Hindawi
International Journal of Photoenergy
Volume 2021, Article ID 6641548, 17 pages
https://doi.org/10.1155/2021/6641548

Research Article

A Novel Design of Photovoltaic-Based Charging Station for Battery Vehicles with Dynamic Demand: A Case of Short Runs

Mohamed Salameh,[1] Tamer Khatib ,[2] and Khaled Alsahili [3]

[1]*Faculty of Graduate Studies, An-Najah National University, 97300 Nablus, State of Palestine*
[2]*Department of Energy Engineering and Environment, An-Najah National University, 97300 Nablus, State of Palestine*
[3]*Department of Civil Engineering, An-Najah National University, 97300 Nablus, State of Palestine*

Correspondence should be addressed to Tamer Khatib; t.khatib@najah.edu

Received 7 December 2020; Revised 17 February 2021; Accepted 19 March 2021; Published 27 March 2021

Academic Editor: K. R. Justin Thomas

In this research, a novel design and operation of solar-based charging system for battery vehicle for a 50 km run is proposed. The proposal is aimed at replacing 110 existing diesel vehicles with 39 electric buses. Several operation scenarios for the charging stations are proposed and analyzed. Scenarios include two different battery charging methodologies and one hybrid option between electric buses and diesel vehicles. An energy model of the adapted electric buses is developed first. After that, load demand and needs including number of daily trips, number of passengers per hour, and hourly energy consumption are determined based on the developed model and gathered information. Results show that a 5.7 MWp photovoltaic system is required to power this transportation line with a loss of load probability of 5% and a trip cost per passenger of 2.05 USD. The simple payback period of the system is found to be 10 years, which is 40% of the system's lifetime. The amount of CO_2 mitigated by the proposed system is estimated as 1,629,387 (kg/year). The social impact of the proposed project is found acceptable; whereas, most of the current employees will keep their jobs with higher salaries by about 145% and less working hours by 50%. Moreover, it is expected that the proposed project will significantly increase the reliability, convenience, and sustainability of the transportation process.

1. Introduction

Electric vehicles (EVs) have been the focus of considerable attention in recent years because of the large amount of carbon dioxide gases released from conventional vehicles [1]. Moreover, the dependency on imported crude oil and the depletion of fossil fuels led to the search for alternative transportation systems such as EVs that are more economical and environment-friendly [2].

The electric vehicle (EV) is classified as a vehicle, which has a battery and operates using electricity supplied from an external power source. One of the EVs is the battery vehicle (BV), which is recharged by a charging station that is either connected to the grid or powered by a standalone renewable energy source [3].

EV charging stations should be optimally sized, planned, and allocated considering the type and the location of the charging stations. In case of grid connected charging stations, the impact of the charging station on the electricity distribution grid should be considered during the planning and sizing phase. Moreover, the geographical location of the charging stations should also be considered [4]. Grid connected charging stations are optimally planned by considering power loss and voltage stability in distribution networks [5]. Moreover, driver's behavior is also considered when optimally planning charging stations [6]. Furthermore, charging schedule and demand nature are also being considered in such an optimization problem [7] as well as driving habits, road nature, and transportation demand [8]. In [8], for example, charging stations for BV are optimally planned and sized. It is recommended in [9] that city traffic networks as well as electrical distribution network should be considered for optimal planning and sizing of the charging stations. Moreover, land price and its adoptability as well as convenience of BV's drivers are considered in this research to optimally allocate the charging stations [9].

On the other hand, in case of charging stations that are powered by a standalone renewable energy system, accurate system sizing for the power source as well as the storage unit is required beside all the aforementioned aspects [10].

Recently, photovoltaic (PV) systems are being utilized as chargers for BV charging stations [10]. There are many benefits for using PV systems for EV's charging stations such as reducing energy demand on the grid as the EV charging power is produced locally from PV. The local use of PV energy partially/fully averts the negative impact of feeding PV energy into grid due to reverse power flow in the lines and overvoltage problems at feeder ends. In addition to that, the use of locally produced PV energy for EV charging reduces the demand charges to be paid to the distribution system operator (DSO) due to increased EV charging load at the workplace. Moreover, DC interconnection of EV and PV is more efficient than an AC interconnection. EV battery doubles up as energy storage for the PV, thereby removing the need for a separate storage device. Furthermore, long parking time of EV paves a way for implementation of vehicle-to-grid (V2G) technology where the EV acts as a controllable spinning reserve for the smart grid. Finally, lower fuel cost and reduced/zero CO_2 emission are due to charging of EV from a renewable source like PV [10, 11].

In [11], the authors have proposed a PV-based charging station for BV. The cost function of the system is optimized by considering stopping rate, establishment cost, and expense discount. Similarly, in [12], the authors have introduced PV-based/grid charging stations without storage. The grid is assumed to power the charging station when PV array is not able to fulfill the demand. Meanwhile, PV excess power can also be injected to the grid. On the other hand, in [13], the authors have introduced a PV-based charging station with regenerative slowing down and battery storage to help the system structure during peak load. The point of the researchers is to use the greatest measure of renewable energy and lessen the charging cost. Similarly, in [14], a hybrid PV/wind-based charging station with battery storage is proposed to deal with the power generation changes during variable natural condition. In [15], it is stated that energy storage is important for off-grid charging stations and the system is designed considering a desired reliability. Similarly, in [16], the cost of off-grid charging stations is minimized subject to specific availability of the system. Meanwhile, in [17], the authors have introduced a state of charge- (SOC-) based control method to deal with deficit cases occurred in the uncertainty in nature of renewable energy source.

In general, most of the aforementioned PV-based charging stations assume that the BVs can be either charged by PV array directly or by a charging battery in case of having the PV array unable to fulfill the power demand of the BVs. This assumption is very well known; however, the focus is always given to the design of the charging station not the load demand assessment as load demand is considered constant in most cases. This actually does fit with battery vehicle research as BV has a very dynamic load demand and the system should be always designed based on that. Moreover, all of these researches assume that the CS will be charging commercial and individual BVs. Meanwhile, none of them have considered transportation lines such as BV buses or small vans. These transportation lines do have picking and dropping stations with dynamic load demand; whereas, PV-based CS is really worthwhile as it might be very competitive to the option of using conventional fuels. In addition to that, all of the aforementioned research utilized conventional designing method for the PV charging system (intuitive or numerical methods) without simulating these charging stations so as to calculate the reliability of these charging stations.

In [18], wind energy is used as a source of a charging station of EVs. The electrical design is not well discussed considering technical implications of the system. In [19], DC-DC technologies for charging EVs based on RE technologies are also proposed. However, the technical details of the power system as well as the design methodology of these systems are not discussed.

Thus, in this research, two centralized PV-based charging stations are proposed to power the transportation line. These charging stations are used to charge BV buses that will replace the current diesel-based shuttles. The charging station size and locations are optimally designed based on road dynamic demand and system lifetime cost. Three main operation scenarios are adapted in this research considering the charging methodology as well as system cost. After that, a full simulation of this process is provided so as to estimate the reliability of the proposed systems.

The main contribution of this research can be summarized by first the estimation methodology of the BV dynamic load demand, second the novel methodology for designing and simulating PV-based charging station for a transportation line considering BV dynamic demand, and finally, the proposed operation methodologies and their performance comparison can be considered as contribution for this research. Finally, this research contains worthwhile information about road demand, road topology, and energy consumption model for a major rural arterial road in Palestine.

2. Adapted Run Needs and Demands

2.1. Run's Demand. In Palestine, Ramallah City is currently considered a commercial and service hub; whereas, many passengers travel every day to this city from Nablus City. The current transportation system is being managed using seven passengers' shuttles that are operated using diesel, which is relatively expensive and emits large amounts of CO_2. Meanwhile, the Palestinian government is recently showing an interest in electric transportation; whereas, electric buses can address the problem of the conventional transportation between Ramallah and Nablus Cities. However, in order to provide an optimal system, optimal sizing of outward and inward charging stations should be done.

In this research, a 50 km run that connects Nablus City and Ramallah City in Palestine will be adapted as a case study. Data for the number of licensed public vehicles (Ramallah-Nablus), the number of daily trips, and peak times for travel during the day are analyzed in this research.

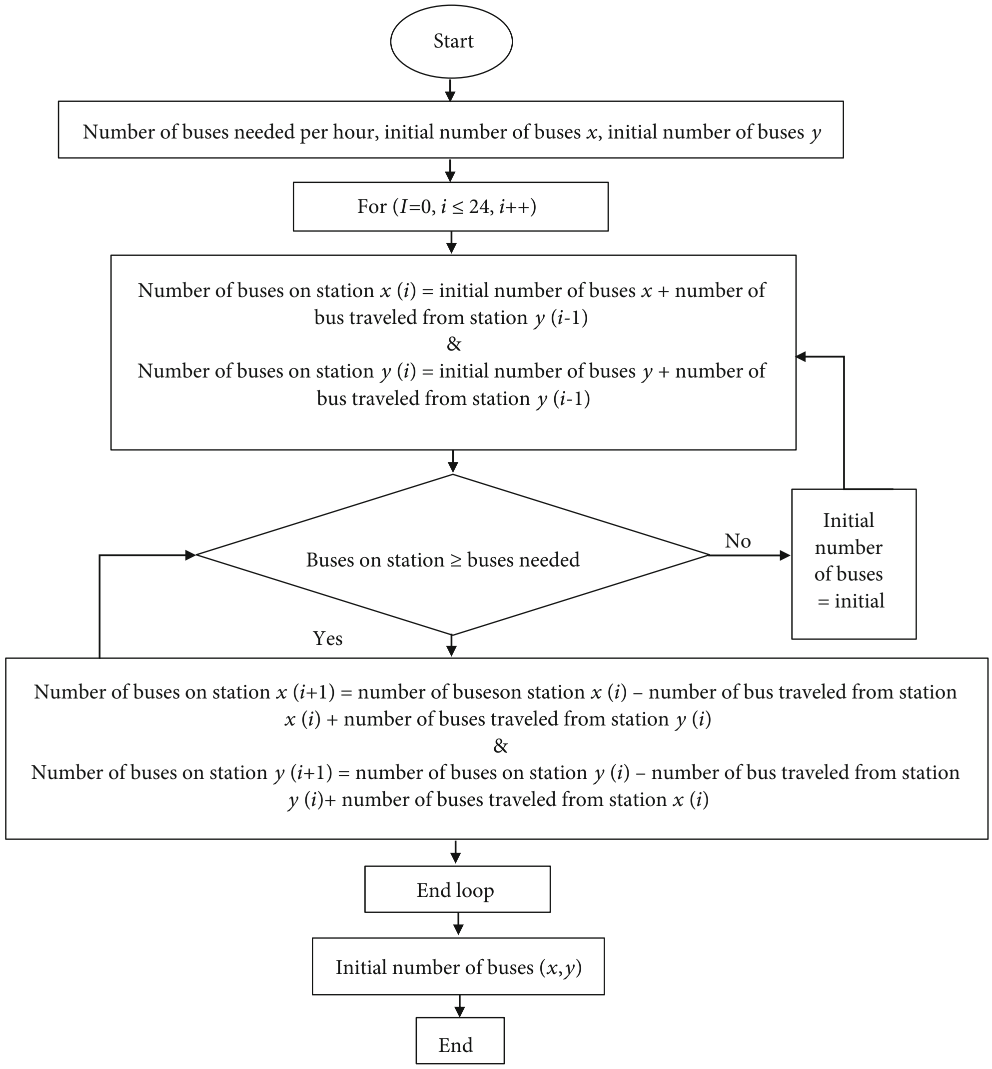


Figure 1: Adapted methodology for calculating the required buses.

Moreover, information is obtained from the drivers such as the number of trips per hour and the number of the currently available diesel shuttles.

To calculate the daily energy hourly profile, the daily number of trips per hour and the amount of energy consumed per hour are calculated. Then, the result of the multiplication of the number of trips per hour by the amount of energy consumed per trip is assumed as the daily hourly energy profile of the road. Based on that, the number of passengers per hour from Nablus to Ramallah and vice versa is calculated.

After that, it becomes possible to determine the number of electric buses required every hour to cover the passengers demand, as one bus can accommodate 28 passengers.

Figure 1 shows the adapted methodology for calculating the number of buses required.

A primary number of buses are assumed at the beginning of the daily road trips, in both Nablus and Ramallah stations; after that, the number of buses required is determined to ensure that there is no shortage of vehicles. Also, the number of buses that are required to be housed in Ramallah and the number of buses that are required to be located in Nablus are determined in this phase.

In this research, the number of buses needed is determined based on three scenarios. Firstly (first scenario), the buses will be charged at the end of the day only, while PV array will be charging the batteries all the day. This scenario is aimed at harnessing the maximum energy collected by PV array during the day. Secondly (second scenario), the buses will be charged by the PV system as a normal solar charger (PV will power the buses, and in case of power deficit, batteries will charge the buses). This scenario is aimed at minimizing the size of required storage batteries and number of required buses and at assuring a continuous charging process by the PV array. Finally, the third scenario is quite similar to the second scenario. The difference between the second and third scenarios is in the merging between diesel operating shuttles and electrical buses. It is assumed in the third scenario that the run's demand will be covered during the peak period by the electrical buses, while the demand during the off-peak period will be covered by the diesel operating shuttles.

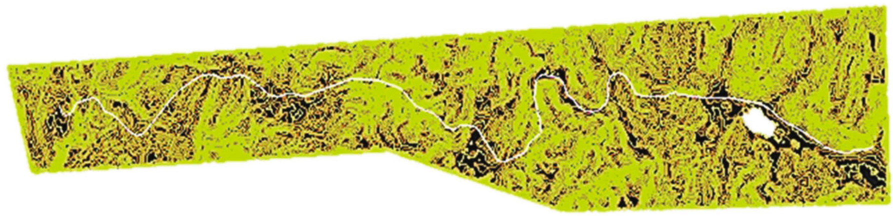


Figure 2: Nablus-Ramallah geography and topography plan.

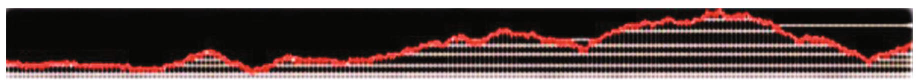


Figure 3: Adapted run's step height (2000 steps, 25 meters each).

2.2. Modeling of E-Bus Energy Consumption. In order to accurately estimate the daily hourly energy profile of the run, the energy consumed by the adapted BV bus is needed to be modeled. Here, it is usually mentioned in the datasheet of any BV bus as energy consumption (kWh) per km. However, this consumption cannot be adapted as it is done under specific conditions of loading and road topology. Thus, accurate energy consumption calculation is needed to be done. Figure 2 shows characteristics of the adapted run that contains geography and topography.

Figure 2 implies data for the length of the road, its typology, and its general terrain. These data are used to determine the vehicles' energy consumption, whether electric or fuel energy, with accordance to the street's angle. The traveled distance is divided into a step of a 25 m, which divides the run into 2000 points. The road angle (grade) is calculated by using the following equation:

$$\Theta = \tan - 1\left(\frac{\text{delta}\, E}{\text{delta}\, D}\right), \quad (1)$$

where Θ is the road gradient angle, E is the elevation, and D is the distance covered.

Figure 3 shows the profile and height of each point of Nablus-Ramallah run based on the adapted steps.

In general, the energy utilization that is considered in this paper is the energy utilization on a battery-to-wheel scope as characterized in [20] and relates to the energy drawn from the battery. In this way, energy misfortunes in the energy flexibly anchor before the battery is not considered as they do not affect the scope of the EV. In that capacity, matrix misfortunes and charging misfortunes are excluded from this model. As [20] concludes, the battery-to-wheel utilization of an electric vehicle is a component of the necessary mechanical energy at the wheels, controlled by the kinematic boundaries over a direction, the drivetrain effectiveness, and the energy utilization of helpers. The absolute required mechanical energy at the wheels as an element of the kinematic boundaries portraying vehicle development can be communicated in the vehicle dynamics equation as follows:

$$E_{ij} = \frac{1}{3600}\left[M_{ij}.g.(f.\cos\varphi) + 0.386.\left(p.C_x.A.v_{ij}^{2}\right) + \left(m_{ij} + m_f\right).\frac{dv}{dt}\right]d_{ji} \quad (2)$$

where E_{ij} is the mechanical energy required at the wheels to drive on a distance, d_{ij} (kWh), M_{ij} is the total vehicle mass (kg), M_f is the fictive mass of rolling inertia (kg), g is the gravitational acceleration (m/s^2), f is the vehicle coefficient of rolling resistance (-), φ is the road gradient angle (°), ρ is the air density (kg/m^3), C_x is the drag coefficient of the vehicle (-), A is the vehicle equivalent cross section (m^2), V_{ij} is the vehicle speed between point i and point j (km/h), and d_{ij} is the distance driven from point i to point j (km).

Here, the amount of energy consumed in the route while going differs from the energy consumed in the way back, due to the change of road angle in relation to the vehicle.

After that, Equation (2) is used to calculate the energy consumed per trip through the route back and forth and compared with the amount of energy expected to be consumed, which is mentioned in the vehicle's datasheet [21].

The amount of energy required per day is calculated by analyzing the number of daily trips for each bus and the amount of energy consumed in each trip. The relationship to calculate the total energy is as follows:

$$\text{Total energy} = (E(\text{N-R}) \times N\,(\text{N-R})) + (E(\text{R-N}) \times N\,(\text{R-N})), \quad (3)$$

where E is the energy consumed per trip, N is the number of trips, N-R is the trip from Nablus to Ramallah, and R-N is the trip from Ramallah to Nablus.

The difference between the total consumption of the vehicles travelling from Ramallah and the vehicles travelling from Nablus is considered. This is because each of them will be affiliated to a different charge station, in the first scenario. Meanwhile, in the second and third scenarios, the total will depend on the bus's location when the battery runs out of energy to determine, which station between Nablus and Ramallah will be responsible for charging.

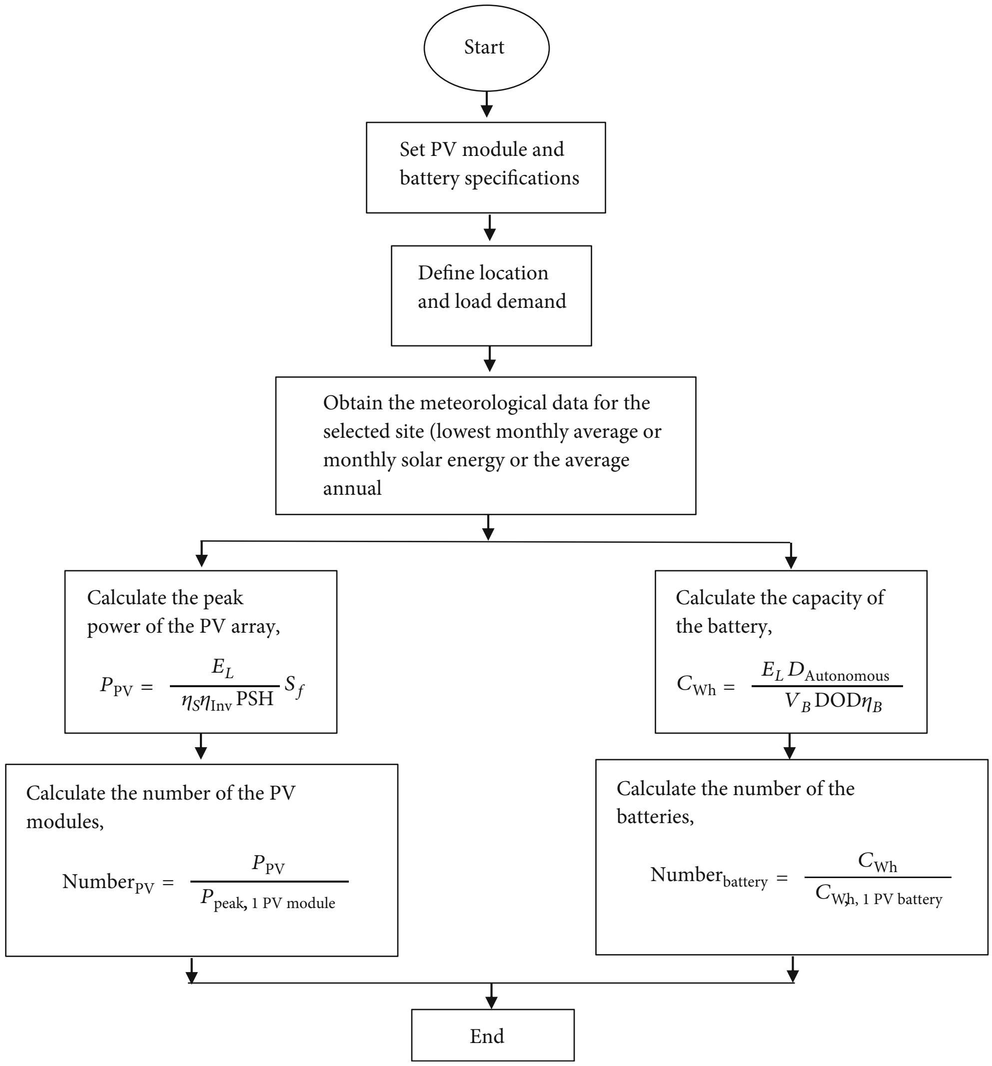


Figure 4: Intuitive method concept for designing PV-based charging system [22].

3. Sizing of Solar Charging Station

In general, any PV-based charging stations consist of a PV array and a power conditioning unit including a charge controller and a battery unit. The charging process is quite simple where DC power is generated by the PV array and then this power is used to charge the batteries via a charge controller that regulates the charging voltage and the charging process; as during the charging process, the battery should not be overcharged [16]. Meanwhile, the discharging process is also simple; whereas, DC power is drawn from the battery via the charge controller so as to regulate the discharging process as well. In our case, there is no need for any DC-AC interface as the adapted buses contain DC power system. Thus, in simple words, the solar batteries will be used to charge the bus batteries directly. However, the voltage rate of the bus batteries is quite high (600 V), and thus, DC-DC converters with high boosting ratio are used.

In this research, three scenarios are adapted. These scenarios vary depending on the operation methodology. In the first scenario, the buses are charged at the end of the day only, while PV array will be charging the batteries all of the day. This scenario is aimed at harnessing the maximum energy collected by PV array during the day. Meanwhile, in the second scenario, normal charging system is applied by charging the buses directly from the PV system, and in case that the PV system does not fulfill the charging demand, batteries are used to fulfill the load demand. This scenario is aimed at minimizing the size of required storage batteries and number of required buses. Finally, the third scenario is similar to the second scenario and includes a combination between diesel operating shuttles and electrical buses. It is assumed in the third scenario that the run's demand will be covered during the peak period by the electrical buses, while the demand during the off-peak period will be covered by the diesel operating shuttles.

In [22], the methodologies of sizing standalone PV systems or solar chargers are investigated. In general, there are three main methods for optimally sizing solar chargers, which are intuitive, numerical, and analytical methods. According to [22], the most accurate method is the numerical method; whereas, the system is designed first based on the

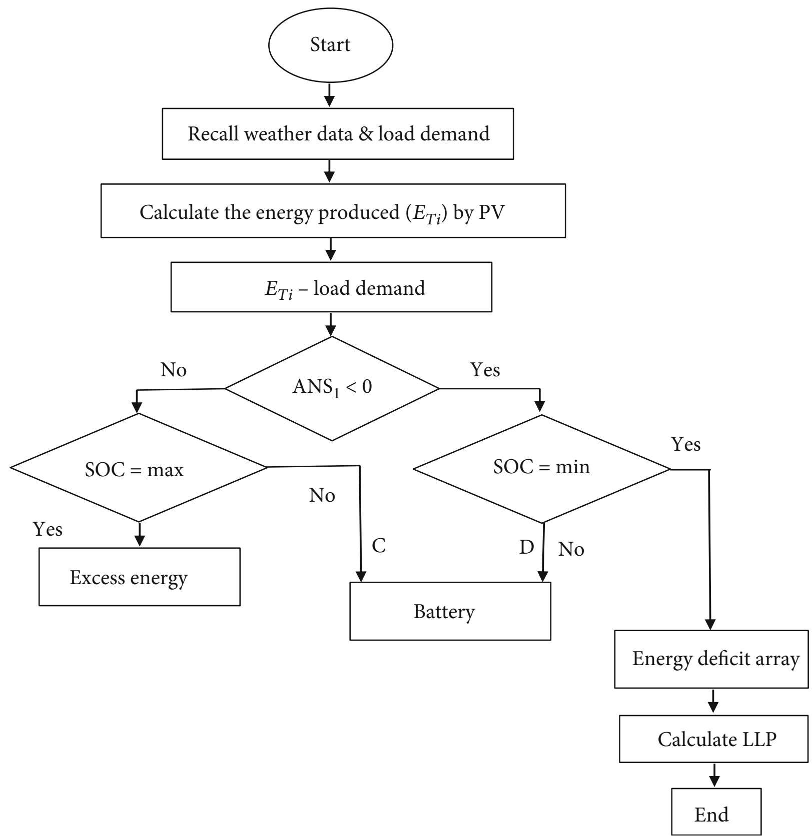


Figure 5: The adapted model for standalone PV system [26].

intuitive method and then it is simulated and evaluated based on specific technical parameters. Based on the values of these technical parameters, a numerical iteration method is applied to the sizes concluded from the intuitive method so as to reach the optimum size that fulfills the adapted technical parameters. After that, the resulted candidates are evaluated based on economical parameters in order to achieve a reliable system at minimum cost.

Based on that, in this research, the system is designed intuitively first based on the reported methodology in [22]. After that, an accurate model of the charging system is adapted based on the validated models presented in [23] so as to simulate the system and refine its size numerically. Moreover, the model presented in [23] is used to validate the performance of the system.

The main concept of the intuitive method is to design the system based on either the worst or average month of solar energy during the year. This process is aimed at achieving the necessary kWh/yr from the required PV system so as to fulfill the load demand [24].

However, the intuitive method utilizes an improved estimation without building up quantitative connection between the subsystems in a standalone PV system or thinking about the variance in solar radiation [25]. Thus, the results of this method need to be refined numerically as previously mentioned. The processes of the intuitive method are shown in Figure 4. This method is mainly based on two equations, which are utilized to estimate the ideal sizes of the PV array; P_{PV} and the storage battery are given as follows:

$$P_{PV} = \frac{E_L}{\eta_S \mathrm{PSH}} S_f, \tag{4}$$

where E_L is the load energy consumed daily, η_S are system's components' efficiency, PSH is the peak sunshine hours, and S_f is the security design factor.

Meanwhile, the capacity of the storage battery can be expressed as follows:

$$C_{Ah} = \frac{E_L D_{\mathrm{Autonomous}}}{V_B \mathrm{DOD} \eta_B}, \tag{5}$$

where V_B is the battery's voltage, η_B is the storage battery's efficiency, DOD is the depth of discharge rate of the battery, and $D_{\mathrm{Autonomous}}$ is the number of autonomous days.

After finding the initial size of the required PV array and battery, the system is modeled based on the reported model in [26].

In general, the DC power is generated from the PV array based on Equation (6) and then flows through a power conditioner to charge the battery [26].

$$P_{PV}(t) = \left[P_{\mathrm{peak}}\left(\frac{G(t)}{G_{\mathrm{standard}}}\right) - \alpha_T\left[T_c(t) - T_{\mathrm{standard}}\right]\right] * \eta_{\mathrm{wire}}, \tag{6}$$

where G_{standard} and T_{standard} are the standard test conditions for solar radiation and ambient temperature, α_T is the temperature coefficient of the PV module power, which can be obtained from the manufacturer datasheet, η_{wire} is the efficiency of wires, and T_c is the cell temperature.

The cell temperature can be calculated by [26] as follows:

$$T_c(t) - T_{\text{ambient}}(t) = \frac{\text{NOCT} - 20}{800} G(t), \quad (7)$$

where NOCT is the nominal operation cell temperature, which is measured under 800 W/m^2 of solar radiation, 20°C of ambient temperature, and 1 m/s of wind speed.

Figure 5 shows the adapted model to simulate the second scenario charging system.

The energy at the front end of a SAPV system or at the load side is given by [24].

$$E_{\text{net}}(t) = \sum_{i=1}^{366} (E_{\text{PV}}(t) - E_L(t)), \quad (8)$$

where E_L is the load energy demand.The result of Equation (8) is either positive ($E_{\text{PV}} > E_L$) or negative ($E_{\text{PV}} > E_L$). If the energy difference is positive, then there is an excess in energy (EE), and if negative, then there will be an energy deficit (ED). The excess energy is stored in batteries in order to be used in case of energy deficit. Meanwhile, energy deficit can be defined as the disability of the PV array to provide power to the load at a specific.

Consequently, the energy flow across the battery can be expressed by the following [26]:

$$E_{\text{Battery}}(t) = \begin{Bmatrix} E_{\text{Battery}}(t-1) * \eta_{\text{inv}} * \eta_{\text{wire}} * \eta_{\text{discharging}} - E_L(t) \quad E_D < 0 \\ E_{\text{Battery}}(t-1) * \eta_{\text{charging}} + E_{\text{PV}}(t) \, E_D > 0 \\ E_{\text{Battery}}(t-1) \, E_D = 0 \end{Bmatrix}. \quad (9)$$

The model illustrated in Figure 4 is developed using MATLAB. A source file that contains variables such as hourly solar radiation (G), hourly ambient temperature (T), and the hourly load demand (L) is used to run the developed code. Moreover, system specifications such as the capacity of the PV array, the capacity of the storage battery, the efficiency the PV module, the allowable depth of charge, the charging efficiency, and the discharging efficiency are defined.

The simulation process undergoes different stages. First, the produced energy by the PV array is calculated. Then, the energy net E_{net} is also calculated. In addition, the maximum condition of charge of the battery (SOC) is given to the variable (SOC) as an initial value. Moreover, metrics are characterized in order to contain the results of battery state of charge (SOC_f), excess energy, and energy deficits (Deff).

Now, a "For loop" is initiated to check the values of the (E_{net}) array. At that point, the energy contrast is added to the variable SOC_i. Here, if the outcome SOC is higher than SOC_{max}, the excess energy is determined and stored in "Damp_f" array. Meanwhile, the Deff is set to zero and the battery state of charge does not change. This condition speaks to the instance of the energy produced by the PV array and is higher than the energy demand. From this step, the battery is fully energized.

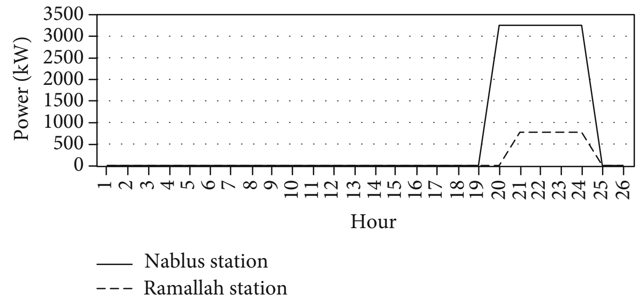


Figure 6: Charging demand for the first scenario.

The second condition speaks to the case that the energy produced by the PV array and the battery together is lower than the energy required. Here, the battery must quit supplying energy at the defined depth of discharge (DOD) level, while the Deff equals the uncovered load demand. In addition to that, the excessed energy here equals zero.

The last condition speaks to the case that the energy produced by the PV array is lower than the load demand; however, the battery can cover the reaming load demand. For this condition, there is no excessed nor deficit energy, while the battery state of charge equals the distinction between the maximum SOC and supplied energy.

Lastly, the battery states of charge values, deficit, and excessed energy values are reviewed and the loss of load probability is calculated.

After simulating the system, it is evaluated by technical and economical parameters. The loss of load probability (LLP) is used as a technical evaluating parameter in this research. LLP demonstrates how regularly a system is not able to fulfill the load demand or the mean load percentage not met by the system. It is characterized as the proportion of total energy deficit to the total load demand during a particular timeframe. LLP can be expressed as follows [22]:

$$\text{LLP} = \frac{\sum_t^T \text{DE}(t)}{\sum_t^T P_{\text{load}}(t) \Delta t}, \quad (10)$$

where $\text{DE}(t)$ is the deficit energy that is characterized as the incapacity of the system to supply power to the load at a particular timeframe, P_{load} is the load demand simultaneously, and Δt is the time period of both terms.

On the other hand, in order to evaluate the proposed three scenarios, the round trip cost per passenger is used. Moreover, a comparison between the round trip cost per passenger under the proposed system and the current system, which is based on seven passengers' van and diesel fuel, is conducted. Finally, the initial investment, savings, and the simple payback period (SPBP) are used as other economical evaluating parameters. The initial investment is the sum of the costs and it includes the cost of buses, the cost of land, and the cost of constructing solar energy stations.

Meanwhile, the trip price per passenger will be determined by calculating the costs of a single trip divided by the number of passengers per trip (bus capacity). This is applied for both cases, which are diesel-based system and electricity-based system.

The SPBP is calculated, after identifying the savings in the new system, which includes the diesel cost and the salaries of the drivers using the following equations:

$$\text{Diesel consumption} = \frac{\text{energy per trip}(\text{kWh}) \times 3600(\text{kJ/kWh})}{36(\text{MJ/litre})}, \quad (11)$$

$$\text{Diesel cost} = \text{diesel comsumption}(L) \times \text{litre cost}\left(\frac{\$}{L}\right), \quad (12)$$

$$\text{SPBP} = \frac{\text{initial investment}}{\text{savings}}, \quad (13)$$

$$\text{Trip cost per passenger} = \frac{\text{operation cost per year}}{\text{number of passengers per year}}, \quad (14)$$

$$\text{Operation cost} = \text{driver salary} + \text{depreciation} + \text{maintenance cost}. \quad (15)$$

3.1. Sizing of the First Scenario Charging System. In this scenario, the PV system will not charge the buses directly. It will only charge the batteries during the day. This means that we need a number of buses that cover the total daily demand and consequently a battery storage system that is able to charge these buses. Similarly, the required PV array size should also be able to fully charge the batteries during the day.

As for the simulation of the system, the flow chart illustrated in Figure 4 is used by utilizing a specific load demand that contains no loads during the day (load demand is zero) so as to assure a continuous charging of the battery. Meanwhile, during the night, the load demand is set equal to the bus's energy demand. Here, the charging process is distributed all over the night considering a fully charged bus by the early morning. This assumption is made so as to reduce the size of the DC system as fast charging DC system is not required in this case. Figure 6 shows the daily demand of the charging stations for the first scenario.

In this scenario, the charging starts at the end of the day; in other words, it starts after the last trip. Knowing this and the daily trip schedule, the charging in Nablus' station is chosen to start at 19 : 00, and in Ramallah's station at 20 : 00. In order to reduce the discharging rate, the charging process is extended to 5 hours in Nablus' station and 4 hours in Ramallah's station. By doing so, the charging will be completed before the start of a new day. In this research, a C60 discharging strategy is adapted for all scenarios so as to maximize the lifetime of the battery [25–27].

3.2. Sizing of the Second Scenario Charging System. In this case, the PV system is assumed to charge the buses directly, while solar batteries are used to charge the buses in case of having the PV system not able to fulfill the load demand. Thus, the PV array should be sized well to be able to provide enough charging current directly to the buses. Moreover, it should also be able to charge the batteries so as to achieve a reliable system. Thus, the intuitive method is used first, and then, the system is simulated using the method illustrated in Figure 4 so as to modify the system until having a reliable system. It is worth to mention that in this research, all of the systems are designed at a 95% availability and 5% loss of load probability. Figure 7 shows the daily demand of bus stations for the second scenario.

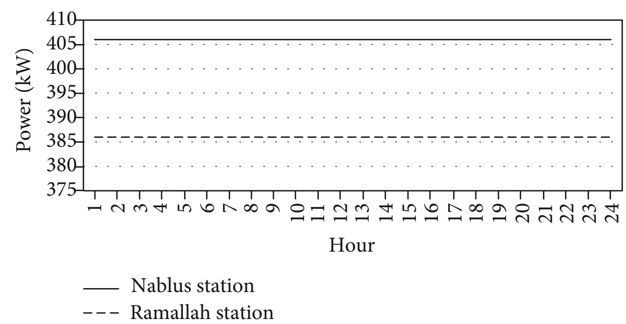


Figure 7: Charging demand for the second scenario.

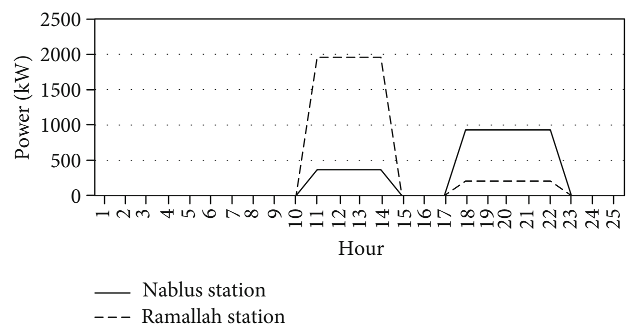


Figure 8: Discharging demand of the third scenario.

The second scenario depends on charging during the day, meaning that the bus will be charged whenever it needs charging not only at the end of the day. As shown in Figure 6 above, the load is almost stable the whole day. This stability happened by extending the charging process for over an hour and distributing it between the two stations. By this, we reduce the discharging rate and the batteries' size will be acceptable and not very large.

3.3. Sizing of the Third Scenario Charging System. As for this case, the charging process is similar to the second scenario. However, the load demand in this case is different as the BV buses will only cover the peak time; meanwhile, the demand during the off-peak period will be covered by the diesel operating shuttles. Figure 8 shows the daily demand of the buses considering the third scenario.

In the third scenario, the load is divided into a morning shift and an evening shift, as shown in Figure 8. The morning shift represents the morning peak period, and the other shift represents the evening peak period. The charging process is also divided into two parts, one that starts after the morning peak period and lasts for 3 hours; in other words, it ends before the beginning of the evening peak period. This technique makes the buses ready for usage before the starting of the second shift. The second part starts after the end of the evening peak period and lasts for 5 hours in order to reduce the charging rate.

4. Results and Discussion

4.1. Results for Run's Needs and Demands: Energy Demand and Number of Trips. Based on Equation (2) and the data given in the datasheet, the energy consumed per trip is calculated for four main cases as shown in Table 1.

Unlike to the result extracted from the datasheet, which depends only on the traveled distance, the energy consumed for the trip, whether the starting point from Ramallah or Nablus, is 56 kWh/trip.

The number of daily trips in both directions is calculated based on the information obtained from the Ministry of Transportation and from the bus drivers. Therefore, the number of passengers is calculated and divided by the capacity of a single bus, which is 28 passengers. Thus, the number of daily trips equals to 100 trips from Nablus to Ramallah and 68 trips from Ramallah to Nablus.

In these research, Proterra buses are used, specifically the Proterra electric bus 35 ft (10.7 m) model. This model can accommodate up to 28 passengers, as previously mentioned, and its battery capacity is 440 kWh with 75% DOD. Based on these data, the number of buses is calculated for each of the three scenarios.

In the first scenario, the number of required buses is 59 distributed between Ramallah and Nablus. The starting point of 50 buses is Nablus; meanwhile, only 9 buses depart from Ramallah. In this scenario, the bus will make 3 trips and then stop until the end of the day so as to be recharged. The number of the needed buses is calculated based on the number of daily trips. From Nablus' station, 99 trips are required; therefore, we need 50 buses to take off from Nablus. Each bus will cover 3 trips; therefore, these 50 buses will completely cover the daily trips of Nablus, in addition to 50 trips from Ramallah's 68. This leaves 18 trips from Ramallah's station, for which we need another 9 buses to take off from Ramallah. By this, we calculated the number of buses that will cover all the daily trips.

Based on the number of daily trips and their distribution throughout the day and after calculating the energy consumed in each trip as shown in Table 1, the energy consumed per hour is calculated according to direction and load as shown in Figure 8 (for scenarios one and two). This energy is calculated by multiplying the number of trips per hour by the energy consumed for each trip. The sum of this energy is the total daily energy consumed.

On the other hand, in the second scenario, the bus will make 3 trips then it will enter the charging process and then return back to service again; this reduces the number of buses required. Therefore, the total number of buses is 39. 38 buses departing from Nablus and the other ones depart Ramallah. In this case, the number of buses is calculated by assuming an initial number of buses and tracking their hourly route.

Table 1: Energy consumption per trip for the adapted runs.

Trip	Bus load	kWh/trip
Nablus-Ramallah	Full	103
Nablus-Ramallah	Zero	67
Ramallah–Nablus	Full	95
Ramallah–Nablus	Zero	61

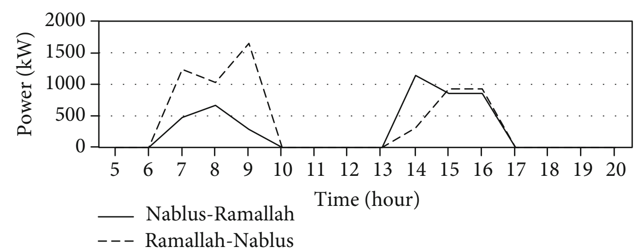


Figure 9: Daily hourly load demand of the adapted run round trip for scenarios 1 and 2.

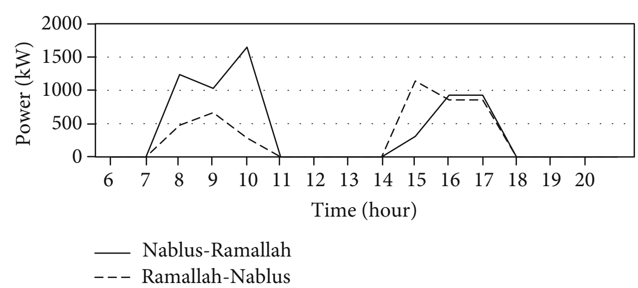


Figure 10: Daily hourly load demand of the adapted run round trip for the third scenario.

Here, although the number of buses is reduced, but the energy requirement of trips along the road remains the same as scenario 1 as shown in Figure 9.

As for the third scenario, the electric buses are assumed to cover the morning and evening peak times only, which are 6 hours divided into 3 hours in the morning and 3 hours in the evening. The rest of the times are covered by diesel buses. The total number of buses is, therefore, 31 buses distributed between Nablus and Ramallah; whereas, 26 buses depart from Nablus, and the other 5 depart from Ramallah. For this scenario, the number of buses is calculated using the same method shown in Figure 9. In this scenario, the number of buses is less than the previous ones. This reduction in number of buses is due to the distribution of the daily demand between electric buses and diesel buses. The energy consumed per day of this scenario is shown in Figure 10.

4.2. Sizing Results of Solar Charging Systems. In this research, a photovoltaic module with a capacity of 440 Wp is used, and a 600 Ah/12.8 V battery is also used. In addition, a double-inductor boost converter is used with a boosting ratio of 1 : 10. The sizing results of all charging stations are summarized in Table 2.

Table 2: Sizing results for all stations.

		No. of buses	PV array (MWp)	PV array configuration	Battery size (600/12.8 v)	Battery configuration	No. of charging ports
1st scenario	Nablus station	50	4.5	2 × 5109	7164	6 × 1194	10
	Ramallah station	9	0.75	2 × 855	2604	6 × 434	2
2nd scenario	Nablus station	38	2.9	2 × 3295	2605	6 × 358	3
	Ramallah station	1	2.8	2 × 3182	1692	6 × 286	6
3rd scenario	Nablus station	26	1.64	2 × 1864	2736	6 × 456	2
	Ramallah station	5	2.16	2 × 2452	2640	6 × 440	4

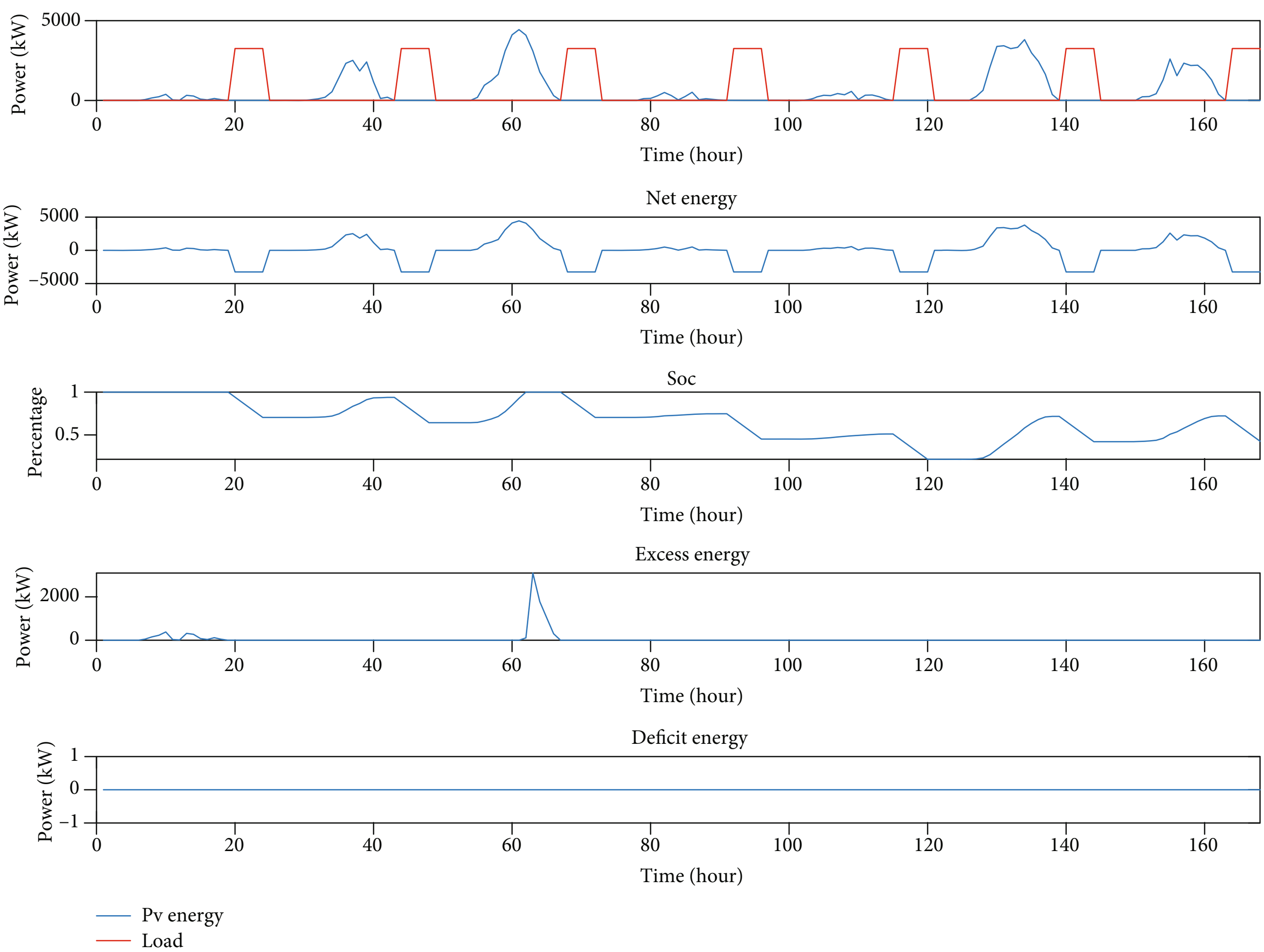


Figure 11: System performance sample for the first scenario: Nablus station.

4.3. System Simulation

4.3.1. First Scenario. Figure 11 shows the proposed system performance for the first week in the year for Nablus station. The first subplot shows a comparison between system charging load and PV power production. Based on this comparison, the control of the system is done, and the states of the charge (third subplot), excess energy (fourth subplot), and deficit energy (fifth subplot) are calculated. In general, the PV system produced about 8.88 GWh, which means that the yield factor of the system is about 1973 kWh/kWp, while the capacity factor is about 45%. Meanwhile, the excess energy recorded is about 3.3 GWh, which is about 37% of system's production. This large amount is due to the large size of the PV array installed so as to fulfill the demand of the associated batteries. Moreover, this shows the importance of

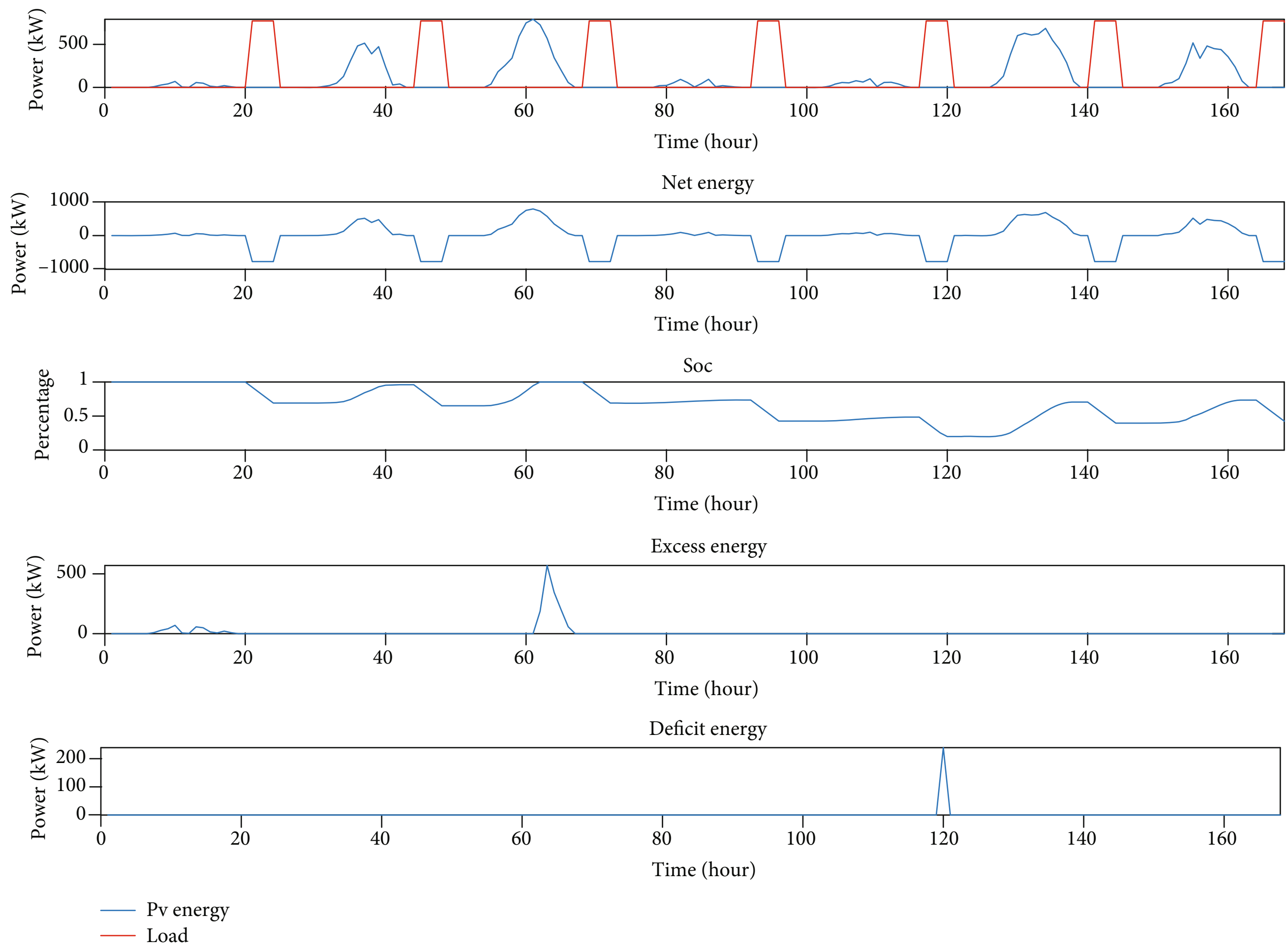


Figure 12: System performance sample for the first scenario: Ramallah station.

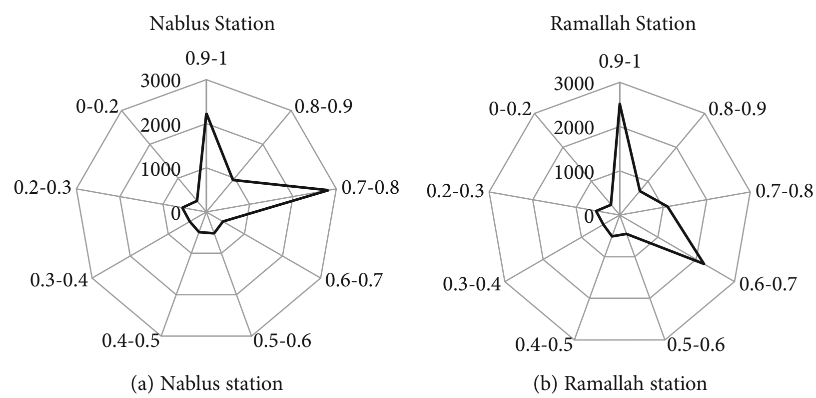


Figure 13: Usage of battery in Nablus station and Ramallah station.

utilizing the energy during the day for direct charging. On the other hand, the system is found relatively reliable; whereas, most of the deficit cases occurred in winter with a loss of load probability of 5%.

As for Ramallah station, the situation was quite similar; whereas, the reliability of the proposed system is found to be acceptable with a loss of load probability of 5%. Figure 12 shows the performance of the system including hourly simulation of the first week in the year. The system generated about 1.63 GWh where 35% of this energy is wasted as excess energy. The yield factor is found higher here with an amount of 2173 kWh/kWp with a capacity factor of 49.6%.

Figure 13 shows the radar charts for battery usage in both Nablus and Ramallah stations. From these figures, it is quite clear that the utilization of the battery in both cases is at border line level; whereas, in Nablus station, about 32% of the

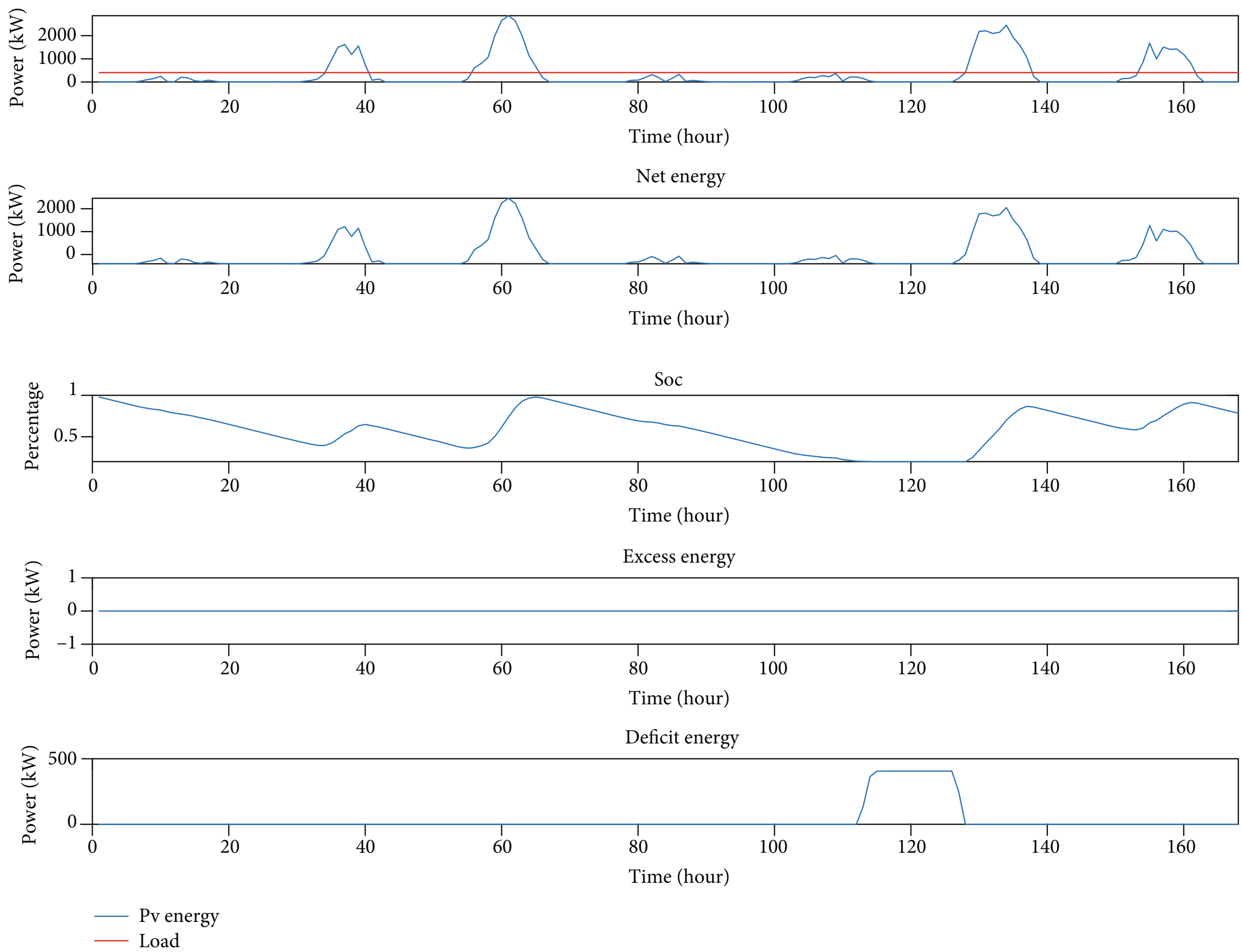


Figure 14: System performance sample for the second scenario: Nablus station.

time the state of charge of the battery is in the range of 70-80%, while about 26% of the time of the year the battery state of charge is in the range of 90-100%. On the other hand, in Ramallah station, the situation was quite better; whereas, about 25% of time of the year the state of charge of the battery is 60-70%. Meanwhile, in about 29% of the time in the year, the battery was slightly used; whereas, the state of charge is in the range of 90-100%.

This level of utilization is expected actually and it is also associated with the high percentage of excess energy; this is because of the high availability assumed (95%). According to [28–30], the most recommended availability of solar charging system is 95%; however, when reducing the availability to 90%, the excess energy can be reduced by almost 25-30%. On the other hand, the usage of the battery will also be boosted by 25-30% by considering the percentage of $SOC_{80\%}$; whereas, $SOC_{80\%}$ is a ratio that shows the number of hours that the battery has a state of charge higher than 80% as compared to the total number of hours in the year. However, considering the adapted case study, this deficit should be covered by conventional vehicle so as to assure the reliability of the service. Such an idea is highlighted later in the third scenario.

4.3.2. Second Scenario. Figures 14 and 15 show the hourly simulation of the proposed system for Nablus and Ramallah stations, respectively. The production of the system in Nablus station is 5.7 GWh, while it is 6.1 GWh in Ramallah station; the yield factor for both stations is approximately 2150 kWh/kWp with excess energy percentage approximately equals to 42% in both cases. Finally, the loss of load probability of both systems is 5%.

Figure 16 shows a radar chart for the usage of the battery in both stations.

From these figures, the battery in this scenario is also not utilized that much; whereas, the $SOC_{80\%}$ for Nablus station is 54%, while the $SOC_{80\%}$ for Ramallah station is 48%. This is also due to the low loss of load probability considered; whereas, these numbers can be significantly rescued in case of reducing the availability of the system to 90%, for example. However, this is still an option, as alternatives should always be available to the E-buses such as conventional buses so as to maintain the reliability of system. Such an idea is considered in the following third scenario for better comparison.

4.3.3. Third Scenario. Figures 17 and 18 show samples of the performance of the proposed system at both Nablus and

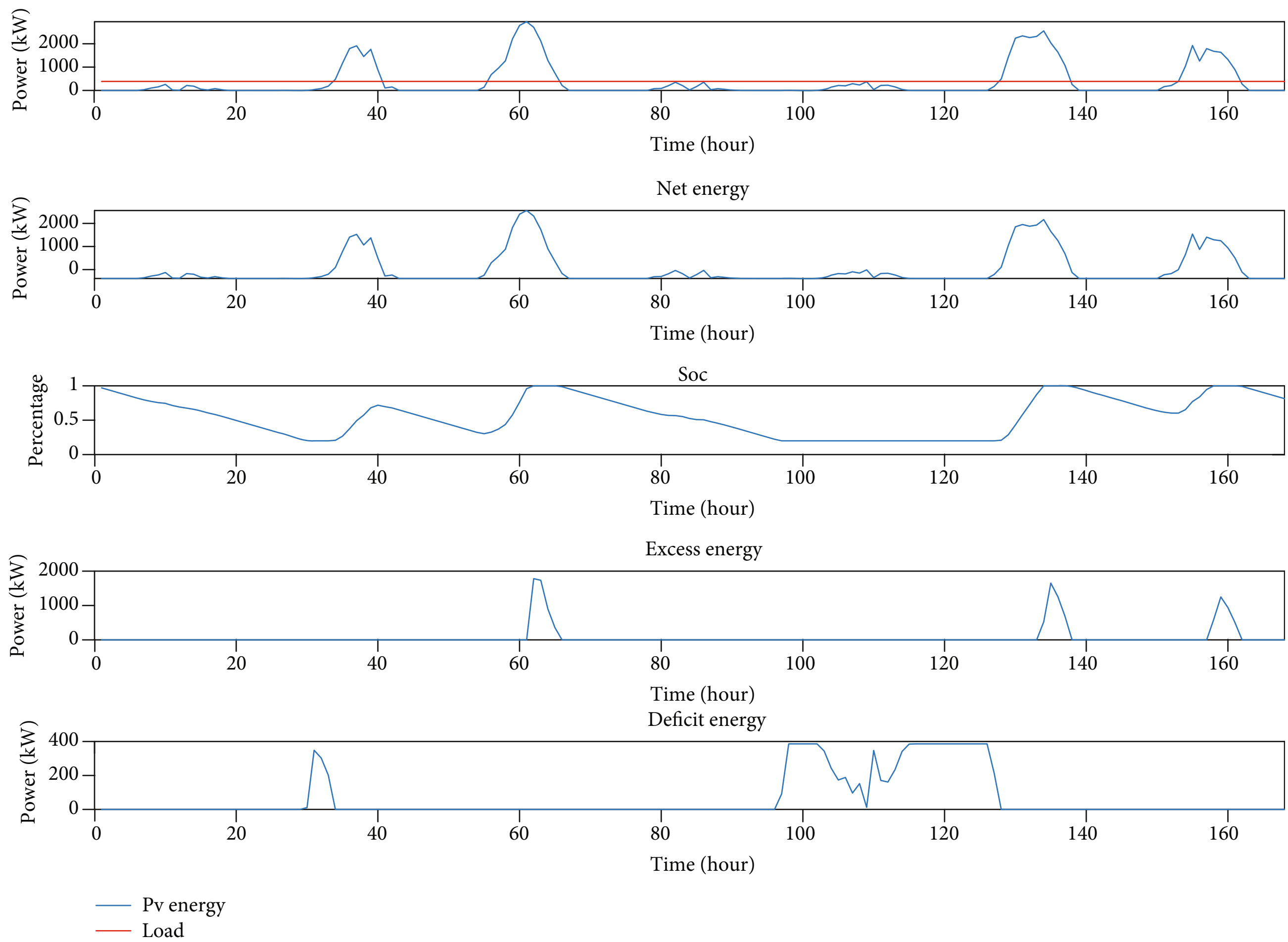
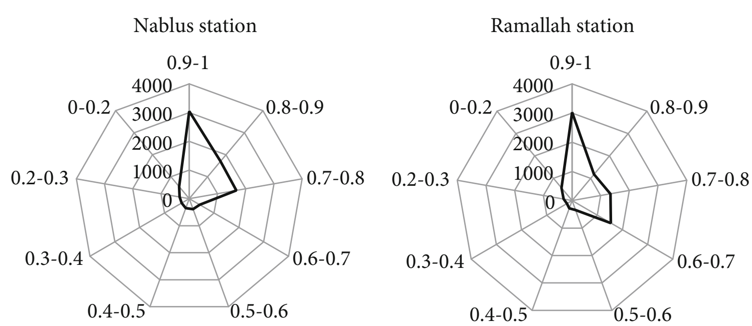


Figure 15: System performance sample for the second scenario: Ramallah station.



(a) Nablus station (b) Ramallah station

Figure 16: Usage of battery in Nablus and Ramallah stations for the second scenario.

Ramallah stations. The PV array generates 3.2 GWh per year and 4.7 GWh per year for Nablus and Ramallah stations, respectively. Meanwhile, the excess energy percentage for both cases is 35% with a loss of load probability of 5%.

Figure 19 shows a radar chart for the battery usage in the third scenario. In this scenario, the battery is not utilized that much; whereas, the $SOC_{80\%}$ for Nablus station is approximately 60%, while $SOC_{80\%}$ for Ramallah station is 67%. However, it is worth to mention that the size of the batteries in this scenario is about 55% of the size of the batteries in the first scenario and 140% of the battery size in the second scenario.

4.4. Proposed System Evaluation and Comparison. Table 3 shows a comparison between the proposed scenarios and the current situation. It shows a comparison between the required PV panels and batteries, buses, and CO_2 amount reduced. However, it is quite difficult to judge the proposed

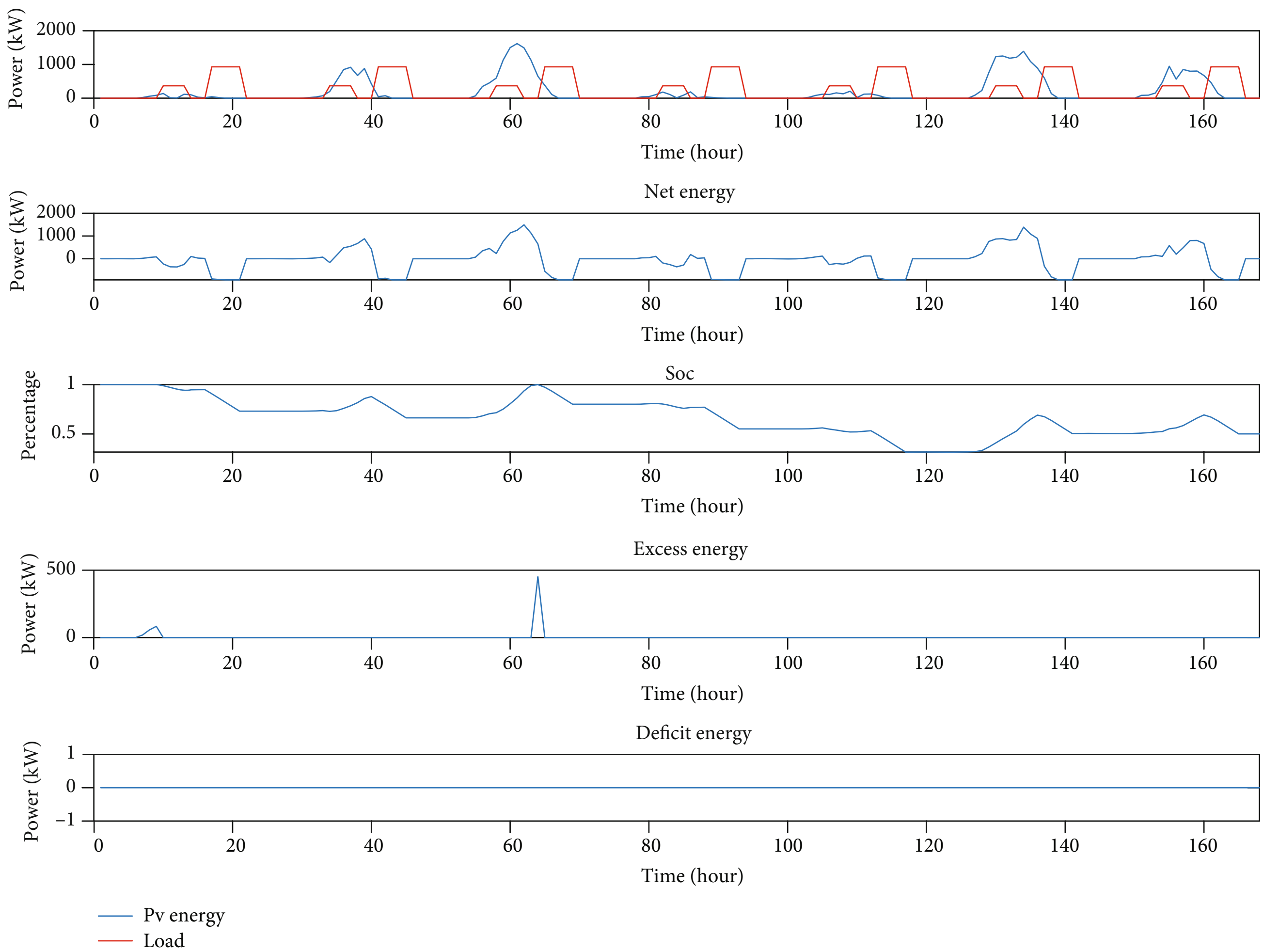


Figure 17: System performance sample for the third scenario: Nablus station.

scenarios without calculating their initial costs, payback periods, and costs per passenger. The initial cost of the system component's price is calculated considering the price of the 1 kWp with batteries of PV system, which is 2023 USD; meanwhile, the cost of additional batteries is 1.3 USD per 1 Ah/12 v. As for other system's component price, it is considered 212 USD per kWp. The bus price is estimated at 200,000 USD, while the land's cost is assumed at 45 USD per 1 m^2 (suburbs). Based on the current prices, the price of diesel liter is estimated as 1.3 USD. The cost of the trip for each person is calculated according to Equation (14), while the depreciation for the components of the solar system is 5%, and for the buses, it is 10%; the annual salary of the driver is 12,000 USD and the maintenance cost is 150 USD per kWp. Finally, the amount of the mitigated CO_2 is found by calculating the amount of diesel saved in each scenario (measured by the number of trips). Therefore, the amount of the mitigated CO_2 is the same in the first and second scenarios.

From Table 3, it is clear that the second option is the best among the three considering the trip cost per passenger. The current trip cost per passenger is 3.5 USD + 40% of this cost as a profit. Thus, the three proposals exceed the conventional option. Based on that, it is recommended to adapt the second scenario considering the trip cost per passenger, investment payback period, and amount of CO_2 mitigated.

4.5. Brief Social Impact Assessment of the Proposal on the Current Jobs and Passengers. As mentioned earlier, currently, there are 110 drivers who are employed by this line with 2 other employees for management issues. The average monthly salary for each driver is about 1,000 USD per month (84 hours a week). Meanwhile, the management employees' average salary is about 800 USD (60 hours a week). However, according to the Palestinian labor law, the maximum number of working hours per week should not exceed 50 + 6 hours for lunch.

Considering the recommended scenario, there will be a need for (59) drivers, (21) management staff as site coordinator, ticket fees collectors, accountant, managing officer and guards and security officers, (2) technical staff for the monitoring of PV system, (2) technical staff for the monitoring of the buses performance, (4) technicians for maintaining the PV system, and (4) technicians for buses maintenance. All these job tasks are supposed to be working 40 hours per week. The total number of the required staff is 92; whereas, 78 of them can be from the drivers themselves, while 10 of

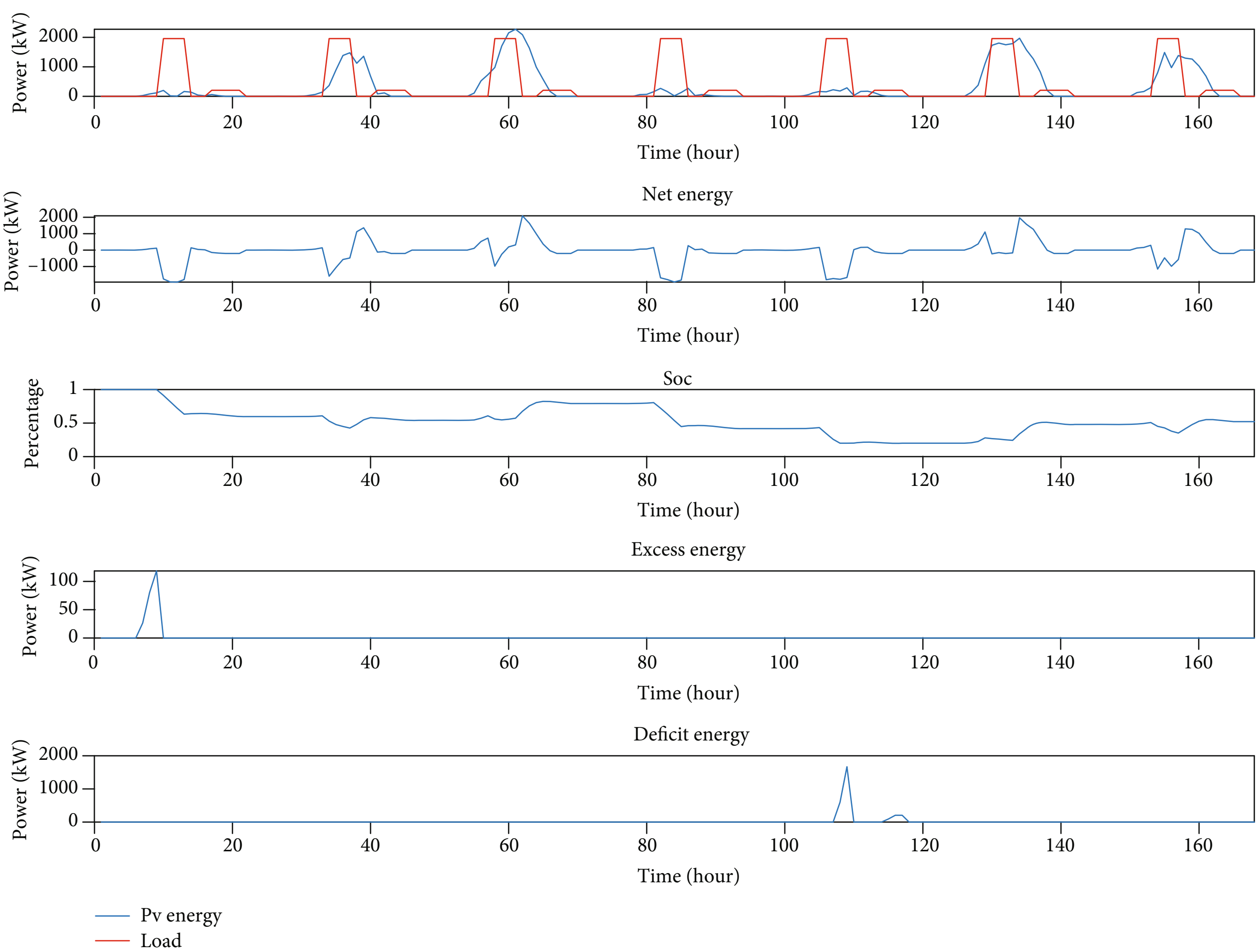
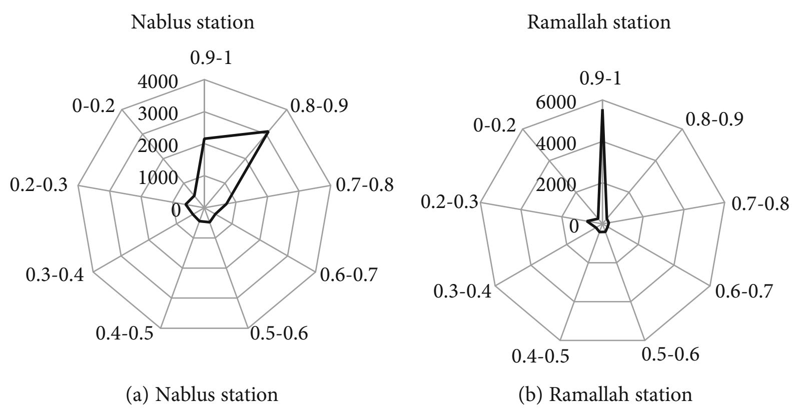


Figure 18: System performance sample for the third scenario: Ramallah station.



(a) Nablus station (b) Ramallah station

Figure 19: Usage of battery in Nablus and Ramallah stations for the third scenario.

them can also be hired from the drivers after some specific trainings.

Although such a project has created about 92 green job opportunities, with much better salaries (150% of the old salaries) and working conditions (about half of working hours), about 20% of the old staff will lose their jobs. Therefore, this cannot be neglected actually, but it is quite expected as we moved from conventional methods to smart systems. Thus, the government here should help with this regard by developing rehabilitation courses for those who are working in conventional jobs. On the other hand, the project will have a positive social impact on the passengers themselves considering the convenience, reliability, and sustainably of the proposed system.

Table 3: Comparison of the proposed scenarios.

	PV panel (MWp)	No. of batteries (600/12.8 v)	Initial cost (USD)	SPBP (years)	Savings (USD)	Land required (m^2)	No. of buses	Trip cost per passenger (USD)	CO_2 (kg/year)
1st scenario	5.2	9,768	32,740,200	14.8	2,210,375	42,000	59	2.85	1,629,387
2nd scenario	5.7	4,297	22,365,000	10.0	2,230,375	45,000	39	2.05	1,629,387
3rd scenario	3.8	5,376	15,910,000	9.4	1,691,202	30,000	31	2.42	1,012,632

5. Conclusion

This paper presented a novel design and operation of solar-based charging system for a 50 km run road located in Palestine between two main cities: Nablus and Ramallah. The proposal is aimed at replacing 110 existing diesel vehicles with electric buses considering three main operational scenarios. The first scenario assumed electric charging of the electrical buses at the end of the day only, while batteries were in charging model all of the day. The second scenario is aimed at utilizing the direct power of the photovoltaic modules and the batteries at the same time. The third scenario was a hybrid system between electric buses and diesel vehicles so that electric buses cover the morning and evening peak periods. Results showed that the first scenario is practically unsuccessful, as it needs a high cost to meet the main goal due to the large required photovoltaic system and number of buses (59 buses). Meanwhile, the second and third scenarios were close to each other considering the payback period. However, due to trip cost per passenger as well as the amount of CO_2 mitigated, the second scenario was preferred. Finally, the proposed system was found to be socially accepted; whereas, most of the current employees kept their jobs with higher salaries by about 145% and less working hours by 50%. In addition, the proposed system significantly increased the reliability, convenience, and sustainability of the adapted transportation line.

Data Availability

Data is available with authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank Ranan Salameh for proofreading the draft of the manuscript.

References

[1] K. Qian, C. Zhou, and Y. Yuan, "Impacts of high penetration level of fully electric vehicles charging loads on the thermal ageing of power transformers," *International Journal of Electrical Power & Energy Systems*, vol. 65, pp. 102–112, 2015.

[2] Y. Song, X. Yang, and Z. Lu, "Integration of plug-in hybrid and electric vehicles: experience from China," in *IEEE PES General Meeting*, 2010.

[3] M. Safaria, "Battery electric vehicles: looking behind to move forward," *Energy Policy*, vol. 115, pp. 54–65, 2018.

[4] C. Edrington, O. Vodyakho, B. Hacker, S. Azongha, A. Khaligh, and O. Onar, "Virtual battery charging station utilizing power-hardware-in-the-loop: application to V2G impact analysis," in *IEEE Vehicle Power and Propulsion Conference*, pp. 1–6, 2010.

[5] W. Kempton and J. Tomić, "Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy," *Journal of Power Sources*, vol. 144, no. 1, pp. 280–294, 2005.

[6] S. Ge, L. Feng, and H. Liu, "The planning of electric vehicle charging station based on grid partition method," in *2011 International Conference on Electrical and Control Engineering*, pp. 2726–2730, 2011.

[7] Z. Bendiabdellah, S. M. Senouci, and M. Feham, "A hybrid algorithm for planning public charging stations," in *2014 Global Information Infrastructure and Networking Symposium (GIIS)*, pp. 1–3, 2014.

[8] M. H. Amini and M. P. Moghaddam, "Probabilistic modelling of electric vehicles' parking lots charging demand," in *21th Iranian Conference on Electrical Engineering ICEE2013, Mashhad*, pp. 1–4, 2013.

[9] L. Zhipeng, F. Wen, and G. Ledwich, "Optimal planning of Electric-Vehicle charging stations in distribution systems," *IEEE Transactions on Power Delivery*, vol. 28, no. 1, pp. 102–110, 2013.

[10] V. Kumar, V. R. Teja, M. Singh, and S. Mishra, "PV Based Off-Grid Charging Station for Electric Vehicle," *IFAC PapersOnLine*, vol. 52, no. 4, pp. 276–281, 2019.

[11] J. Pinak, V. M. Tulpule, S. Yurkovich, and G. Rizzoni, "Economic and environmental impacts of a PV powered workplace parking garage charging station," *Applied Energy*, vol. 108, pp. 323–332, 2013.

[12] P. Goli and W. Shireen, "PV integrated smart charging of PHEVs based on DC link voltage sensing," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1421–1428, 2014.

[13] J. C. Hernandez and F. S. Sutil, "Electric vehicle charging stations feeded by renewable: PV and train regenerative braking," *IEEE Latin America Transactions*, vol. 14, no. 7, pp. 3262–3269, 2016.

[14] X. Li, D. Hui, and X. Lai, "Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 464–473, 2013.

[15] S. J. Tong, A. Same, M. A. Kootstra, and J. W. Park, “Off-grid photovoltaic vehicle charge using second life lithium batteries: an experimental and numerical investigation,” *Applied Energy*, vol. 104, pp. 740–750, 2013.

[16] L. S. A. Grande, I. Yahyaoui, and S. A. Gómez, “Energetic, economic and environmental viability of off-grid PV-BESS for charging electric vehicles: case study of Spain,” *Sustainable Cities and Society*, vol. 37, pp. 519–529, 2018.

[17] H. Mehrjerdi, “Off-grid solar powered charging station for electric and hydrogen vehicles including fuel cell and hydrogen storage,” *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 11574–11583, 2019.

[18] M. Zahir Hussain, R. Anbalagan, D. Jayabalakrishnan et al., “Charging of car battery in electric vehicle by using wind energy,” *Materials Today: Proceedings*, 2020.

[19] A. Turksoy, A. Teke, and A. Alkaya, “A comprehensive overview of the DC-DC converter-based battery charge balancing methods in electric vehicles,” *Renewable and Sustainable Energy Reviews*, vol. 133, p. 110274, 2020.

[20] C. De Cauwer, M. Maarten, T. Coosemans, J. van Mierlo, and S. Heyvaert, “Electric vehicle use and energy consumption based on real-world electric vehicle fleet trip and charge data and its impact on existing EV research models,” in *In Proceedings of the International Electric Vehicle Symposium and Exhibition*, pp. 1–11, Kintex, Korea, 2015.

[21] D. Cauwer, J. V. Mierlo, and T. Coosemans, “Energy consumption prediction for electric vehicles based on real-world data,” *Energies*, vol. 8, no. 8, pp. 8573–8593, 2015.

[22] T. Khatib, I. A. Ibrahim, and A. Mohamed, “A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system,” *Energy Conversion and Management*, vol. 120, pp. 430–448, 2016.

[23] H. A. Kazem, T. Khatib, and K. Sopian, “Sizing of a standalone photovoltaic/battery system at minimum cost for remote housing electrification in Sohar, Oman,” *Energy and Buildings*, vol. 61, pp. 108–115, 2013.

[24] G. M. Masters, *Renewable and Efficient Electric Power Systems*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2nd edition, 2013.

[25] K. Liu, X. Hu, H. Zhou, L. Tong, D. Widanalage, and J. Macro, “Feature analyses and modelling of lithium-ion batteries manufacturing based on random forest classification,” *IEEE/ASME Transactions on Mechatronics*, p. 1, 2021.

[26] K. Liu, Z. Wei, Z. Yang, and K. Li, “Mass load prediction for lithium-ion battery electrode clean production: a machine learning approach,” *Journal of Cleaner Production*, vol. 289, p. 125159, 2021.

[27] K. Liu, Y. Shang, Q. Ouyang, and W. D. Widanage, “A data-driven approach with uncertainty quantification for predicting future capacities and remaining useful life of lithium-ion battery,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 4, pp. 3170–3180, 2021.

[28] M. Sidrach-de-Cardona and L. L. Mora, “A simple model for sizing stand alone photovoltaic systems,” *Solar Energy Materials & Solar Cells*, vol. 55, no. 3, pp. 199–214, 1998.

[29] T. Khatib and W. Elmenreich, “Novel simplified hourly energy flow models for photovoltaic power systems,” *Energy Conversion and Management*, vol. 79, pp. 441–448, 2014.

[30] T. Khatib and W. Elmenreich, “Optimum availability of standalone photovoltaic power systems for remote housing electrification,” *International Journal of Photoenergy*, vol. 2014, 5 pages, 2014.