6 pm and supplied the load demand while charging the batteries. Batteries supplied as much as possible of the remaining load demand, as reflected in Fig 8 (b), and diesel generators were used during the early hours of the morning when every other source was unavailable.

The total contribution of each source over the whole year for load demand can be shown in Figure 9. The proportions only take into considerations the load consumption and does not include the power needed to charge the batteries. The two most dominant sources are PV and batteries. The latter is a little higher because most of the consumption takes place at night. However, batteries are charged using PVs and EDL when available. Diesel generators are used as back-up and provide 13% of the total demand, while EDL contributes to a humble 7% of the total consumption.

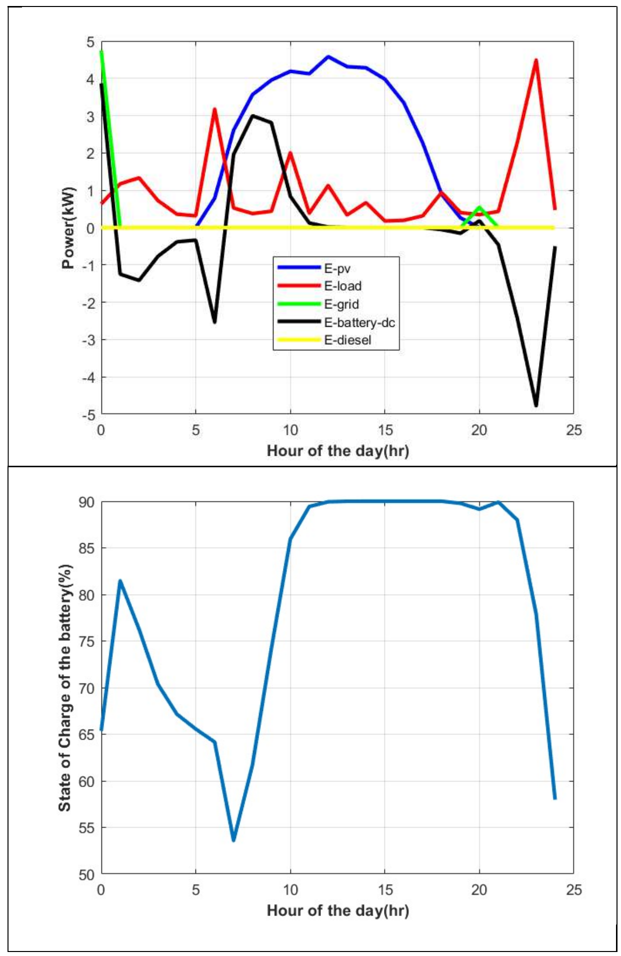

Figure 7. Energy management on a summer day.
(a) Contribution of resources.
(b) SOC of the battery.

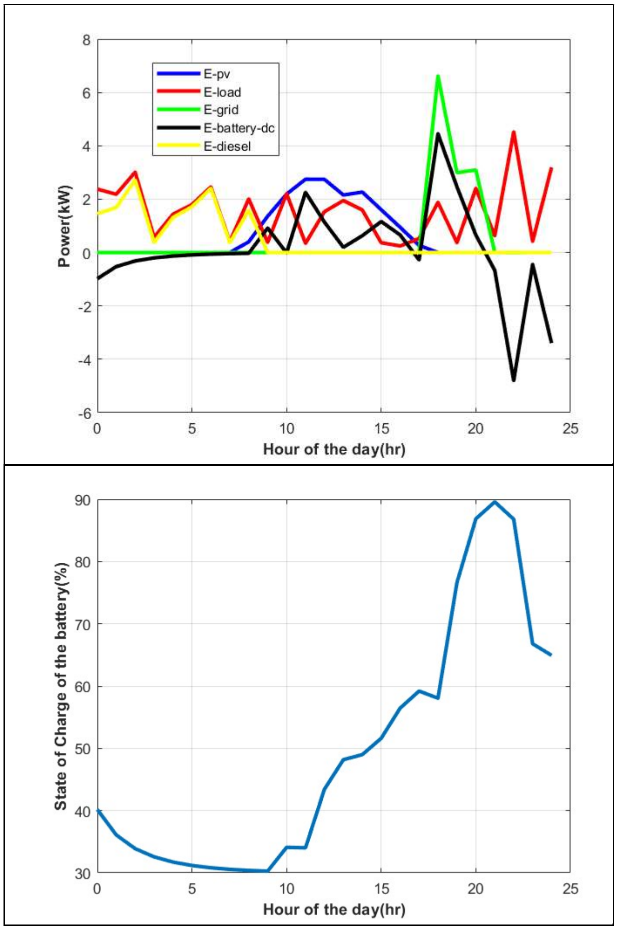

Figure 8. Energy management on a winter day.
(a) Contribution of resources.
(b) SOC of the battery.

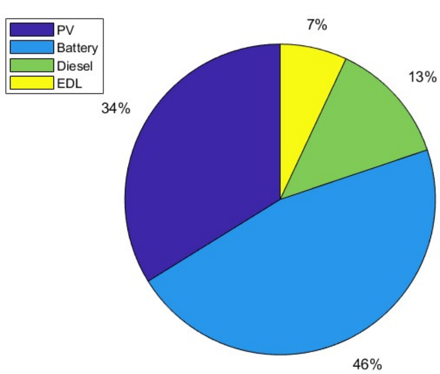

Figure 7. Contribution of each source to the load demand.

IX. Conclusion

In this report, an energy management algorithm has been developed for a hybrid energy system consisting of photovoltaic panels, battery energy storage, the Lebanese utility grid and diesel generators. Residential load data has been collected and preprocessed, followed by determining the total power produced by the PV system through an Anisotropic Sky Model and modelling the grid outage with an average of 9 hours and a random error. The algorithm considers cost and pollution minimization and prioritizes photovoltaic panels, followed by the grid and battery storage. The system uses diesel generators as backup and charges the battery whenever there is an excess production of solar energy or an availability of the grid. Simulations show the validity of the algorithm and aggregate results reveal the dominance of PV and battery storage systems.

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