International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 11 Nov. 2025, pp: 170-178 www.ijaem.net ISSN: 2395-5252

Design and Development of a Solar Power Plant in Order to Reduce Over Reliance on Hydropower

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Date of Submission: 05-11-2025 Date of Acceptance: 15-11-2025

ABSTRACT
Zambia's electricity generation is highly dependent on hydropower, which exposes the country to power deficits during periods of low rainfall. This over-reliance has been especially evident during droughts, where reduced water levels in reservoirs have led to significant electricity shortages. The main objective of this study is to design and develop a small-scalable solar power model aimed at understanding how solar energy power generation can reduce Zambia's dependency on hydropower and enhancing its energy resilience. The research combines a comprehensive literature review with practical experimentation to develop a small solar power plant that can integrate effectively, thus translating into scalable solar plant.The study highlights the importance of diversifying Zambia's energy mix, emphasizing the potential of solar energy to provide a reliable, environmentally friendly, and cost-effective alternative.The proposed prototype features a 30 W solar array charging a 12 V DC battery; the stored DC power feeds an inverter that converts it to AC, which is then stepped up by a transformer for transmission. From thefindings, the benefits of solar energy are a sustainable, cost-effective compared to hydropower. Diversifying Zambia's energy sector in this way can strengthen the nation's energy security and help manage climatic related impacts.
Keywords; Hydropower**,** Transformer, Solar energy**,** Inverter**,** Battery

I. INTRODUCTION

Energy is a critical component of socioeconomic development, driving industrial growth, technological advancement, and improved living standards. In Zambia, the electricity sector has historically relied heavily on hydropower, which accounts for more than 80% of the nation's energy generation. While this has served the country well in the past, overdependence on hydropower has made Zambia's power supply system vulnerable to climatic fluctuationsparticularly droughts that lead to reduced water levels in reservoirs such as the Kariba Dam. The recurring energy crisis of recent years have exposed this vulnerability, underscoring the urgent need to diversify the national energy mix.

Motivation

This paper illustrates Zambia's unique opportunity to harness its untapped solar potential, contributing to a more diversified and resilient energy mix.

Scope

This study was limited geographically to Zambia, and it focused on the role of solar power station in Zambia basically the generation, transmission, and distribution about System components, design, and operation by developing a prototype solar power plant.

Problem Statement

The over-reliance on hydropower has exposed Zambia's energy sector to vulnerabilities, particularly during periods of low rainfall. This paper proposes a solar energy model aimed at enhancing the country's energy security.

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General Objective

The main objective of this research was to enhance Zambia's energy resilience through solar based power generation for efficient transmission to reduce over reliance on hydropower generation.

Specific Objective

1. To elect solar modules and array for the prototype solar power generation.
2. To construct overhead power transmission line that which will support the cables or conductors.
3. To install power transformers that will regulate energy levels to desired values.
4. To connect electric cables that will carry generated power from the power plant to the load.

Research questions

1. How do you elect solar modules and array for the prototype solar power generation?
2. How do you construct overhead power transmission line that which will support the cables or conductors?
3. How do you install power transformers that will regulate energy levels to desired values?
4. How do you connect electric cables that will carry generated power from the power plant to the load?

II. LITERATURE REVIEW

The global energy landscape is transitioning from reliance on fossil fuels to renewable sources, addressing challenges like climate change and energy security. Developed nations are prioritizing investments in solar and wind energy, while emerging economies like Zambia face the dual challenge of expanding energy access and reducing carbon emissions (Mwansa Kaoma et al. 2015). This study situates Zambia's solar energy potential within this global context, highlighting its role in mitigating the country's energy crisis and contributing to a sustainable energy mix.

According to Roger and Jerry (2004) the history of photovoltaic energy or solar cells started way back in 1876 in United States of America. William Grylls Adams along with a student of his, Richard Day, discovered that when a solid material - selenium was exposed to light, it produced electricity, Selenium photovoltaic cells were converting light to electricity at 1 to 2 percent efficiency. An electricity expert, Werner von Siemens, stated that the discovery was scientifically of the most far-reaching importance, that certain materials produced small amounts of electric current when exposed to light. The selenium cells were not efficient, but it was proved that light, without heat or moving parts, could be converted into electricity. In 1957, Calvin Fuller, Gerald Pearson, and Daryl Chapin, of Bell Laboratory, patented a way of making electricity directly from sunlight using silicon-based solar cells. The trio discovered the silicon solar cell. This cell produced enough electricity and was efficient enough to run small electrical devices. This discovery was the beginning of a new era, leading eventually to the realization of harnessing the almost limitless energy of the sun for the uses of civilization. (Pathak M, Girotra, 2012) Photovoltaic, or PV for short, is the word that describes converting sunlight into electricity: photo, meaning pertaining to light and voltaic meaning producing voltage. It took, more than 100 years, however, for the concept of electricity from sunlight to become more than just an experiment.

Solar has become the world's favorite new type of electricity generation, according toInternational Energy Agency(IEA) and International Renewable Energy Agency (IRENA) showing that more solar photovoltaic (PV) capacity is being installed than any other generation technology. Worldwide, some 71-73 gigawatts of net new solar PV capacity were installed in 2016. Wind energy came in second place (55GW), with coal relegated to third (52GW), and followed by gas (37GW) and hydro (28GW).

According to the International Energy Agency (Africa Energy Outlook, 2014), Africa's energy sector is crucial to its future development because it remains one of the most poorly underdeveloped regions within the global energy industry. Though Africa is endowed with energy resources which are more than sufficient to meet domestic needs, more than two-thirds of its population does not have access to modern energy. Those that do have access to modern energy very often experience high prices for supply that is of poor quality and rely on an under-developed system that is not able to meet their needs. Therefore, effective development of Africa's energy resources, could unlock huge gains across the economy.

Furthermore, presently in Africa, a severe shortage of essential electricity infrastructure was undermining efforts to achieve more rapid social and economic development (Mwanza et al. 2017). For the minority that have a grid connection today, supply is often unreliable and costly.Even the use of back-up generation to produce electricity is also costly, (e.g., running on diesel or gasoline). Urban populations in sub-Saharan Africa have seen the fastest growth in electricity access compared to rural areas, though service reliability remains a major challenge (Afrobarometer, 2022).Notably, reform programs have started to improve efficiency and to bring in new capital, including from private investors, and off-gridbased generation.

As described by (Tasmania Government, 2012) Tasmania is part of the NEM, which is a wholesale market in which generators sell electricity in eastern and southern Australia. The NEM covers five regions Queensland, New South Wales Victoria, South Australia, and Tasmania that are physically linked by an interconnected transmission network.Its electricity generation is primarily hydro and, as a result, the state is highly dependent on rainfall for electricity generation. Peaking capacity is provided by four gas turbines, with base load capacity from a combined cycle plant, all of which comprise the Tamar Valley Power Station. Due to high water levels and the interconnector, the combined cycle plant was thought to be redundant and was decommissioned in 2014 to be subsequently sold. However, on 20 December 2015 Bass link had to be shut down due to a cable fault offshore. This event coincided with a particularly dry period, leaving dams severely depleted, which meant that Tasmania’s security blanket for such times of drought had been lost. Actions taken to minimize the consumption of water from Hydro Tasmania's storages included:

- Recommissioning of the gas-fired Tamar Valley Power Station
- Striking agreements with the three major industrial customers – the two Tamar Valley smeltersBell Bay Aluminum and TEMCO, and Norske Skog's paper mill at Boyer - to reduce their load by a combined 180 MW
- Deploying up to 200 MW of portable diesel generators
- Bringing Hydro Tasmania's cloud seeding programmed, usually scheduled to start in May each year, forward by a month.

Despite these actions, during the 2016 energy crisis in Tasmania, wholesale electricity prices rose sharply, and the state faced significant economic risk(AER, 2016). Fortunately, the gas pipeline from the mainland was still operational so that emergency supplies for the gas-fired power plants could still be delivered. The moral of this event is very clear: energy security is an essential element of any power system. In addition, diversity of energy technologies is an important aspect of energy security, as is diversification of supply sources.

The 2014-16 Brazilian drought was a severe event that affected the southeastern part of the country, including the major metropolitan areas of São Paulo and Rio de Janeiro (Coelho, 2016). This drought led to significant water shortages, high temperatures, and other severe impacts on the region. As over seventy percent of Brazil’s electricity is generated by hydropower there was concern that a lack of water may also lead to energy rationing in addition to water rationing Jon (Gerberg, 2015). Thermal plants were used to fill the energy gap, but the switch was very costly. In response to decreased hydroelectric power, rolling power cuts were also instituted. A novel approach to the problem was to install floating PV arrays on the dams to generate power when water supplies were depleted. The logic behind placing solar panels on dams is that hydro acts as a back-up for the variable output of the PV and utilizes the same transmission infrastructure. Thus, water is saved during daylight hours. In addition, one of the most expensive aspects of grid scale PV is its associated transmission requirements which are avoided in this situation. Floating solar panels are more efficient than land-based arrays, largely since they have water on hand to cool them down. (Phillips, Dom, 2014) Float voltaic is also appealing because it is cheaper to float panels over water than to rent or buy land. They can be constructed more quickly than land-based installations, and more easily tucked out of sight. Finally, floating arrays also shade the water and consequently reduce algae blooms and water evaporation. Brazil’s first floating solar arrays came on-line in March 2016.

Gaining a wide and comprehensive understanding of the chosen subject area, a literature review was completed. The literature review included the reading of a range of textbooks along with credible internet sources journals and practical experience. Relevant aspects of these sources were then used to formulate notes, which were then used in their relevant section of the report. The knowledge

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gained from the literature review was then applied to design and develop solar power plant and transmission line. Materials listed below were procured and arranged as the required by the designed and developed system. Below are the hardware specification and system block diagram.

System Design:

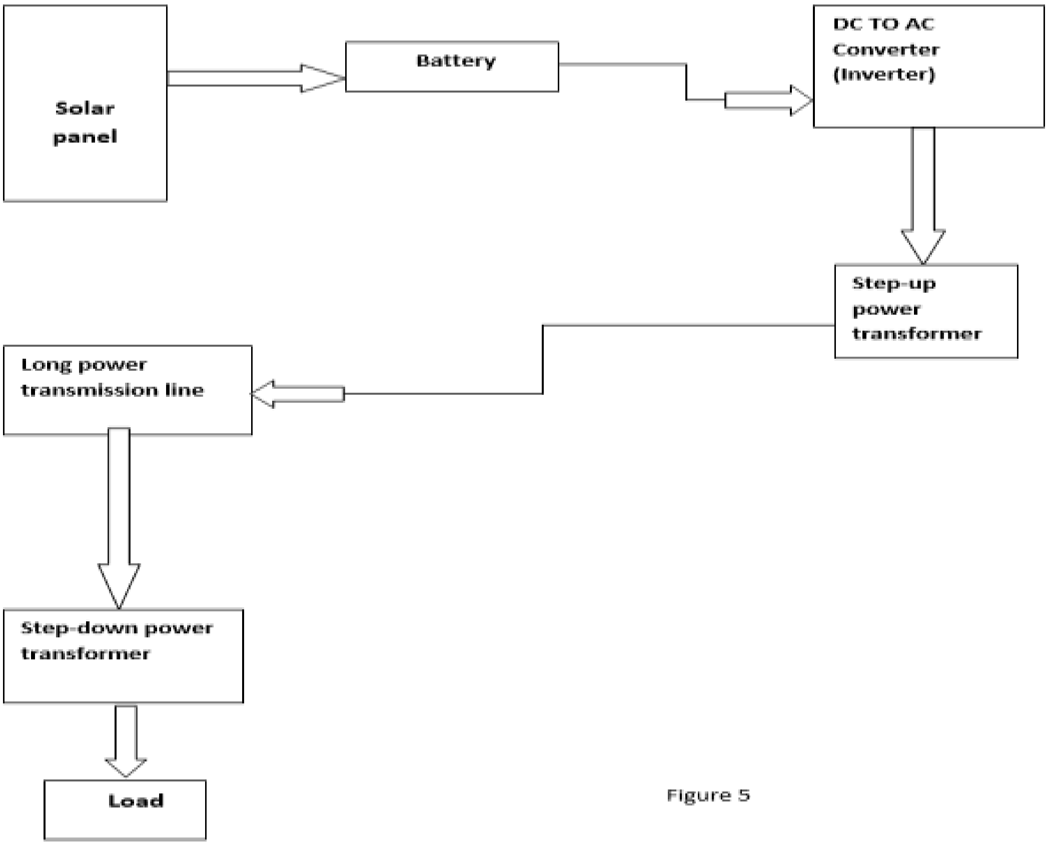

Figure 5

III. RESULTS

This project required examining the concepts of how a solar power plant system worked and how to connect the panel, the batteries, the step-up transformer, the inverter, the towers, the step-down transformer, and the load together.(Russell,Scott, 2005) Investigating commercially available systems assisted in determining what equipment is required to build a complete solar power plant structure as shown above. The next stage was to establish the equipment necessary to operating the system so it would be durable and cost effective. The design of the system began with the number of lumens needed to illuminate a predetermined area. This information established the wattage and the types of lamps that fit the criteria. The most common types of lamps currently used for outside lighting are the high-pressure sodium and the low-pressure sodium lamps. The determination of the lamp dictated the wattage of the solar panel and the batteries. The panel rating established the number of batteries and the type of controller that was necessary to handle the voltage and current outputs. The 100-watt high pressure sodium bulb was selected for this study because it provided the necessary 9,500 lumens to fill the needs of the project, matched the lamps used on city streets, and had a fast start-up time. The energy usage of the lamp determined the number of amp hours the battery would have to provide without recharging for four days. Deep-cycle batteries using lead acid gel are designed to handle the strain of recharging and have longer life spans ranging from four to seven years, compared with the standard lead acid type with an average lifespan of less than three years. For a panel of more than 150W, the output voltage was 26V, dictating that the system needed two batteries connected in series to limit the current draw on the cells. To control the charging of the batteries, a maximum power point

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tracker was incorporated to deliver the optimal voltage to increase the efficiency of recharging.

Operation

In this research every solar panel contained photovoltaic cells. PV cells took light and turned the light into electricity. When sunlight stroked the solar panel, cells got to work by producing direct current (DC) electricity. Since a solar cell was the only generator in a solarpower system, it was one of the most important parts in a solar power system.

The light from the sun falls on the surface of the solar panelsand it's absorbed by the cells create thus electric current is produced. Figure 2 shows the process schematically. Red wavy arrows on the picture represent sunlight, and encircled minuses stand for electrons-negatively charged particles. Red arrows symbolize the direct electric current. In physics, this effect is known as photo-effect.

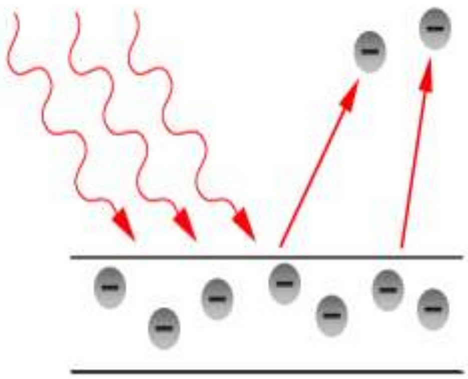

Figure. 2

The battery took the DC voltage and charged itself and stores the voltage for future use to supplement on voltage generation drop and ensure continuity of supply during bad weather. The direct current (DC) thus generated which was 12V DC was converted into an alternating current (AC) 12V with the help of a special tool called inverter. The 12 voltages AC was then fade to the step-up power transformer 12V/220V. The 12V was fade on the primary of the step-up power transformer which had few windings on its side. It reduced the value of current and raised the voltage value on the secondary of the step-up transformer since it had more windings to 220V from 12V AC. This high voltage was fade to the long transmission power line for efficient transmission to a step-down transformer which reduced the voltage value from 220V to 110V. Finally, the 110V was supplied to the load center (which was a lamp, and it became on.).

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Protection and earthling

It was a truism that electricity was dangerous and could cause accidents, if not treated with respect. A large part of any system design was concerned with ensuring that accidents will not happen, or that if they do, their effects will be limited. It might be reasonably argued that these considerations are the most important part of a design engineer's task. If these matters are given the care they deserve, the likelihood of faults on the electrical installation will be small. Nevertheless, it was still necessary to provide protection against such faults as may happen. (Yongqing, 2009) the general principle of protection is that a faulty circuit should be cut off from the supply and isolated until the fault can be found and repaired. The protective device must detect that there was a fault and must then isolate the part of the installation in which it had detected the fault (Wallington, 2010).

Two dangers to be prevented are fire and shock to people and livestock. In turn these dangers can arise from three kinds of fault, namely a short circuit, an overload, and a fault to earth. If through a fault in the wiring or in an appliance the line or phase and neutral conductors become connected, the current that flows are limited only by the sum of the resistance of the cables of the permanent wiring and the impedance of the accidental contact between the two cables the latter generally being regarded as negligible. If the fault connecting the line and neutral has a negligible impedance the two conductors are effectively short circuited. The current that flows through the conductors is a short-circuit current and is very high and if allowed to continue would burn the insulation. The high conductor temperature resulting from the excessive current could start a fire. If the excess current continues to flow further after the insulation had been damaged, there is also a possibility that the conductor might touch exposed metal and give a shock to anyone touching the metal. If the fault that connects the line and neutral had some impedance the current flowing through the fault and conductors is less than the current in a short circuit of negligible impedance. It is still likely to be higher than the maximum current the circuit can safely carry and if it persists over a period, it can cause serious damage. (Russell, Scott, 2005), when an over current is flowing in a circuit, which is electrically sound, it is described as an overload. A fault to earth occurs if through some defect the line conductor becomes connected to earthed metalwork. The effect is like a short circuit, but whereas a short circuit will not raise exposed metalwork, termed exposed conductive parts, above zero potential, an earth fault will.

Transformer protection

In this project both transformers (step up and step-down transformer) were protected by fuse protection. A fuse is a short piece of metal, inserted in the transformer circuit, which melts when excessive current flows through it and thus breaks the circuit. The fuse element is generally made of materials having low melting point, high conductivity, and least deterioration due to oxidation e.g., silver, copper etc.(Wallington, 2010), it is inserted in series with the circuit to be protected. Under normal operating conditions, the fuse element is at a temperature below its melting point. Therefore, it carries the normal current without overheating. However, when a short circuit or overload occurs, the current through the fuse increases beyond its rated value. This raises the temperature and fuse element melts (or blows out), disconnecting the circuit protected by it. In this way, a fuse protects the transformer from damage due to excessive currents. The time required to blow out the fuse depends upon the magnitude of excessive current. The greater the current, the smaller is the time taken by the fuse to blow out. In other words, a fuse has inverse time-current characteristics. Such a characteristic permits its use for over current protection. The function of a fuse is to carry the normal current without overheating but when the current exceeds its normal value; it rapidly heats up to melting point and disconnects the circuit protected by it. In order that it may perform this function satisfactorily, the fuse element should have the following desirable characteristics low melting point e.g., tin, lead, high conductivity e.g., silver, copper, free from deterioration due to oxidation e.g., silver, and low cost e.g., lead, tin, copper.

Transmission line protection

This project transmission line was protected by earth wire ground protection. The overhead earth wire or ground wire is the form of lightning protection using a conductor or conductors. It is attached from tower to tower above the transmission line and well-grounded at regular interval. The earth wire intercepts the direct lightning strikes, which would strike the phase conductors. The ground wire has no effect on switching surges. (Russell, Scott. 2005), when the lightning strikes an earth wire at mid-span, waves are produced which travel in opposite directions along the line. The waves reach the adjoining tower, which passes them to earth safely. The earth wire is effective only when the resistance between the tower foot and earth is sufficiently low. Overhead lines and substation equipment can be protected against direct strokes to a considerable extent by using earth or ground wires, which shield the equipment. There are non-shielding methods, such as use of lightning arresters and spark gaps. Shielding methods do not permit an arc to form between the conductor and ground. Hence, they are preventive in nature. In case of non-shielding devices, the overvoltage incident on the protective device is allowed to find a path to ground to discharge the surge and in general prevent the flow of dynamic current that follows thereafter. Therefore, they are often made of steel. The ground wires are solidly connected to ground at each tower in transmission and distribution system.

Solar, inverter and controller protection

The solar array, inverter and controller were protected by Ground fault protection. Ground fault protection ensures that if there is a short within the solar array, the current flow is cut off immediately. This averts the risk of damage to either the controller or the solar array, and significantly reduces the risk of electrocution. Ground fault protection works by measuring the current entering and exiting a circuit. If everything is working correctly, the current in should equal the current out. However, if there is a leak or a partial short circuit, the system will see a difference in current and immediately shut down. A partial short circuit could occur if a solar panel was broken or if somebody touched an exposed cable. Most solar inverters and solar controllers incorporate ground fault protection, using a Residual Current Device (RCD) built into the unit. For this project the ground fault protection for DC and AC circuits are separate: The ground fault protection is installed between solar panels, controller, and inverter to prevent them from being damaged and ensure safety of personnel. Furthermore, the ability to isolate parts of the system is important, especially while installing the system and carrying out maintenance therefore, a fuse between the battery and the controller and inverter is incorporated, so that If something goes wrong with the system, it is far better to blow a cheap fuse than fry a battery or a solar controller and it is easier to disconnect the solar panels from the rest of the system for maintenance or in case of an emergency (Russell, Scott. 2005).

IV. RECOMMENDATION

It is recommended that this solar project be integrated with complementary wind energy systems to ensure a stable power supply during suboptimal solar conditions.

In addition, solar panels should be installed on people's roofs by ensuring that each is connected to the main grid so that all unused power should be transmitted to other places where it is needed. In these systems, the solar panels generate electricity, which is used within the home during the day, with any excess energy being fed into the grid and used by other homes nearby. At night, these homes then use electricity from the utility grid. These systems are called grid-tie systems. Grid-tied solar electric systems effectively create a micro power station that provides energy not just for our self, but for the local community. Electricity can be used by other people as well as our self.

Furthermore, Access to sunlight is limited at certain times (e.g., morning and night). Although solar energy can still be collected during cloudy and rainy days, the efficiency of the solar system drops. Solar panels are dependent on sunlight to effectively gather solar energy. Therefore, a few cloudy, rainy days can have a noticeable effect on the energy system the mirror towers should be elected to track maximum solar energy. Solar panels generate the most energy when they are facing directly at the sun. To overcome this solar tracker are mounted on a tower mounted system to move the panels throughout the day to capture the maximum amount of sunlight. Performance of a solar system is at its worst during the winter months. However, by tilting the panels to capture as much of the sunlight as possible during the winter, this can significantly boost the amount of power that can be generated at this time. Some solar trackers simply move the angle of the panels from left to right (single-axis trackers), whilst more advanced trackers adjust both the angle from left to right and the tilt (double-axis trackers). Solar trackers work using sensors and electric motors or hydraulics, consuming a small amount of electricity. The amount of energy they consume is a small fraction of the additional energy they capture from the sun's rays. Consequently, adding solar tracking for a solar array can have significant real world performance improvements to solar power plant.

Finally, preventative maintenance and routine checks to prolong efficiency of the power plant.

V. CONCLUSION

Use of Technology

Implementation of this project on national scale will significantly help to reduce over reliance of hydropower which depends solely on water and as the result it is affected by poor rainfall season

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resulting into power deficit. In a nutshell generation of solar energy has tremendous projection scope in Zambia. The geographical location of the country stands to its benefit for generating solar energy.

Development of the System as a Solution

The over-reliance on hydropower has exposed Zambia's energy sector to vulnerabilities, particularly during periods of low rainfall. This paper proposes a solar energy model aimed at enhancing the country's energy security.

Possible Application

This paper illustrates Zambia's unique opportunity to harness its untapped solar potential, contributing to a more diversified and resilient energy mix.

Final Remarks

This study presents a scalable solar power model that integrates innovative transmission systems, providing insights into optimizing solar deployment in Zambia's energy mix.

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