International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 8 Issue 6 Ser. I ǁ 2020 ǁ PP. 11-18

Solar Photovoltaic and Battery Energy Storage System Design for a Constant Direct Current Bus Voltage Regardless of Fluctuations

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Date of Submission: 07-07-2020 Date of acceptance: 22-07-2020

I. INTRODUCTION

The design of an effective and efficient system is essential to the optimum utilization of solar power via photovoltaic or PV cells to generate electricity, especially considering the power fluctuations resulting from environmental conditions such as solar irradiance, temperature, and other weather-induced factors

II. BACKGROUND ON THE DISADVANTAGES OF SOLAR POWER AND PHOTOVOLTAIC CELLS

Note that the photovoltaic effect and solar cell theory provide the foundational mechanism behind the operations of PV cells. The photovoltaic effect is specifically a physical and chemical phenomenon first demonstrated by Edmond Becquerel in 1839 (Guarnieri, 2015) that involves the change of current between two separate electrodes due to unsymmetrical illumination (Copeland, Black, & Garrett, 1942). Electricity generation transpires because the absorption of light excites the electron, thereby bringing it to the higher-energy state (Bagher, Vahid, & Mohsen, 2015). In PV cells, three factors affect electricity generation: adsorption of light to generate the charge careers, the separation of charge careers, and the collection of these charge careers (Sharma, Jain, & Sharma, 2015; Bagher, Vahid, & Mohsen, 2015). The capacity of panels composed of PV cells to generate electricity effectively and efficiently depends on the amount and quality of available radiant energy from the sun. Hence, fluctuations due to solar irradiance, temperature, and other weather-induced factors determine the feasibility of using a PV system as a critical power source.

To expound further, a notable disadvantage of solar power via PV cells is the continuity or permanency of power generation. Remember that a PV panel can only generate electricity under broad daylight (Bhatia, 2014). It is fundamentally unusable during nighttime. Weather and environmental conditions such as overcast or cloudy weather, level of precipitation during rainy seasons or winter, and during the prevalence of dust or haze are also important performance indicators (Bagher, Vahid, & Mohsen, 2015). There are also concerns about geographical variability and compatibility. Some areas in the world render PV systems less practical because of their natural weather-induced temperature profile or insufficient amount of solar radiation they receive. For example, solar radiation in the tropics such as Southeast Asian countries is at an average of 0.25 kW/m2 while in northern European countries such as Hungary, it is only at 0.16 kW/m2 on average (Lakatos, Hevessy, & Kovác, 2011). PV panels alone are inherently unreliable energy sources because of the dependence of PV cells on environmental factors. Hence, an entry PV system needs to include other components that would address these factors.

Concerns over permanence necessitate the use of a suitable battery energy storage within the entire PV system to ensure a continuous supply of electricity to the load despite the inoperability and inconsistency of PV cells. Note that a battery also stores the surplus or unused power harvested by a PV panel.Nevertheless, there is a need to identify and utilize suitable battery technologies to maximize the use-case of installed solar panels under varying environmental conditions. Of course, storage provides additional costs and technical considerations to the entire PV system (Vega-Garita, Ramirez-Elizondo, Narayan, & Bauer, 2018). Effective and efficient battery technology and overall storage system supplement and partly determine the overall effectiveness and efficiency of PV cells, the entire solar panel, and the specific PV system (Steffens, 1991). More specifically, the performance of a PV system depends on the design of the battery storage, as well as the operating conditions and maintenance of the battery. It is critical to take into consideration factors such as functions, types, aging factors, recharging capacity, and protection methods when choosing and deploying a specific system for battery storage (Ponnusamy, Harikumar, & Raghavan, 2013). Nevertheless, the fact remains that solar power via PV cells is an intermittent source of renewable energy, and technologies pertaining to battery energy storage are essential in the overall design of an effective and efficient PV system.

There are also other inefficiency issues stemming from the type and components of a particular PV cell. To start off, so-called first-generation panels based on silicon are also large, heavy, and bulky, thereby consuming a large amount of space if there is a higher requirement for power or electricity generation (Sharma, Jain, & Sharma, 2015). On the other hand, those second-generation panels based on thin-film semiconducting materials are considerably thinner than their first-generation counterparts. Still, they require an expansive surface area to generate power that can rival their first-generation counterparts (Bagher, Vahid, & Mohsen, 2015). Aside from choosing among the different types of solar panels, it is also important to take into consideration variations in the use of specific components or materials, the inclusion of enhancements, and the application of novel technologies or innovations. When considering the general efficiency of PV systems and solar panels, including PV cells, it is important to take into consideration the rate at which sunlight is converted into power and how this relationship changes over time (Jordan & Kurtz, 2013). Cost should also be taken into consideration when designing or evaluating the effectiveness and efficiency of a PV system. Remember that PV panels are costly to purchase and install, which negatively impacts the cost efficiency of the entire PV system (Bhatia, 2014). Essentially, the disadvantageous aspects of developing and fabricating PV cells, as well as of manufacturing and assembling PV panels, affect the feasibility of a PV system in terms of cost and economic value

III. THE MAJOR COMPONENTS OF A PHOTOVOLTAIC SYSTEM

A typical PV system has four major components. These are the photovoltaic array, a solar charge controller, inverter, and storage system via battery devices. The following are concise details of each component:

3.1. Photovoltaic Array

The building block of a PV system is the PV array or PV panel composed of several PV modules, which, on the other hand, are composed of PV or solar cells. These cells are electronic devices made primarily of semiconducting materials that convert light into energy through the photovoltaic effect. To be more specific, semiconductors that exhibit the photovoltaic effect can convert solar radiation into direct current electricity, thus generating electrical power (Bhatia, 2014). The array is essentially an assembly of PV modules, which, on the other hand, is a collection of individual photovoltaic cells.

Nevertheless, the array should be mounted on a stable and durable structure that could withstand environmental factors such as wind, rain, and hail. A guideline by the Office of Energy Efficiency & Renewable Energy of the U.S. Department of Energy (2013) noted that the mounting structures should tilt the PV array in a fixed angle determined based on the maximum exposure to direct sunlight. However, mechanical mounting structures with a solar tracking system automatically adjust the angle and spatial orientation of the PV array based on the direction of sunlight or weather conditions.

3.2. Solar Charge Controller

PV cells often produce irregular levels of voltage and current. They are either too high or too low. Note that this voltage and current come from the PV cells and go to the battery storage system or directly to a load. The variations can overcharge the battery or overload and underload a particular appliance. A solar charge controller regulates the incoming voltage and current to prevent damage to the battery and appliance, prolonging their lifespan (Oo, Lwin, & Tun, 2016). It is included in a PV system primarily to extend the life of its battery storage component, as well as to ensure a consistent flow of power to the load.

There are two types of solar charge controller: pulse width modulation or PWM and maximum power point tracking or MPPT (Singh et al., 2017). A PWM charge controller tapers the current from the PV array by adjusting the duty ratio of switches based on the condition of the battery and charge status. For example, it slowly reduces the charging current based on an algorithm when the voltage of the battery reaches the regulation set point, thus preventing overheating and gassing. Key advantages of this type of solar charger include charging efficiency, overheating prevention, reduction of stress from current and voltage variability, prolonged battery life, and reversing battery sulfation.

On the other hand, an MPPT charge controller is more advanced and expensive than a PWM. Based on a synchronous buck converter circuit, it adjusts the voltage from the PV array according to the charging voltage of the battery, while also choosing the ideal maximum power point or current-voltage point on the current-voltage curve. Take note that it specifically maximizes the power from the PV array by adjusting the input voltage to respond efficiently to the varying voltage requirement of the battery and the load. The advantage of MPPT over PWM include more precise regulation, maximum power utilization, and performance invariability under cold temperatures. Both PWM and MPPT will have the same performance when used in a PV system placed under a tropical and subtropical climate, but the former would perform considerably less under cold temperatures, thus making its use-case subjective and relevant due to its inherent operating temperature requirement.

3.3. Solar Inverter

A PV array produces a variable direct current or DC as an output. However, when connecting the entire PV system into a commercial electrical grid or a localized off-grid network, there is a need to use a solar inverter to convert the DC output into alternating current or AC. Note that most appliances used in residential and commercial settings also require AC input.

There are several types and configurations of inverters, according to the Office of Energy Efficiency & Renewable Energy (2013). A single inverter is the most common configuration integrated into a PV system. It is less expensive and requires fewer maintenance because it can be cooled and serviced easily when needed. So-called microinverters are integrated into individual PV modules of a PV system. Their use-case centers on the variability of exposure to radiant energy of each module, thereby making them useful in large PV systems. However, they need to be replaced once every 25 years. They are also considerably expensive than a single solar inverter.

Smart inverters are advanced solar inverters used by utility providers. They allow providers to communicate with inverters and the PV system from a distance, provide insights into supply and demand trends, enable automation, promote the stability of the electricity grid, and lessen the possibility of power outages.

3.4. Battery Storage

Remember that a specific storage system using batteries is crucial to address the continuity and permanence issues of a PV system. The performance of such a system depends on the design of a storage system, including the choice of batteries (Ponnusamy, Harikumar, & Raghavan, 2013). Essentially, the purpose of these batteries is to store energy during daytime or, more specifically, while the PV modules and PV cells are gathering and converting radiant energy into electricity. Charged batteries allow the uninterrupted power supply to homes equipped with PV systems. However, batteries also play a role in stabilizing electrical grids, including localized community and commercial grids (Office of Energy Efficiency & Renewable Energy, 2013).). Effective and efficient battery technology and overall storage system increase the use-case rationale of solar power through PV systems (Steffens, 1991).

IV. ADDRESSING FLUCTUATIONS THROUGH BATTERY AND PV MODULE SELECTIONS

4.1. Optimal Battery Technology for a Specific Storage System

Remember that a specific storage system is essential in the design of the entire PV system to address the reliability issues of solar power due to the variability in environmental conditions. Rechargeable batteries remain the most feasible solution for designing and implementing this storage system. Note that these batteries store surplus power from the PV system so that electricity remains available during nighttime or adverse weather conditions (Ponnusamy, Harikumar, & Raghavan, 2013). However, there are different types of battery technologies conventional lead-acid battery, valve regulated lead-acid battery, nickel-cadmium battery, and lithium-ion battery. Note that lead-acid batteries are the most inexpensive and reliable, but they have a shorter lifespan and lower energy density than other battery types. They are typically employed in small-scale, residential PV systems. The most promising battery technologies are based on lithium-ion, but they are more than thrice as expensive as lead-acid batteries and costlier than nickel-cadmium batteries (Hoppmann, Volland, Schmidt, & Hoffmann, 2014).

Despite the higher cost, lithium-ion batteries have several advantages. Aside from the fact that it has higher energy density than lead-acid batteries, it has the capacity to store higher power or charge (Ponnusamy, Harikumar, & Raghavan, 2013), researchers have argued that it would soon become a primary choice for mainstream PV system because of its better aging features and higher energy efficiency (Braun, Büdenbender, Magnor,& Jossen, 2009; Divya& Østergaard, 2009;). Note that it also has both higher volumetric and gravimetric energy densities than other rechargeable battery technologies due to its higher operating voltage of 4V, which on the other hand, stems from its utilization of water-free, non-aqueous electrolytes compare. Other rechargeable batteries use aqueous electrolytes that limit their operating voltage to less than 2V (Manthiram, 2017). Other advantages of lithium-ion batteries include low self-discharge property that allows more extended idle storage or inoperability compared to other batteries, a longer lifespan that translate to energy and cost efficiency, minimal internal resistance for keeping direct current constant, nearly zero memory effect that would enable incomplete discharge and prolong further their lifespan, and a high open-circuit voltage that represents their full voltage value (Kim et al., 2019).

The prominent applications of lithium-ion batteries are in consumer electronic devices. In fact, advancements in the development of technologies and innovations in devices such as laptop computers, tablet computers, smartphones, and wearable devices have been due in part to this battery technology. Using lithium-ion batteries had enabled the development of power-intensive and high-performing consumer electronic devices with a smaller physical profile (Nitta, Wu, Lee, Yushin, 2015; Manthiram, 2017). The technology has also seen an increased application in electric and hybrid vehicles due to the advantages mentioned above. Furthermore, it has also been considered as a critical innovation in the promotion of grid-energy storage systems for renewable, albeit intermittent energy sources such as solar power and wind power (Biomgren, 2016; Walter, Kovalenko, & Kravchyk, 2020).

Of course, there are known disadvantages and limitations. These batteries can be a safety hazard because they contain electrolytes that are susceptible to combustion due to overheating or short-circuit charging, thus resulting in a thermal runaway phenomenon. A specific module could also swell, resulting in explosion and damage to both the battery itself and the system in which it was integrated (Wang et al., 2012). Apart from overcharging or subjected the battery to excessive levels of electrical load, physical damages due to mishandling and improper storage could also trigger explosion and fire (Chen, Liu, He, Yuen, & Wang, 2017). There is also the issue of voltage limits. The cells of these batteries are predisposed to chemical stress when subjected to a voltage ranges 2.5 and 3.65/4.1/4.2 or 4.35V. The excessive voltage could result in premature aging, performance degradation, and thermal runaway because of the reactive nature of the battery cells (Väyrynen & Salminen, 2012).

Despite their drawbacks, lithium-ion batteries, they remain a promising battery technology. Several case studies have observed and analyzed the performance of lithium-ion batteries as a specific storage system in various iterations of PV systems. One study involved the use of an iron phosphate type of lithium-ion batteries. Results revealed that the configuration achieved 14.5 percent solar energy to battery charge conversion efficiency, an overall PV system efficiency of nearly 15 percent, and a battery charging efficiency of almost 100 percent (Gibson & Kelly, 2010). Another study compared different lithium-ion configurations to include lithium cobalt oxide or LiCoO2, lithium nickel oxide cell or LiNiO2, lithium nickel cobalt aluminum oxide, lithium manganese oxide or LiMnO2, and lithium iron phosphate or LiFePO4. Results from previous studies point to the fact that LiFePO4 batteries are one of the more stable and mature lithium-ion technologies. Nonetheless, based on the literature and an emulated integrated model, results revealed that LiFePO4 is the most suitable configuration for a PV system with an integrated battery storage system due to its better tolerability when it comes to temperatures variance and different charging-discharging profiles (Vega-Garita, 2019). Note that the cost of these batteries is higher than lead-acid batteries and other rechargeable counterparts, an analysis based on multi-parameter economic model revealed that prices are actually decreasing due to commercialization and further technological advancements. The analysis concluded that given the baseline lifespan of lithium-ion batteries, as well as the price trends in the market, using them in a PV system is cost-efficient. The profitability dimension could soon be achieved with further developments in technology (Naumann, Karl, Truong, Jossen, & Hesse, 2015).

4.2. Optimal PV Module for More Efficient Solar Power Generation

Of course, when designing an efficient PV system, it is also essential to select the optimal PV technology that could efficiently capture radian energy for storage. First-generation PV panels based on silicon are the earliest and most popular PV technology due to their high power efficiency. Data from 2015 indicated that approximately 85 to 90 percent of PV systems used in the market are based on silicone technology or, more specifically, the combination of mono-crystalline and multi-crystalline silicon cells (Cengiz, 2015). However, significant drawbacks revolve around the fact that the resulting panels require the utilization of a large surface area because they are large and bulky. They are also expensive to manufacture and fabricate compared to other solar cell technologies (Sharma, Jain, & Sharma, 2015).

A more economical counterpart of first-generation PV technology is based on thin-film technologies. However, they are generally less efficient at power conversion. A notable contender is amorphous silicon or a-Si thin-film cells, a non-crystalline allotropic form of silicon (Parida, Iniyan, & Goic, 2011). It also has 40 times higher rate of light absorptivity than monocrystalline silicon, thus enabling it to become the top priority among all other thin-film technologies in the market (Mah, 1998). However, it only has a yield of only around 7 percent compared to the 18 percent of first-generation, silicon-based cells. This is due to the fact that it suffers from a degradation of 15 to 35 percent because of the Staebler-Wronski Effect mechanism (Bagher, Vahid, & Mohsen, 2015). A comparison between a-Si solar cells and first-generation cells concluded that the former needs considerable research and development to improve its performance, especially their efficiency (Gul, Kotak, & Muneer, 2016).

Numerous studies have explored ways of improving thin-film PV technologies. Using glasses with better quality, enhancing the transparency of oxides, introducing more sensitive and resistive films, employing a treatment to enhance light absorption, and higher deposition temperatures produced efficiency levels higher than 16 percent. The level increased further to 20 percent due to small-area cell conversion efficiency and improvement in champion module efficiency (Basol & McCandless, 2014). Other studies investigated the effects of adding substrates to the semiconducting material. Examples of these substrates include metals and compounds, insulator, rigid structure, and flexible structure, among others, as well as the use of different fabrication techniques to include plasma-based or hybrid processes. The inclusion of substrates can promote or tackle adsorption, reflectivity, contact, and buffer issues (Choppra, Paulson, & Dutta, 2004). Researchers are also improving the power conversion efficiency of PV cells by identifying and applying coating materials. The primary principle behind this method is to use anti-reflective coatings to increase light input or absorption of radiant energy, reduce optical losses, increase electrical yield, and improve the lifespan of the panels (Khan & Rahman, 2019; Rajvikram & Leoponraj, 2018). Nanocoatings allow protection of the surface from corrosion, the introduction of water-proofing or hydrophobic properties, and the prevention of surface material from developing blisters or lamination degradation. Some nanocoatings can improve the tensile and impact, as well as the thermal properties of materials (Nguyen-Tri, Nguyen, Carriere, & Xuan, 2018). A study revealed that a single-layer anti-reflective coating of silicon dioxide and with a thickness of around 100 nm resulted in an increase in efficiency of between 3 to 4 percent. However, a triple layer of the same compounds resulted in an improvement in the power conversion efficiency of up to 39 to 40 percent. A multi-layer coating of nanoparticles can significantly reduce the reflective property of solar cells, thus resulting further in better absorption of light energy (Vikas, 2015). Providing these panels with hydrophobic and hydrophilic properties can also improve further their efficiency. Another study applied a coating of greater than 600 nm of thickness to PV cells. Results indicated an increased absorption of light with a maximum value of 99 percent of the wavelength. These findings suggest that nanocoating can improve the absorption of lit across the visible spectrum (Baquedano, Torné, Caño, & Postigo, 2017).

V. DESIGNING A PV SYSTEM WITH AN INTEGRATED BATTERY STORAGE SYSTEM

The findings from the review and analysis of relevant results brought forth a conceptual framework for designing a PV system with an integrated battery storage technology that addresses fluctuations for a constant direct bus voltage. Note that two critical factors have been identified in this design: the choice of the battery technology for the storage system, and the choice of the PV technology that can effectively and efficiently capture solar power. Based on the results, lithium-ion battery technology and first generation, silicon-based OV panels with the nanocoatings constitute the major components of the system

It is also important to note that this suggested design is based on an assumption that the PV system is an off-grid renewable energy technology for use in a small household with a power consumption demand of 1,419.6 kw/H per month. The assumed consumption demand is based on the use of an 18 watt fluorescent lamp used for 4 hours per day, 60 watt fan used for 2 hours per day, and a 75 watt refrigerator that runs 24 hours per day.

The following are the sizing considerations:

- **PV Panel Option:** A single PV module has an average wattage of 200 watts. Considering the power consumption demand of the household, the PV system requires 8 PV modules with the excess wattage serving as a buffer.
- **Inverter:** The inverter is 200 watts based on the calculation of the total watts of all appliances, which is 153 watts. Note that an allowance has been made because an inverter should be around 20 to 30 percent bigger than the wattage consumption
- **Battery:** Below are the computation for the battery sizing requirement:

$$\text{Battery capacity} = \frac{[(18\text{ W x 4 hours}) + (60\text{ W x 2 hours}) + (75\text{ W x 12 hours})] \times 3}{(0.85 \times 0.6 \times 12)}$$

The formula was derived from the summation of total appliance use [(18 W x 4 hours) + (60 W x 2 hours) + (75 W x 12 hours)]; nominal battery voltage of 12 V; and a 3-day allowance for self-sufficiency. Based on the computation, the required total ampere-hours is 535.29 Ah. Hence, the battery should be rated at 12 volts with a 600 Ah to power the entire household with allowances for a 3-day autonomy.

Below are other critical considerations for the design of the PV system:

- **Charge Controller:** Remember that a PV system with an integrated battery storage system requires a solar charge controller to regulate the incoming voltage and current to prevent damage to the battery and appliance, prolonging their lifespan. The recommended type of charge controller for the proposed PV system is a maximum power point tracking or MPPT charge controller. Note that it specifically maximizes the power from the PV array by adjusting the input voltage to respond efficiently to the varying voltage requirement of the battery and the load. It also has the advantage of precise regulation, maximum power utilization, and performance invariability under cold temperatures, as well as operability despite cold weather conditions.

- **Nanocoating:** To ensure efficiency of the entire PV system, nanocoating has also been included in the suggested design. It is important to reiterate the fact that the chosen PV panel has an assumed capacity of 200 watts per module. However, this is an average. The wattage can be lower or higher, depending on environmental and external factors such as weather conditions. To ensure a 200-watt or higher operation, the addition of nanocoating is essential. Studies revealed that it can increase efficiency by 16 percent because it tackle adsorption, reflectivity, contact, and buffer issues, as well as issues concerning the absorption of radiant energy, reduced optical losses, increased electrical yield, lowered maintenance requirement, and improved lifespan.

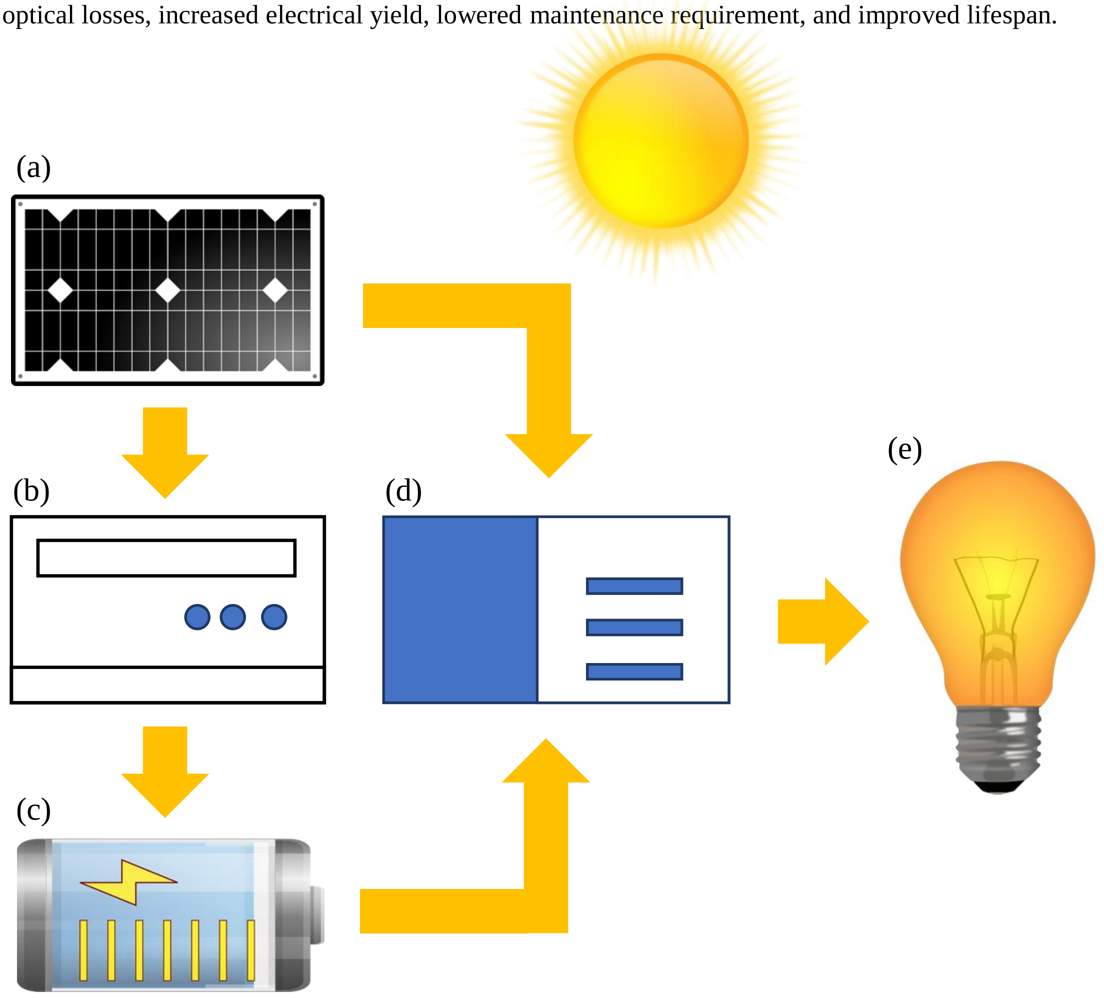

Fig. 1. The proposed V system design with integrated battery storage system for a small household with a power consumption demand of 1,419.6 kw/H per month: (a) photovoltaic panel with 8 PV modules, each an average wattage of 200 watts; (b) a solar charge controller for regulating voltage and current; (c) a lithium-ion battery or a set of lithium-ion battery at 12 volts with a 600 Ah to power the entire household with allowances for a 3-day autonomy; (d) a 200watt inverter; and (e) the load.

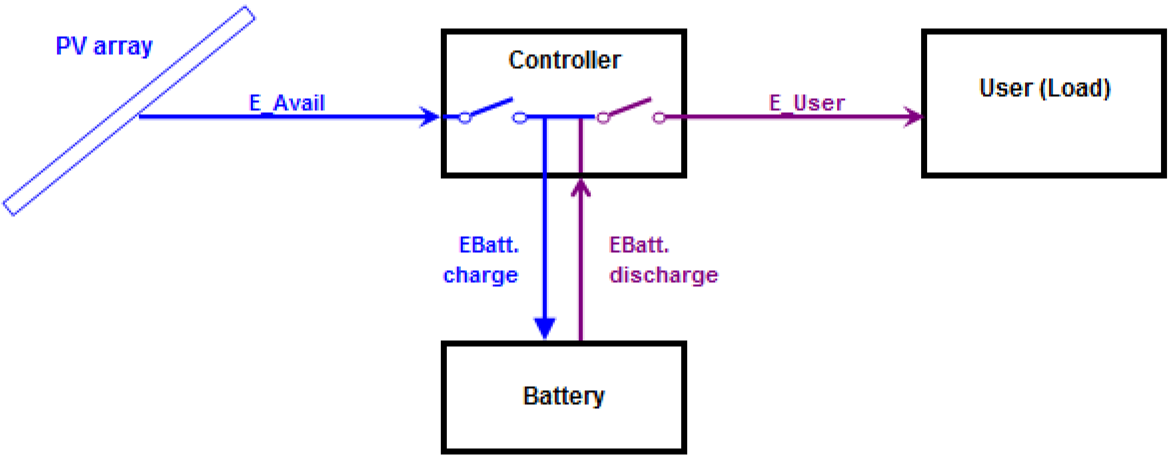

Fig. 2. A simplified off-grid PV system with integrated battery storage system showcasing a configuration that uses a controller to switch between a direct PV-to-load flow of generated electricity and an indirect PV-to-battery-to-load indirect flow of electricity from the panel and the storage, to the load.

Based from the framework, several components and characteristics are critical to the design of a PV system with internal battery storage that provides a constant source of power regardless of fluctuations in the major source of energy. The first component is the actual PV panel. Regardless of the type and built characteristics, the specific PV modules should have a considerable level of efficiency based on industry benchmark. The first-generation PV cell technology remains the most practical choice. Efficiency is important because it represents the capacity of the individual PV cells and the entire PV panel to capture radiant energy from the sun and convert it to DC. The panel should always maximize energy absorption and conversion. The second critical component is the battery storage. Lithium-ion battery has been considered an ideal choice despite its cost because of its longer lifespan, higher recharge count, and low internal resistance that assures effective storage of energy surplus and delivery of power to the load. Other factors that contribute to the overall efficiency of the system are the choice of the charge controller and inverter. These devices are essential in the entire PV system, especially for power households or communities, because they provide protection to the battery and load by regulating inconsistencies in voltage and current levels.

VI. CONCLUSION

The PV system with internal battery storage design presented in this paper identified major components and their respective characteristics for constant direct current regardless of fluctuations due to environmental or external factors. Of course, it is important to note that the presented framework remains conceptual. Further studies should focus on its application in real world settings, as well as in setting involving higher power consumption requirements. Nevertheless, the design remains grounded on established findings from the literature. In designing a PV system, it is also important to take note of the compatibility of the components to the power consumption requirement and the specific use-case scenario. Not all components and system are designed the same.

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