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Electrical load profile management based on storage energy scenarios for residential PV storage system

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Abstract
photovoltaic generation is variable from hour to another based on the sun energy and hence the consumer cannot use and utilize all the energy produced from PV system. Therefore, the ability of applying the management technique can be appear by storing this surplus energy in batteries and then discharge it at night. For this purpose, this work presents an optimized storage energy system design in order to utilize the not beneficiary PV energy as well as to shave peak loads at night. It is found that 500Ah battery bank is required to cover the peak loads (2.4kWh) at night for residential consumer of Baghdad city. Because batteries are expensive, it was necessary to suggest methods to store this energy and discharge it in the proper time. Therefore, six applicable scenarios for storage energy were suggested and built using MATLAB software to optimize the electricity usage and reduce the losses. These scenarios provide a desired change in the load profile shaping (main function of DSM). The implementation of active demand side management dependent on traditional demand side management.

Keywords: DSM; PV; Battery system; Scenario; Storage energy; Storage system; Load profile shaping.

1. Introduction

The term Demand Side Management (DSM) was created after 1973 when energy crisis was happened in USA. Then, the demand side management was introduced publicly by Electric Power Research Institute (EPRI) in the 1980 [1]. DSM has different meanings for different people categories. For utility company, DSM means avoiding or postponing the need to build new power plant by reducing or shifting consumer’s energy use period. For domestic consumer, it means a way to save money by reducing their electricity bill. For industrial customers, DSM means low production cost and hence more competitive product. In other words, DSM refers to steps taken by consumer and utility to change the amount or timing of energy consumption to produce the desired change in the electrical load profile (load profile shaping) [2]. DSM has several objectives of load-shaping as shown in Figure 1 in which represented by peak clipping, load shifting, valley filling and energy conservation [3].
PV technology offers the most direct method to convert solar energy into electrical energy without carbon dioxide emissions. Solar energy is based on the photovoltaic effect, which was first observed in 1839. Leading energy scientists recognized in 1973 that solar cells is a viable candidate for future non-fossil energy supply. The growth of solar PV systems in the past 7 years has been tremendous all over the world because this energy is used as a load management tool as well as it is renewable, sustainable,

pollution free, fuel free and noiseless. Complete PV solar system may include charge controller, batteries for electricity storage and DC/AC inverters. These additional parts of the PV solar system form the balance of system (BOS) components [4].

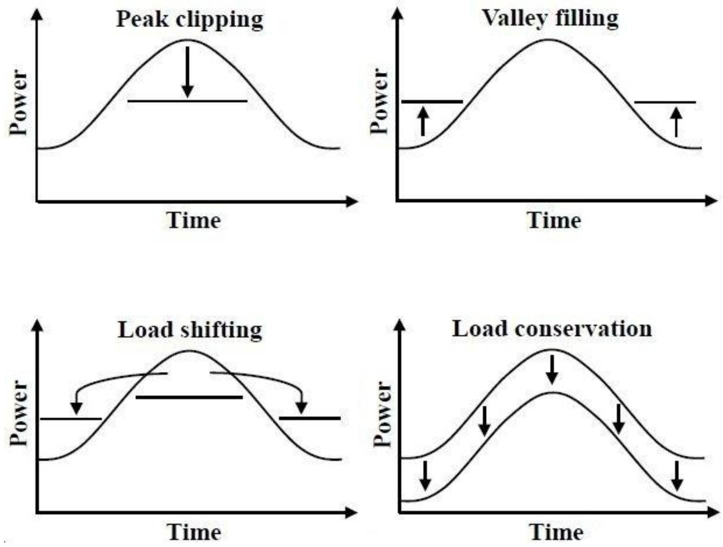

Figure 1. Demand side management objectives [3].

PV modules converts the solar energy directly to electrical energy, but the sun does not shine all around the clock. Then it is possible to store the electrical energy in batteries. Storage Energy is the process of holding energy produced at a specific time for usage at a late time. The storage system appears to be one of the most popular choices in the electrical grid because it provides a solution for peak load demand shaving and storing residual energy from PV generation [5].

The energy stored in the battery is expensive because the high cost of battery. Therefore, it is necessary to optimize the design of this element and then manage this energy. Strategies of storage energy (method of charging and discharging) provides a desired change in the load profile shaping (main function of DSM) and optimum use of electrical energy produced from PV system. The combination of DSM and PV with storage system provides an active demand side management (ADSM).

Recently, the researchers have been shedding light on electrical energy management and the application of its objectives. From literatures, A. Oudalov, et al. [6] demonstrated a sizing methodology and optimal operating strategy for a battery energy storage system to provide a peak load shaving and minimize the energy cost based on dynamic programming. H. Delavaripour, et al. [7] presented the optimum calculation of battery size when used as energy storage in standalone systems with renewable energy resources. The focus in this analysis is on the effect of battery charging/discharging characteristics on system reliability and cost. J. Bergner, et al. [8] presented autonomous forecast-based operation strategies for residential battery systems that can be used to improve grid integration of PV systems. M. Resch, et al. [9] focused on control strategies for residential batteries of (PV) systems in order to determine the best control strategy for storage systems in Germany based on technical and economic perspectives. A. A. Abbood, et al. [3] presents implementation of management techniques using solar cells for residential sector in Baghdad city. The estimation of solar radiation data and PV system design has been simulated based on MATLAB software. The applied techniques are the capability of application the load-shifting technique from high load periods to low load periods, and ability to store the surplus energy produced from PV generator in batteries for usage this energy at a later time.

in this study that will be as a future work based on reference [3], a storage system design is presented as well as general algorithms for six applicable scenarios of storage energy are demonstrated which can be applied for each day of the year (i.e. for each system size and each load). These scenarios are affecting on load profile shaping to implement ADSM objective.

2. Mathematical model for residential PV storage system design

Solar cell is a tool that converts the incident light into electricity, but, the sun doesn't shine all the time. So, batteries is used for storing energy in the daytime and discharge this energy at the night. Because there are a surplus energy from PV in the low loads and over-generation periods, the consumer can store this energy in batteries and then discharge it. The purpose of this process is to apply the strategy of demand side management by peak load shaving at night. The design steps and its results as follows.

2.1 Battery sizing

The battery storage (kWh) required for the photovoltaic energy system can be calculated by the following equation [10]:

$$S = \frac{N_c \times E_L}{DOD \times \eta_r \times \eta_v} \quad (1)$$

where, N_c : Period of storage required (days). E_L : Daily load demand of energy (kWh). η_r : Efficiency of charge controller. η_v : Efficiency of inverter. DOD : Deep of discharge, which represents the percentage of the rated capacity withdrawn from the battery in which assumed 50% to increase the life time of the battery, given by [7],

$$DOD = 1 - SOC \quad (2)$$

where, SOC : The state of charge, which gives an indication of the battery state during charge and discharge as compared to its full-charge state and given by [7]:

$$SOC = \frac{Surplus\_usable\_energy(kWh)}{Total\_usable\_energy(kWh)} \quad (3)$$

Finally, the required ampere-hours (C_{Ah}) of battery is given by [10]:

$$C_{Ah} = \frac{S}{V} \quad (4)$$

where, V : System voltage in volt (V), in which assumed 12V.

2.2 Storage energy results

In this work, the designing of the storage energy were calculated depending on the nightly peak loads of the summer month, June, and the winter month, January, then the sizing of the batteries were done in this system. Figure 2 shows the required energy in the peak period for June month of Baghdad city where the area filled with a hatch lines represents the load demand (E_L) to be covered by batteries which equal 2.4 kWh from (18-23) PM.

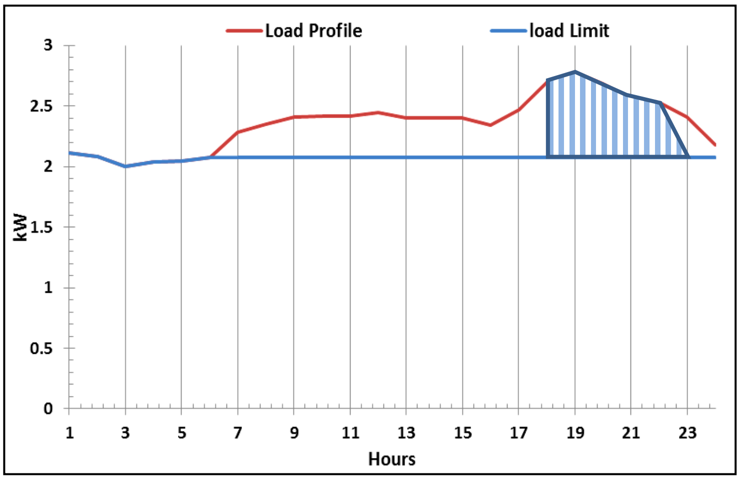

Figure 2. Baghdad load profile per residential consumer of June and the required energy at night.

After the application of the proposed program using MATLAB software, the obtained results are: the storage capacity (S) of the batteries is 5.647kWh, the ampere-hours required (C_{Ah}) is 470.5Ah with assumption of 50% deep of discharge (*DOD*), and The BOS efficiencies is assumed to be 85%. The available size of battery in the market is 100Ah, so a battery bank consists of 5 batteries with a rated of 12V 100Ah for each one was used, therefore, the total storage is 6kWh. All the above parameters and design specifications are illustrated in Table 1.

Table 1. Design parameters and specifications of storage system.

Parameter	Value
Peak load period	(18-23) PM
Size of PV system [3]	2 kWp
Energy demand in peak period (E_L)	2.4 kWh
System efficiencies (BOS)	85 %
Deep of discharge (*DOD*)	50 %
Battery storage (S)	6 kWh
Battery voltage	12 V
Number of batteries	5
Rated ampere-hours of each battery	100 Ah
Total ampere-hours required	500 Ah

On other hand, the required energy in the peak period for January month to be covered by the battery system equal 2.24kWh from 18 PM to 23 PM as shown in Figure 3. because the energy required for June have the same the required energy for January as well as for more flexibility in design, the load of June was considered in all the calculations.

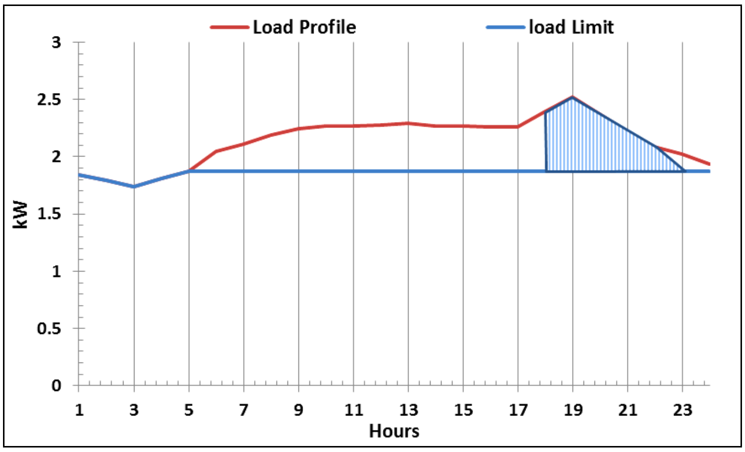

Figure 3. Baghdad Load profile for residential consumer of January and the needed energy in the peak load period.

The other design components of the photovoltaic system are the charge controller and the inverter. The charge controller is a device that matches between the PV modules and the battery. From the datasheet of the used PV module, the short circuit current is 6.46A in Ref. [3] and with the assumption of six connecting modules in parallel with a safety factor of 1.25 according to Ref. [11], the total current of charge controller is 48.45A with rated 12V (depending on the available sizes in the markets).
Since the size of the system is 2kWp in Ref. [3], and the effect of losses will be 1.75kW, then the invertor output power is 1.75kW and with a safety factor equal to 1.25, the size of the inverter is 2.18kW (depending on the available sizes in the markets).

3. Scenarios of storage energy and its results

The battery system and the method of storage energy are very important factors as a demand side management tools because:

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1. Battery provides a solution of nightly peak loads (peak shaving). Also, it is a solution to store the surplus energy produced from PV generation and then discharge this energy (shifting the PV generation).
2. Strategies of storage energy (method of charging and discharging) provides a desired change in the load profile shaping (main function of DSM) and optimum use of energy produced from PV system.

Therefore, it is important to suggest a methods for storing energy in a way that improves the load profile shape. In this work, a six general algorithms for each method of charging energy were built based on MATLAB software which can be applied for each day of the year (i.e. for each system size and each load).

The outputs of simulated program of each charging method are: hours of charging, power taken at each hour, state of charge at each hour as well as the power corrections in some of charging methods and percentages required for simulation. The method of discharging is the same for each scenario because this depends on the load of the concerned month and the sixth month was the dependent in this work.

Since only the surplus energy from PV generation in the daytime is shifted to another hours at night, the percentages of hourly, monthly and annually demand saving with and without the batteries will be the same and will not affected by the battery system.

3.1 First scenario of battery charging

The principle operation of this method is that the battery will be charged from solar cells until fully charged with 100% SOC and then supply the load. The time of charging is the morning period. The effect of solar generation before taking the effect of the batteries charging and discharging is shown in Figure 4. The figure shows the impact of solar generation on peak load demand in the daytime.

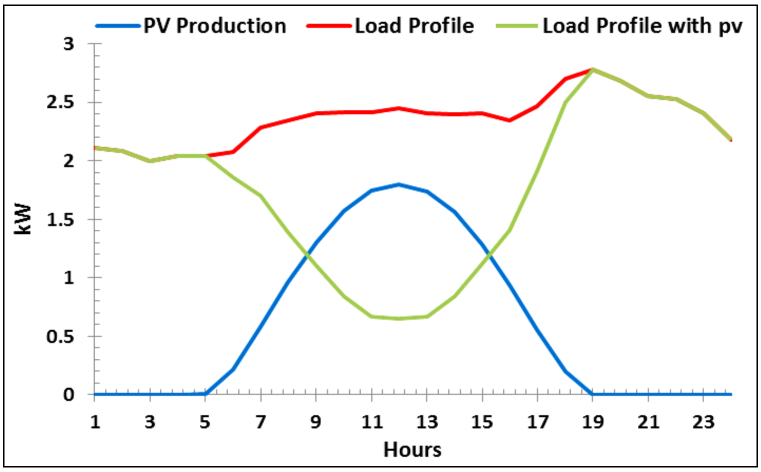

Figure 4. Effect of PV production on Baghdad load demand per residential consumer for June.

The algorithm of the first strategy is as shown in Figure 5. The power flow of this strategy is depicted in Figure 6. where 23% of PV production is taken to charge the batteries. The solar cells charge the batteries until be fully charged at 100% SOC at 10AM where the power at this hour is not all the PV produced power because the simulated program has the ability to detect the surplus energy at this hour and correct it to be optimized and reduce the losses. While the discharge period starts at 18PM and SOC will be decrease according to discharged power at each hour.

Moreover, the operation of this scenario can be also seen in Figure 7. which explains the state of charge at each hour. It is obvious that the state of charge started from 50% (initial SOC) because it is dependent on the deep of discharge (DOD) of the battery system in which assumed 50% as illustrated in the previous table.

Therefore, the resultant load profile before and after adding PV and battery with this strategy is as shown in Figure 8.

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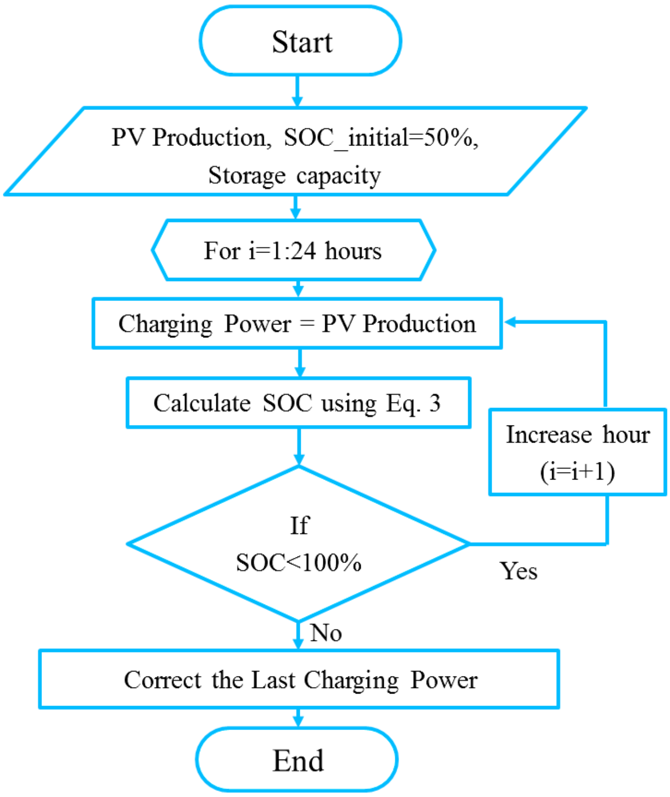


Figure 5. Flowchart of first scenario for storage energy.

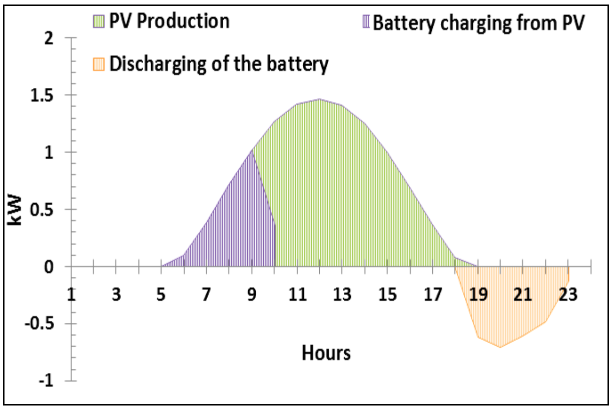


Figure 6. Power flow between the PV and battery.

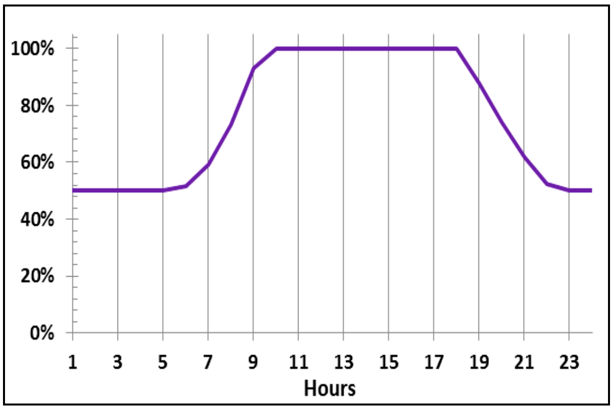


Figure 7. State of charge.

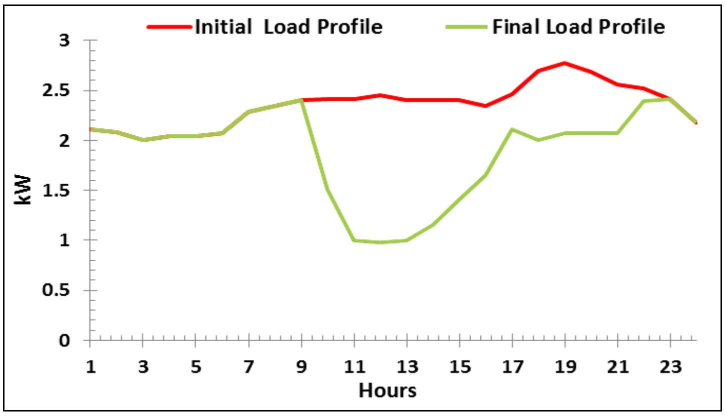


Figure 8. Effect of first scenario on load demand.

3.2 Second scenario of battery charging

The principle operation of this scenario is that the battery will be charged from PV production with a dynamic power from over-generation hours (noontime period). The algorithm of this scenario is as shown in Figure 9. The operation of this strategy is as shown in Figure 10. In order to overcome the problem of high generation in the high irradiance periods, this scenario is developed. The idea of this method is assuming a percentage from maximum element in PV production matrix as a limited power, and then this percentage is increased dynamically with a small tolerance. If the subtraction of the limited power from the PV production equal to a positive value, then this energy can be used as a charging energy. The SOC is computed in each step in charging and discharging process, therefore the program check the last SOC in the charging period and if it is equal to 100%, the program will stop and the percentage, hours of charging, SOC and the charging power in each hour will be displayed, if not, the percentage will be increased and the operation will be repeated.

The resulting load profile before and after PV and battery with this strategy is as shown in Figure 11.

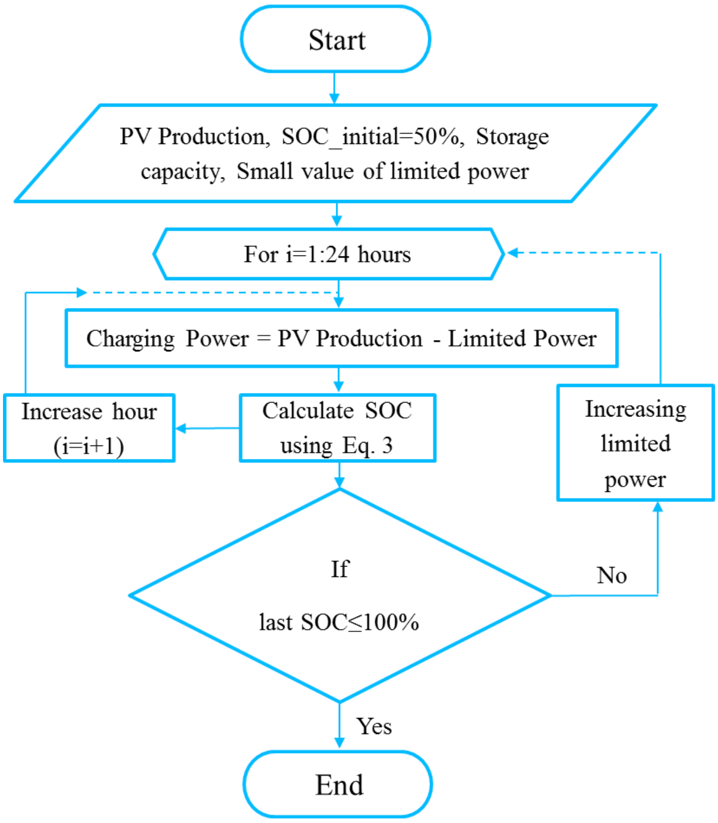


Figure 9. Flowchart of second scenario for storage energy.

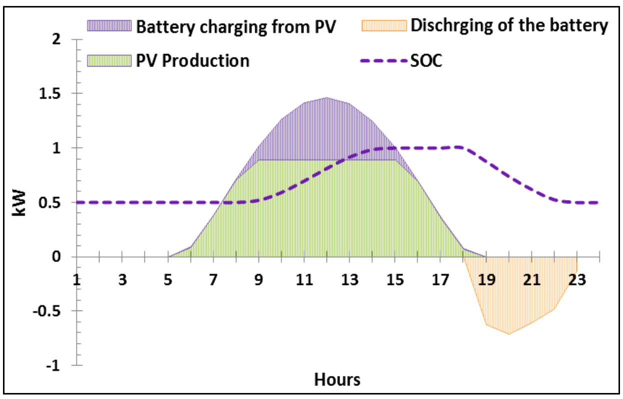


Figure 10. Principle operation of second scenario.

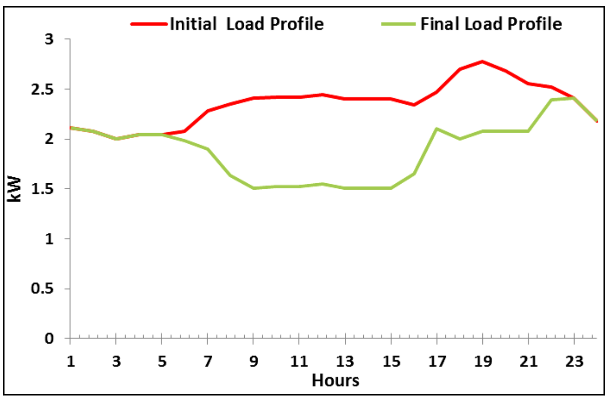


Figure 11. Effect of second scenario on load demand.

3.3 Third scenario of battery charging

The principle operation of this strategy is that the battery will be charged from PV production in two periods, the first from morning period (as suggested in first scenario), and the second from over-generation hours with a dynamic power (as suggested in second scenario). The algorithm of this charging method is as shown in Figure 12.

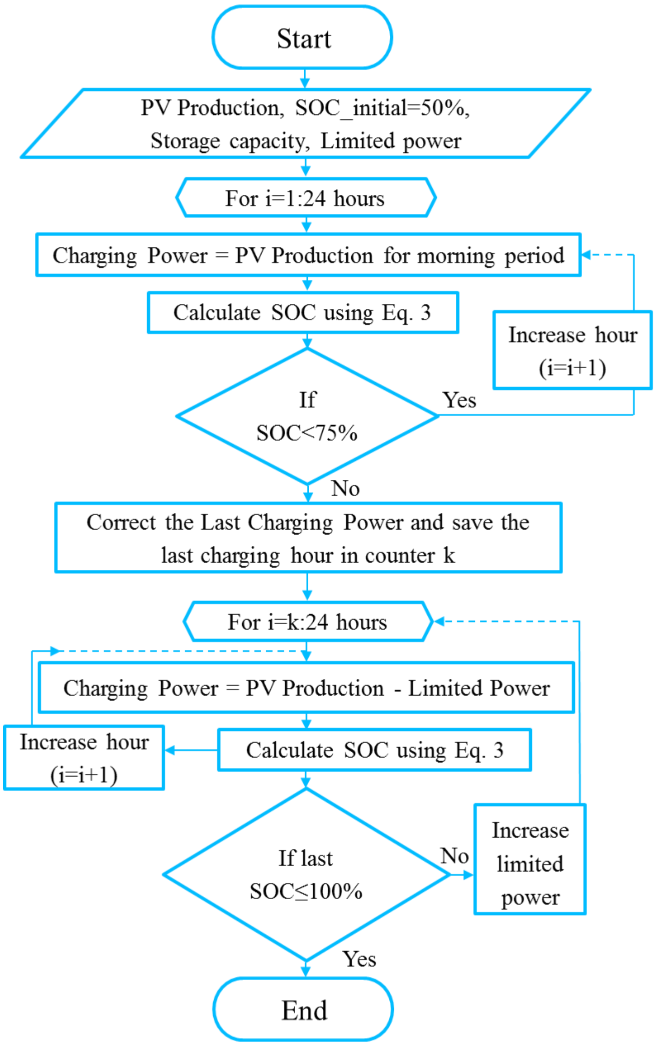


Figure 12. Flowchart of third scenario for storage energy.

The results of this strategy are shown in Figure 13. This strategy is a combination of the first and the second scenarios. In low irradiance months, the consumer is needed the energy at over-generation periods, therefore the second scenario is not efficient for winter months, so another method is required to reduce this energy taken from the solar cells. This approach presents a solution to solve the above problem where the battery will be charged from the PV production in two periods, the first period from the morning and the second from over-generation hours (noontime period) with a dynamic power. The first charging period charges the battery SOC to 75% and the second period to 100%. The resulting load profile before and after adding PV and battery with this scenario is as shown in Figure 14.

3.4 Fourth scenario of battery charging

The principle operation of this scenario is that the battery will be charged from PV production in the off-peak periods (low loads periods) if we assume that the tariff is reduced in these hours. The electricity tariff can be divided into positive tariff which means the increment of electricity unit price at a specific period due to increasing the load demand (on-peak period), and the negative tariff which means the decrement of electricity unit price at a specific hours because of the reduction of the load demand (off-peak period). This can be seen in Figure 15. The algorithm of this strategy is as shown in Figure 16.

In this method, the solar cells charges the battery in the off-peak periods with equal energy in each period as shown in Figure 17. In the first period the SOC reaches to 75% and then reaches 100% in the second period. Also, the simulated program has ability to check the last charging power to reduce the losses. The resulting load profile from this method of storage energy is shown in Figure 18.

3.5 Fifth scenario of battery charging

The principle operation of this strategy is that the battery will be charged from PV production with a constant power at each hour in the first half of daytime as shown in Figure 19. After the battery is fully charged, PV production will supply the load. The algorithm of this scenario is as shown in Figure 20.

At morning, the energy produced from solar cells is very low and this power used totally to charge the battery. After that, the PV production is increased and the program detect this increasing and cut a constant power to charge the batteries and this power is estimated by the program according to the battery size. Also, the operation principle can be noted from SOC curve where the slope is increased regularly in which indicates that the charging power is constant in each hour.

Consequently, the produced load profile after simulation program is as shown in Figure 21.

3.6 Sixth scenario of battery charging

The principle operation of this method is that the battery will be charged from PV production with a changed power at each hour according to production at that hour. The algorithm of this scenario is as shown in Figure 22.

The estimated results after simulation procedure can be seen in Figure 23. In this strategy, the battery will be charged each hour according to the PV production at that hour. The principle operation is assuming a small percentage which multiplied by the solar production at each hour with increasing SOC in each step, then the program checks the last SOC until reaching 100%. This percentage is increased dynamically with a small tolerance in each loop until reaches to a value that makes SOC 100% (fully charged). The resultant load profile before and after adding PV and battery with this scenario is as shown in Figure 24.

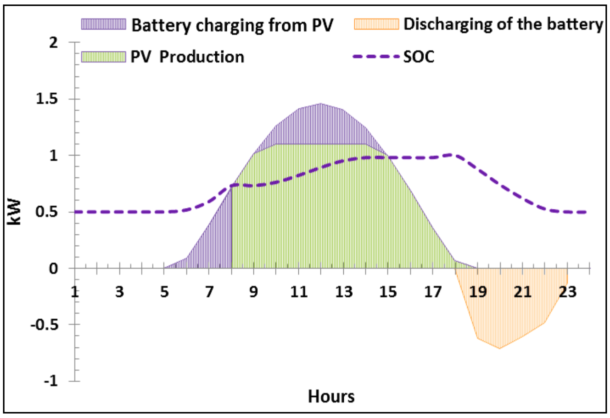


Figure 13. Obtained results for third scenario.

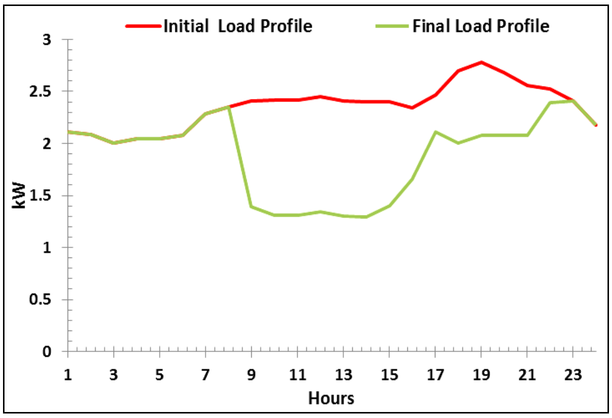


Figure 14. Effect of third scenario on load demand.

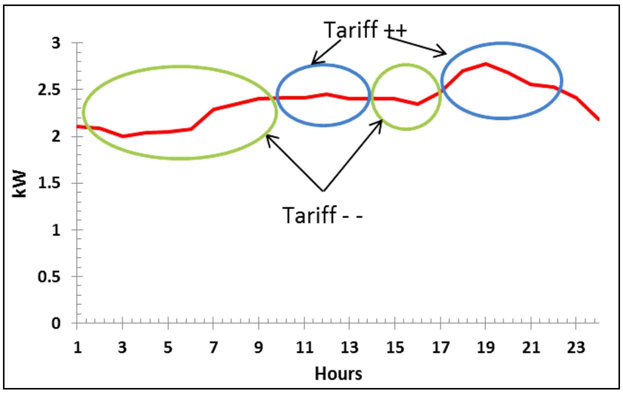


Figure 15. Load profile with on-peak and off-peak periods.

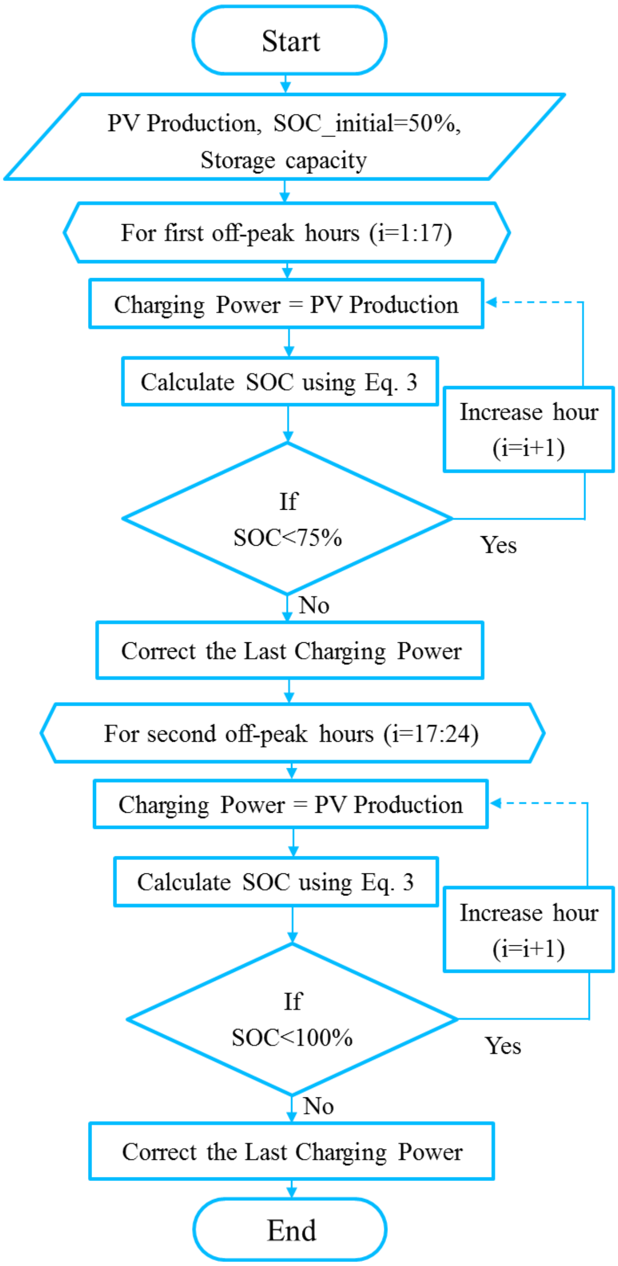


Figure 16. Flowchart of fourth scenario for storage energy.

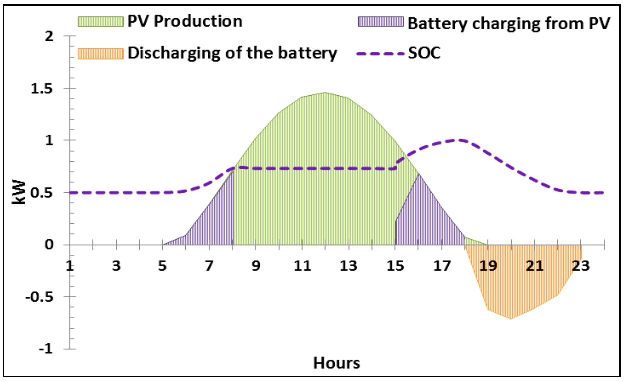


Figure 17. Power flow between the battery and PV generation.

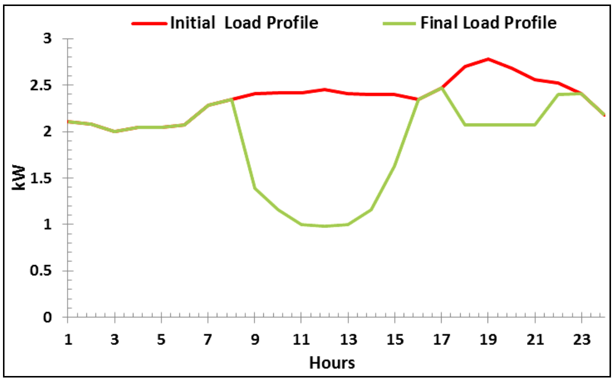


Figure 18. Effect of fourth scenario on load demand.

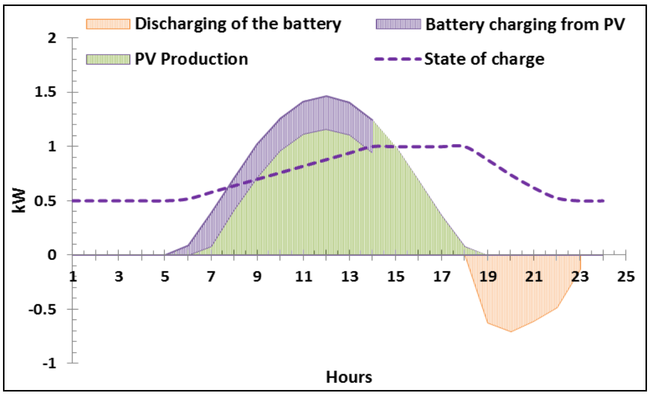


Figure 19. Operation of constant charging power method.

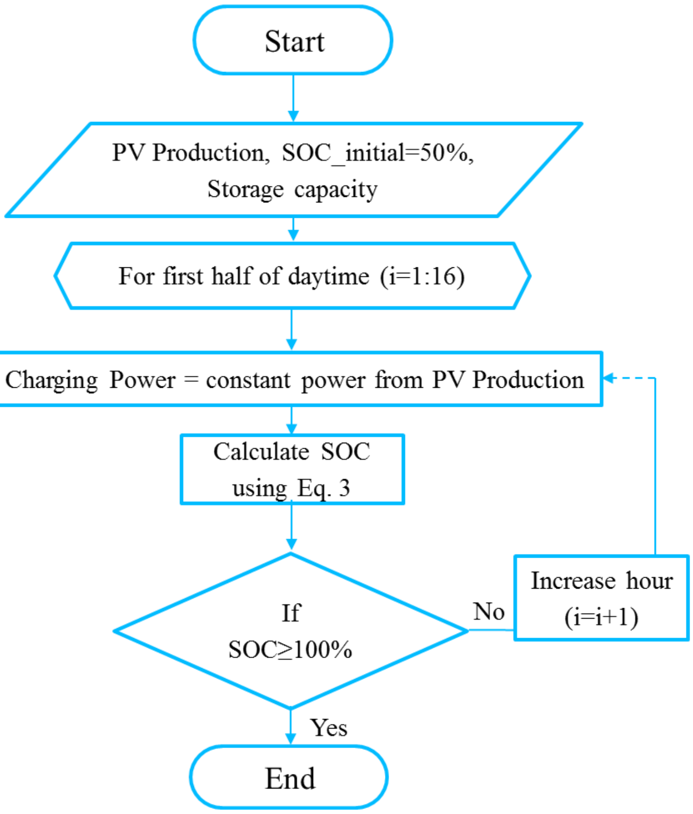


Figure 20. Flowchart of fifth scenario for storage energy.

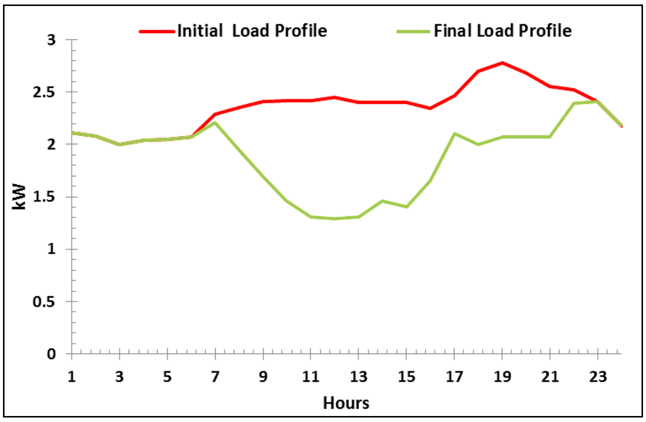


Figure 21. Effect of fifth scenario on load demand.

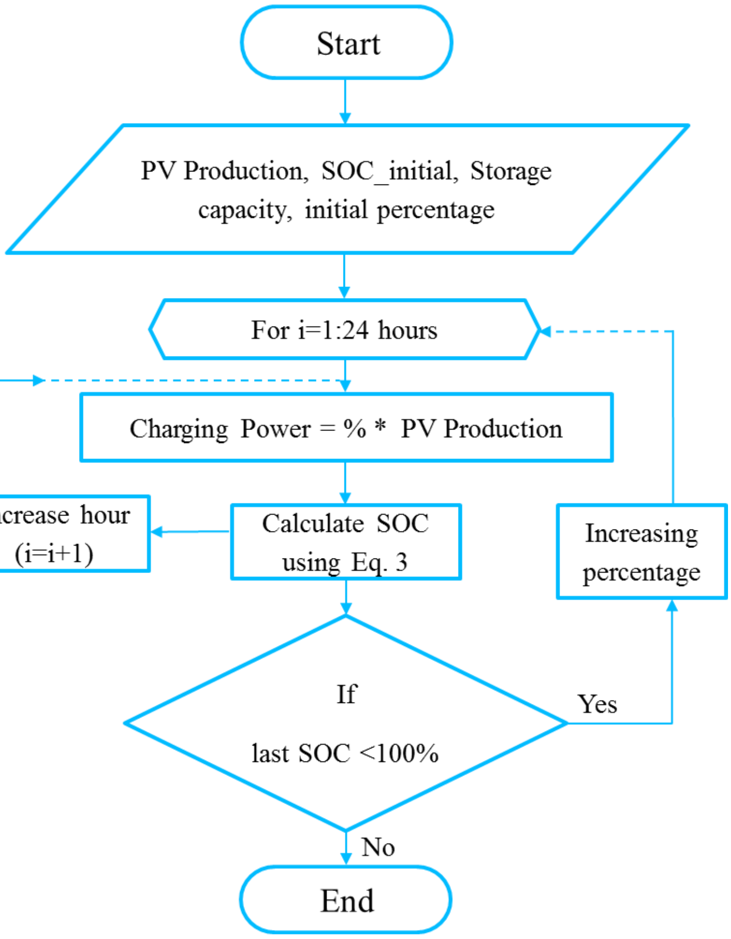
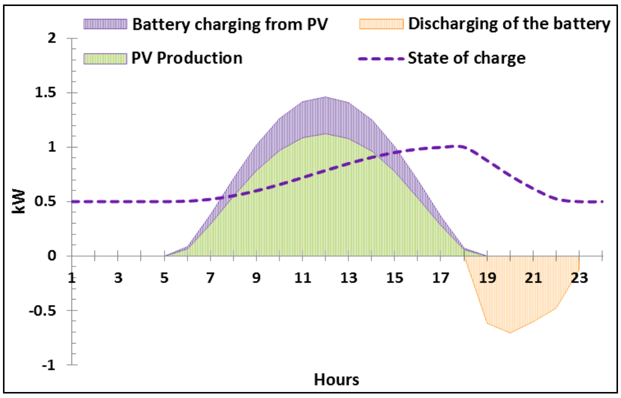


Figure 22. Flowchart of sixth scenario for storage energy.



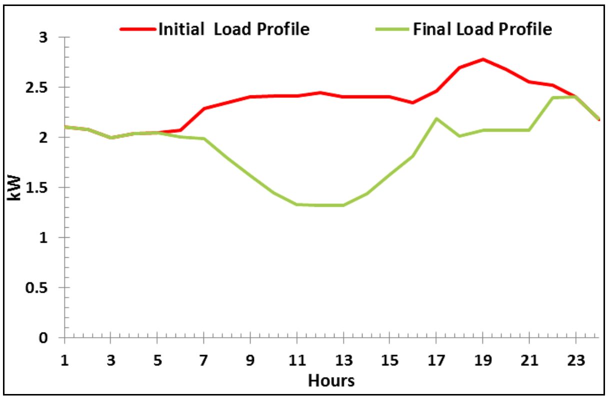


Figure 23. Simulation results of sixth scenario. Figure 24. Effect of sixth scenario on load profile.

The resulting load profile for all scenarios by using MATLAB is as shown in Figure 25. It is clear that the solar generation reduces or clips the peak load in the daytime while the battery shaves the peak load in the night (this is the application of demand side management). Furthermore, there are a surplus energy produced in the high period generation at noon time which can be either utilize by application the load-shifting technique or by selling this power to the utility companies.

All previous control methods are applicable but depending on the application of traditional demand side management, i.e. depending on the tariff (unit price of electricity) in which imposed on the consumer. Therefore, the consumption of electricity will be as shown in scheme in Figure 26. In the high price electricity unit periods of grid, the consumer takes electricity from PV panels and battery system as well as the grid, while in the low price periods, the energy is drawn from grid whereas the PV panels charge the batteries or supply loads or sell residual energy to the utilities.

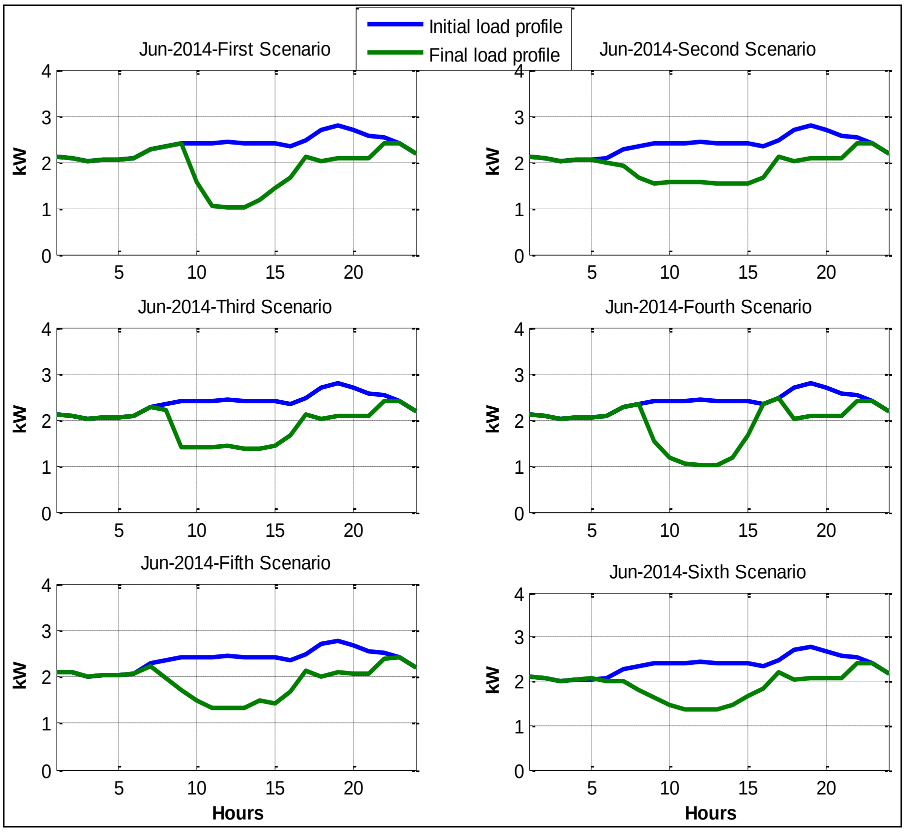


Figure 25. Initial and final load profile with including PV and battery systems.

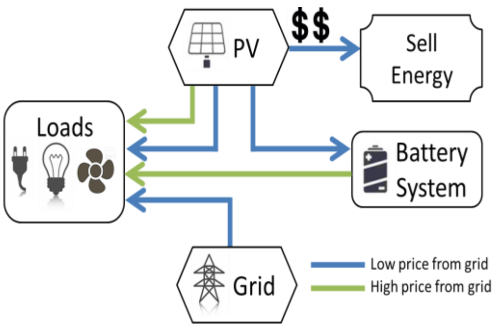


Figure 26. Power flow scheme between grid, PV panels and battery system.

4. Conclusion

In this work, a 500Ah 12V battery system for each residential consumer is suggested in order to clip the peak load at night as well as to store the surplus energy produced from solar cells. Then, six scenarios for storage energy is suggested to improve the load profile shaping and to reduce the losses energy produced from PV system. The using of battery system with storage energy scenarios provides an active demand side management (ADSM). The application of ADSM is depending on the implementation of the traditional demand side management. Traditional DSM means imposing tariff structure to make consumer know the worth of energy (DSM as for consumer means reducing electricity bill). Therefore, this work is still limited unless imposing tariff structure upon the consumer. For future work purposes, this study can be more analyzed and more important based on the economic dispatch and analysis.

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