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## **Diploma Thesis**

**Economic efficiency in solar energy based on  
microcontrollers**

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### **Declaration**

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In Prague on 30/3/2024

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# **Economic efficiency in solar energy based on microcontrollers**

## **Abstract**

The solar energy system represents one of the most crucial energy sources in the current decade, deriving its significance from its status as a renewable energy source and its environmentally friendly nature. Numerous factors contribute to enhancing the performance of solar energy systems, with one critical factor being microcontroller. The selection of an efficient type of microcontroller plays a pivotal role in the economic efficiency of a solar energy system. This study aims to investigate the economic efficiency of solar energy systems based on two types of microcontrollers contained in the charging controller namely, Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). This study conducted in Tartous city, Syria, with the aim to assist investors and stakeholders in making decisions regarding solar energy investment. The study found that the solar energy system relying on MPPT microcontroller is more economically efficient than its counterpart relying on PWM, where The payback period in the solar energy system according to MPPT and PWM microcontroller was found 15, 20 years respectively.

**Keywords:** Economic efficiency, solar system, microcontroller, charger controller, Pulse Width Modulation, Maximum Power Point Tracking, payback period.



# **Ekonomická účinnost ve sluneční energii založená na mikrokontrolérech**

## **Abstrakt**

System solární energie představuje jednu z nejdůležitějších energetických zdrojů v současné dekádě, získává svůj význam ze svého postavení jako obnovitelný zdroj energie a své ekologicky šetrné povahy. Řada faktorů přispívá k zlepšení výkonu solárních energetických systémů, přičemž jedním z klíčových faktorů je mikrokontrolér. Výběr efektivního typu mikrokontroléru hraje rozhodující roli v ekonomické efektivitě solárního energetického systému. Tato studie si klade za cíl zkoumat ekonomickou efektivitu solárních energetických systémů založených na dvou typech mikrokontrolérů obsažených v nabíječce, a to Pulzní Modulace (PWM) a Maximální Bod Moci (MPPT). Tato studie byla provedena v městě Tartus, Sýrie, s cílem pomoci investorům a zúčastněným stranám při rozhodování o investicích do solární energie. Studie zjistila, že solární energetický systém spoléhající se na MPPT mikrokontrolér je ekonomicky efektivnější než jeho protějšek spoléhající se na PWM, kde byla nalezena doba návratnosti ve solárním energetickém systému podle MPPT a PWM mikrokontroléru 15, 20 let.

**Klíčová slova:** Ekonomická účinnost, solární systém, mikrokontrolér, nabíječka, Pulzní Modulace, Maximální Bod Moci, doba návratnosti.

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# 1 Introduction

The global focus on developing and implementing new energy sources has intensified due to the finite nature of oil and gas reserves, as well as the escalating costs and environmental impact associated with their extraction. In this context, solar panels have emerged as a promising alternative energy source, offering a cleaner and more sustainable option for power generation. While some experts view solar energy as a viable solution for the future, others remain skeptical about its cost-effectiveness, citing the initial high investment required for solar panel installation. Despite differing opinions, the longevity and efficiency of solar panels suggest that over time, the benefits of utilizing this renewable energy source will outweigh the initial expenses, making it a compelling option for long-term energy production (Sekisov et al., 2020). Solar power plants require supplementary components aside from solar panels, including Solar Charger Controllers (SCCs), which manage the charging of batteries with electricity produced by the solar panels. Batteries function as storage units for the generated electrical energy. Thus, the inclusion of supplementary equipment is essential for the efficient functioning of solar power generation systems. When it comes to charging batteries using solar panels, a Solar Charger Controller (SCC) is essential as the intermediary for charging. SCCs are available in two varieties: Maximum Power Point Tracker (MPPT) and Pulse Width Modulation (PWM) (Putra et al., 2022).

The microcontroller is programmed to oversee the charging progress of the battery and determine the appropriate times for receiving power from the solar panel and disconnection once it nears full capacity. Through programmed algorithms, the microcontroller can efficiently oversee the charging process, ensuring the battery operates optimally and lasts longer (Ashiquzzaman et al., 2011). Microcontrollers are economical computing devices with numerous benefits. Their versatility stems from their ability to store and execute customized programs. Programming a microcontroller enables it to make decisions tailored to particular circumstances and preferences. Furthermore, its capacity for mathematical and logical operations enables it to replicate intricate logic and electronic circuits efficiently (Das et al., 2015).

Previous studies have presented varied results regarding the economic efficiency of solar energy (Swarnakar and Datta, 2016; Duong et al., 2019; Ariae et al., 2019;

kodirov et al., 2020; Sekisov et al., 2020; Bednárová et al, 2023). Conversely, other previous studies have focused on the technical aspect of microcontrollers (Acharya and Aitha, 2020; Faizal et al., 2022; Putra et al., 2022; Verma, 2023). This study will rely on measuring the economic efficiency of solar energy systems based on PWM and MPPT microcontrollers.

## **2 Objectives and Methodology**

### **2.1 Objectives**

This study aims to verify the economic efficiency of solar energy based on different microcontrollers. More specifically, there are two main types of microcontrollers found in charge controllers, namely pulse width modulation (PWM) and maximum power point tracking (MPPT). These two types differ in terms of both technological performance and economic aspects. This study aims to measure the economic efficiency of these systems through the payback period in Tartus city in Syria. The objectives of this research can be formulated as follows:

1- Verifying the economic efficiency based on the payback period in the solar energy system relying on PWM microcontroller in Tartus city in Syria.

2- Verifying the economic efficiency based on the payback period in the solar energy system relying on MPPT microcontroller in Tartus city in Syria.

3- Assisting investors and stakeholders in making decisions regarding solar energy investment in the Syrian markets.

### **2.2 Methodology**

To achieve the research objectives, this study relies on assessing the economic efficiency of two types of solar energy systems utilizing different microcontrollers, namely pulse width modulation (PWM) and maximum power point tracking (MPPT). The economic efficiency of these systems was measured based on the calculation of the payback period as equation (1):

$$\text{Payback period} = \frac{\text{cost of solar system}}{\text{saving cost}} \quad (1)$$

The cost of the solar energy system was measured based on the prices of solar panels, charge controllers (PWM/MPPT), batteries, and inverters in the Syrian market. The cost of the two solar energy systems was calculated using the same equipment, with the only difference lying in the type of microcontrollers in the charge controller: one utilizing PWM and the other MPPT.

The *saving cost* was measured according to Robles-Algarín et al. (2022) study, which relies on calculating the quantity of savings resulting from transitioning to a solar energy system compared to local electricity prices. The method for calculating saving cost follows the following steps.

Firstly, the outputs of the solar energy were evaluated in Tartus city in Syria. The solar installations are of medium scale for commercial purposes, featuring a 4kWp installed capacity and a total annual photovoltaic power generation of 6.426 MWh. The data pertaining to the Irradiation and theoretical values of the outputs of the solar energy system were collected from the "The World Bank, Global Solar Atlas" site.

Secondly, the outputs of each solar energy system, based on (PWM) and (MPPT) configurations, were measured according to the results of the Robles-Algarín et al. (2022) study, Where the study reveals that The MPPT microcontroller demonstrated an efficiency of 97.74%, whereas the PWM microcontroller-based solar system showed an efficiency of 68.20%.

Thirdly, *saving cost* was calculated by multiplying the outputs of the solar energy systems by the local electricity price.

The equation (1) provides the payback period for both solar system based on PWM microcontroller and MPPT microcontroller.

## **3 Literature Review**

### **3.1 Economic efficiency, system description and controllers in solar energy**

The rapid growth of solar power has made it a key renewable energy source in many countries' power systems, playing a crucial role in ensuring energy security and addressing climate change. The construction of photovoltaic (PV) systems with favorable incentives has attracted both domestic and foreign investors, easing the financial burden of power project investments. As a result, the development of PV technology is expected to alleviate electricity shortages, bolster supply security, and ease operational pressures on power systems (Huyen et al., 2021). kodirov et al. (2020) highlighted several key points regarding the use of solar energy. Firstly, they noted that while solar panels may be less cost-effective due to high installation and repair costs, they can still be a viable option in challenging geographical areas such as mountainous regions, foothills, deserts, and nature reserves. They suggested that implementing solar energy projects in such areas through public-private partnerships could be beneficial. The researchers also emphasized the importance of ensuring continuous energy supply to essential facilities like hospitals and recreation centers. They recommended that government subsidies be directed towards promoting the use of solar energy in these sectors, considering it a socially significant and urgent issue for the state.

The energy sector has transitioned towards autonomous power sources, incorporating pricing systems that align with market economy principles. Numerous governments globally are emphasizing the uptake of alternative energy for residential and industrial purposes (Olczak et al., 2022). Chesser et al (2018) identified several key correlations related to solar electricity pricing. These include a positive relationship between electricity prices and solar photovoltaics, as well as a negative relationship between electricity prices and electricity demand.

The utilization of renewable energy sources in the business sector is a prominently debated subject across all sectors of the national economy in the present era of promoting sustainability. Elevating the percentage of energy derived from renewable sources not only enhances environmental standards but also paves the way for

bolstering socio-economic growth within the national economy (Bednárová et al, 2023). The growing prominence of micro renewable energy systems (MRES) like Photovoltaic (PV) is becoming integral to national energy plans. As more customers embrace these installations, there is a noticeable trend: reduced demand on traditional utility providers. This shift can drive price hikes, prompting even more customers to switch to MRES in search of cost savings and environmental benefits (Chesser et al, 2018). Solar photovoltaic (PV) systems offer numerous benefits. They boast a long lifespan of around 20 years and can be easily installed and operated even in challenging geographical locations such as mountainous or remote areas. They are adaptable for use in mobile applications and require minimal maintenance. PV systems can function independently of the main power grid or can be connected to it. They efficiently convert solar energy into electricity without generating pollution, noise, or fluctuations. Due to their relatively low energy density, PV modules require ample surface area to generate sufficient power. Ongoing industrial advancements and technological innovations in PV cell production are expected to enhance the productivity and effectiveness of these systems over time (Mehr et al., 2022).

Defining the criteria and possibilities of supporting the implementation of environmentally-friendly technologies in business practices is crucial for determining the quality and progress of environmental sustainability across various sectors. The key factor that drives effective adoption of pro-environmental technologies in business is the return on investment, which plays a fundamental role in shaping environmental standards and promoting sustainable development in primary, secondary, and tertiary industries (Bednárová et al, 2023). Olczak et al. (2022) identified key success factors for renewable energy adoption, including raising public awareness about the efficient use of fuel and energy sources, aligning national regulatory frameworks with modern electricity production requirements, providing effective financial support for renewable energy applications, ensuring cost-effectiveness while maintaining quality standards, and developing reliable tariff calculation methods for renewable energy utilization.

Government intervention plays a significant role in establishing economic efficiency in solar energy markets worldwide. Due to the higher cost of photovoltaic (PV) technology compared to conventional fossil fuel-based energy generation methods, governments offer various incentives to the PV industry, including subsidies, incentive

programs, and feed-in tariffs. These incentives aim to encourage the adoption of PV systems by reducing their upfront costs and providing financial incentives for electricity generation. Common forms of government incentives include tax credits for PV system buyers and feed-in tariffs that guarantee the price of electricity generated by PV systems. When PV installations produce surplus energy, owners can sell the excess electricity on the market at the guaranteed price, potentially earning a profit. Governments utilize "white certificates" as an additional mechanism to promote economic efficiency in energy markets. These certificates verify that a specific reduction in energy consumption has been achieved, similar to carbon emission trading. White certificates are tradable assets and are coupled with obligations to achieve predefined energy savings targets. Failure to meet these targets incurs penalties for certificate holders. They are issued to producers upon achieving designated energy consumption reduction targets, allowing producers to either utilize them for their own compliance or sell them to entities struggling to meet their targets (Bayraktaroglu, 2009).

An unsustainable reliance on fossil fuels or nuclear energy has resulted in significant pollution issues and challenges associated with the disposal of radioactive waste, while a more stable approach involves harnessing renewable resources. The escalating environmental risks, diminishing fossil fuel reserves, and escalating costs of natural gas, petroleum, and electricity have prompted a shift towards renewable energy sources that are clean, abundant, and eco-friendly. Scholars emphasize that adopting efficient energy consumption practices at reasonable costs is crucial for the progress of nations. Therefore, countries aspiring for advancement should prioritize clean and cost-effective energy sources (Ariae et al., 2019). Solar energy is not only economically sustainable due to its renewable nature but also because photovoltaic technology produces low carbon emissions when generating electricity. This technology is environmentally safe, as it does not create noise or emit toxic greenhouse gases. Additionally, solar panels are highly efficient even at high temperatures. They can operate both onshore and offshore, generating significant amounts of energy without harming the environment or requiring large amounts of land. By reducing air, noise, and water pollution, solar energy plays a crucial role in mitigating global warming (Verma, 2023).



It is essential to foster self-sufficiency in energy resources among the population. This can be achieved by incentivizing solar panel manufacturers, localizing production of solar panels and collectors, and stabilizing electricity payments for a set duration (2-3 years) based on calculations. Moreover, legislative amendments regarding the purchase of solar panels and facilitating bank loans for users are necessary steps to promote the adoption of solar energy (kodiroy et al., 2020). According to Ariaie et al., (2019), it was warned that if the current trajectory of energy consumption persists, the finite reserves of coal, petroleum, and natural gas will be depleted in approximately 122, 42, and 60 years respectively. Fossil fuels currently dominate the energy landscape, accounting for 80% of total energy demands, while nuclear and renewable sources make up the remaining 20%. In 2005, global CO<sub>2</sub> emissions totaled 26.6 billion tons, with 41% attributed to power generation from fossil fuels. Projections indicate that this figure will rise to 44.8 billion tons by 2030. Furthermore, research suggests that CO<sub>2</sub> emissions from electricity generation alone are expected to increase by 46% by the year 2030.

One of the key metrics for evaluating investment in solar energy systems is the initial investment costs and the subsequent returns on these investments. In Azerbaijan, the potential of solar energy utilization was assessed in terms of its economic viability, given the country's considerable solar energy resources and the capacity to fulfill a significant portion of its energy needs through solar power. However, challenges related to the economic feasibility of solar energy projects and the required investment were identified as significant obstacles. For instance, the investment cost for implementing a solar system for a single household was estimated to be approximately EUR 500. Scaling up to larger projects, such as providing solar power for a tourism facility with 257 beds, would entail significantly higher costs, ranging from EUR 32,125 to EUR 42,833. This cost range is comparable to similar solar system installations in other regions, such as Slovakia. Furthermore, there have been initiatives to integrate solar energy systems with agricultural production, as evidenced by a project in Central Vietnam with a total investment cost of EUR 670,000 (Bednárová et al, 2023).

To optimize costs, PV solar system will prioritize utilizing solar power and store any excess energy for later use. The stored electricity will be tapped into when solar power is insufficient to meet household needs, ensuring minimal reliance on grid electricity.

By strategically managing their energy sources, households can minimize purchases from the national grid and avoid costly electricity rates, ultimately reducing overall expenses (Van et al., 2023). However, The rise in prices of traditional energy sources and fossil fuel-generated electricity has made solar energy increasingly attractive for homebuilding. As the costs of extracting and transporting traditional fuels continue to climb, renewable energy sources like solar power are becoming more cost-effective. The integration of concentrators in solar installations has proven to enhance thermal energy conversion by raising the temperature of the coolant and improving photovoltaic efficiency, reducing the need for expensive solar cells. While high and medium concentration concentrating systems require effective tracking systems, which can increase costs and operational complexity, stationary concentrators with secondary reflector systems like linear and angular heliostats offer improved technical and economic performance for solar systems (Sekisov et al., 2020).

The solar energy sector is experiencing rapid growth, with electric solar station capacity increasing by an average of 50% annually. Currently, solar energy contributes around 3% of the world's total electricity demand, and experts predict that by 2050, it could cover 20-25% of global electricity needs. Furthermore, the cost of solar electricity is decreasing, making it more affordable each year by approximately 4%. Scientists anticipate that by 2030, solar and thermal energy costs will be on par, paving the way for widespread implementation of solar power plant projects (SPP) (Sekisov et al., 2020). According to data from The International Renewable Energy Agency (IRENA), a growing number of countries, now totaling 160, have set new targets for renewable energy, indicating a global interest in this sustainable energy source. Among the various renewable energy options, photovoltaic (PV) power stands out as one of the fastest-growing industries worldwide. The PV market is characterized by three distinct trends: the rise of rooftop residential solar installations, which offer utility savings for consumers; the increasing adoption of rooftop solar systems by production factories to optimize costs and enhance productivity, typically ranging from 20 kWp to 1 MWp in capacity; and the development of large-scale solar plants (PV plants) with capacities ranging from 5 MWp to 1 GWp, catering to the growing global demand for electricity (Duong et al., 2019).

Households can significantly reduce electricity bills by utilizing a grid-tied rooftop solar power system with a storage component, which offers a high level of economic efficiency. Future projections suggest that costs for both solar power systems and storage will decrease by up to 50%, further enhancing the economic viability of this setup. The key factor influencing the economic efficiency of such a system is the balance between the amount of solar electricity generated during the day and the household's consumption needs during daylight hours. This difference determines the required capacity of the storage system, with smaller differences leading to lower initial investment costs. Optimizing this balance is crucial for maximizing cost savings and improving overall economic efficiency (Van et al., 2023). Meeting the requirements for supplying solar energy to residential areas involves establishing an autonomous power system, designating space for solar panel installation, optimizing light exposure, managing energy resources efficiently, and understanding daily energy consumption patterns in housing design (kodirov et al., 2020). Tongsopit et al (2019) conducted an analysis on the economic aspects of electricity self-consumption from distributed solar photovoltaics in Thailand. Their findings, which evaluated three different schemes (no compensation for excess electricity, net metering, and net billing), demonstrated that all customer classes can benefit financially, with net metering providing the most advantages to customers. These conclusions have significant implications for national policy.

Verma's study in 2023 underscores the reliability of solar energy as a cost-effective source of electricity due to its low maintenance requirements and initial infrastructure investment. Solar technology emerges as an efficient means to conserve company resources, thereby safeguarding wealth. The study highlights the potential of solar energy to enhance sustainability by reducing reliance on traditional fuel sources. Moreover, the economic feasibility of solar technology is emphasized, as it offers long-term benefits with minimal maintenance costs over a 20 to 30-year period, contrasting significantly with the expenses associated with fossil fuel energy generation. Duong et al., (2019) study find that Based on the financial analysis, the PV rooftop system demonstrates advantages in providing power to the load and decreasing reliance on the distribution grid. Nevertheless, the duration required for the project to recoup its costs is considerable, necessitating consumers to make annual payments to offset the nighttime electricity demand shortfall (Duong et al., 2019).

Establishing a business in solar energy holds significant promise for the future, given its virtually limitless energy potential and ease of integration into daily life. The adaptability and eco-friendliness of solar technology are key advantages, as solar panels efficiently convert sunlight into electricity without harmful emissions or environmental repercussions. In a world increasingly concerned with ecological issues, solar power offers a sustainable solution that aligns with the urgent need to address environmental challenges. (Sekisov et al., 2020). To optimize costs, PV solar system will prioritize utilizing solar power and store any excess energy for later use. The stored electricity will be tapped into when solar power is insufficient to meet household needs, ensuring minimal reliance on grid electricity. By strategically managing their energy sources, households can minimize purchases from the national grid and avoid costly electricity rates, ultimately reducing overall expenses (Van et al., 2023).

Solar energy is a prominent renewable energy source that is gaining traction worldwide to combat energy scarcity and environmental degradation. Advancements in power electronics and semiconductor technology have significantly reduced the installation costs of solar projects, leading to the rapid expansion of solar power plants, particularly in countries like China and the United States. In addition to large-scale solar power plants, small solar systems are becoming popular among consumers with lower energy needs. Rooftop solar systems are increasingly viewed as a cost-effective solution for reducing reliance on the grid and enhancing self-sufficiency in power supply. When considering the installation of a rooftop system, factors such as design capacity, cost efficiency, and return on investment should be carefully evaluated (Duong et al., 2019). Optimizing the utilization of grid-connected rooftop solar power systems with storage is crucial for balancing benefits between households and utility providers. This involves accurately sizing the installation to maximize storage system usage and align it with household energy consumption patterns. To incentivize initial projects, the government can introduce regulations that ensure the selling price of electricity from storage batteries equals peak-hour rates or even exceeds those of regular projects. Additionally, preferential policies or financial support can further encourage the adoption of solar power systems with storage, promoting sustainable energy practices and economic efficiency (Van et al., 2023).

In their analysis, Gürtler and Paulsen (2018) examined the impact of solar power generation forecasts on electricity prices. A unique aspect of their regression model is the incorporation of a variable based on simulation that represents the power generation technology influencing prices at a specific time. One of the key findings from their study is that minimizing forecast errors in wind and photovoltaic power generation leads to a decrease in price volatility. However, Olczak et al. (2022) concluded: The involvement of prosumers in solar power plants plays a crucial role in influencing tariff policies within the solar electricity market, where Prosumers enhance competition and help regulate the dominance of energy companies, leading to lower consumption tariffs. Furthermore, by implementing effective state policies, the participation of prosumers in solar energy production can align with sustainable development goals. The relationship between electricity production and consumption, as demonstrated by price parity, consistently impacts pricing strategies in this sector.

The increasing popularity of residential solar PV systems in the electricity market can be attributed not only to declining system costs but also to a positive feedback loop. As more customers reduce their reliance on the grid by installing solar PV systems, the expenses incurred by electric utility companies do not decrease in proportion to the reduced electricity consumption. This is because utilities must cover fixed costs related to transmission and distribution infrastructure over long periods. Consequently, utilities may need to raise electricity prices to offset these losses, potentially encouraging more customers to adopt solar PV systems (Chesser et al., 2018). Solar systems are simple to set up and cost-effective, offering long-term functionality. These installations can operate efficiently for many years, making them a reliable and economical choice for sustainable energy solutions (Sekisov et al., 2020).

Despite the efforts of oil-rich countries to promote renewable energy sources, the high initial cost of solar energy systems makes it challenging for businesses and households to invest in them, especially when compared to the lower cost of non-renewable energy sources (Bednářová et al, 2023). However, Chesser et al., (2018) conclude: Australia and the UK face heightened risks due to the rapid addition of residential solar PV systems to the grid. Addressing this challenge requires a reevaluation of existing renewable energy policies to ensure a sustainable approach for both current and future micro-RES adopters. To meet environmental objectives,

stakeholders in the electricity market must promote the adoption of solar PV in a manner that is fair to all customers, without penalizing non-adopters through increased electricity costs.

the increasing demand for electricity and heat globally is driven by various factors such as the depletion of traditional energy resources, escalating costs, environmental concerns, and other related issues. In response to these challenges, developed nations have initiated programs to promote the adoption of renewable energy sources (RES). Until 2020, efforts are being made to raise the share of RES in EU countries to 29% and in China to 15%, demonstrating a commitment to supporting the utilization of renewable energy (Kodirov et al., 2020). Furthermore, Kodirov et al. (2020) underscored the environmental benefits of solar and wind energy, highlighting their minimal impact on the environment compared to traditional energy sources. They acknowledged that initial costs of energy production using these technologies may be higher, but emphasized that as natural resources deplete, the long-term benefits of renewable energy sources become increasingly clear. Ultimately, the researchers concluded that supporting the use of non-traditional energy sources is crucial for environmental conservation and should be a priority for future generations. They emphasized the importance of considering the long-term environmental impacts of energy production and the need to transition towards sustainable energy sources for a cleaner and healthier future.

Households can significantly reduce electricity bills by utilizing a grid-tied rooftop solar power system with a storage component, which offers a high level of economic efficiency. Future projections suggest that costs for both solar power systems and storage will decrease by up to 50%, further enhancing the economic viability of this setup. The key factor influencing the economic efficiency of such a system is the balance between the amount of solar electricity generated during the day and the household's consumption needs during daylight hours. This difference determines the required capacity of the storage system, with smaller differences leading to lower initial investment costs. Optimizing this balance is crucial for maximizing cost savings and improving overall economic efficiency (Van et al., 2023). Advancements in power electronics and semiconductor technologies are driving down the upfront costs of PV systems and minimizing ongoing maintenance expenses. As a result, solar energy

production costs are becoming more competitive with traditional fossil fuel sources like coal (Duong et al., 2019).

The growing prominence of micro renewable energy systems (MRES) like Photovoltaic (PV) is becoming integral to national energy plans. As more customers embrace these installations, there is a noticeable trend: reduced demand on traditional utility providers. This shift can drive price hikes, prompting even more customers to switch to MRES in search of cost savings and environmental benefits (Chesser et al, 2018). the prevailing choice in renewable energy systems is solar energy. This preference stems from its versatility, allowing implementation at both individual household and industrial levels to meet small-scale energy needs, as well as on a larger scale to address commercial demands in megawatts (Acharya and Aitha, 2020). In a study conducted by Chesser et al. (2018) it was discovered that: (1) Escalating costs of residential electricity result in heightened adoption rates of residential solar photovoltaic systems, (2) Adoption of residential solar photovoltaic systems contributes to the escalation of residential electricity prices, (3) Implementation of residential solar photovoltaic systems has an adverse impact on residential electricity consumption (Chesser et al., 2018).

Photovoltaic (PV) power stands out as one of the most rapidly expanding renewable energy technologies, notably in large-scale commercial ventures and in off-grid setups serving rural areas lacking access to traditional electricity grids (Olivero-Ortíz et al., 2021). This surge is attributed partly to the notable reduction in manufacturing costs of solar panels, which have witnessed a significant decline in recent times. Moreover, with panels boasting a lifespan of approximately 30 years, the return on investment for such PV systems is becoming increasingly appealing (Robles-Algarín et al., 2022).

### **3.1.1 Solar system**

Solar energy outside Earth's atmosphere measures at  $1366 \text{ W/m}^2$ , but it decreases to only  $160 \text{ W/m}^2$  upon reaching the Earth's surface. Nonetheless, the solar energy received by the Earth's surface is immense, totaling about  $3 \times 10^{17} \text{ J/year}$  or  $2 \times 10^{17} \text{ W}$ . Remarkably, covering just 0.1% of the Earth's surface with solar cells boasting 10% efficiency would be sufficient to meet the current global energy demand. (Fianti et al., 2021). Solar radiation has a positive effect on the power output of PV systems by increasing their energy generation. However, high temperatures can have a negative

impact on the efficiency of the system, leading to reduced power production Duong et al., (2019). however, The performance of a PV system can be significantly affected by unpredictable weather conditions such as sun obstruction and shading, leading to a notable decrease in power output and potential deviations in the expected results (Duong et al., 2019).

Due to the considerable advantages associated with solar energy, the concentration on utilizing and controlling solar power via solar panels emerges as a prominent focal point in the field of renewable energy investigation (Mehr et al., 2022). Residential solar photovoltaic (PV) systems and other micro renewable energy systems (micro-RES) have the potential to make significant contributions to a country's climate change objectives. However, they also pose a disruptive threat to the traditional electrical industry. Until 2018, users of micro-RES still depend on the national electricity grid when their systems are unable to generate power due to unfavorable weather conditions. Yet, advancements in residential battery storage technology, coupled with falling prices, may lead to a transformation similar to the shift from landline telephones to mobile devices in the telecommunications industry (Chesser et al., 2018).

A key issue in the solar energy domain is determining the best-suited solar panel technology for constructing solar power plants, aiming to optimize energy usage and minimize expenses. Recent progress in this area has led to positive developments in solar cell technologies. It is essential to examine the attributes of each technology carefully and select appropriate criteria and subcriteria to identify the most suitable solar panel technology (Mehr et al, 2022). Photovoltaic systems consist of essential components such as solar panels, controllers, and rechargeable batteries. These components work together to generate a constant current based on the efficiency of the solar cells. The electrical output is typically between 10 mW/cm<sup>2</sup> and 25 mW/cm<sup>2</sup>, depending on the efficiency of the solar cells, which ranges from 10% to 25%. For example, a 15.6cm x 15.6cm solar cell with 19% efficiency can produce 4.6 watts of power at peak performance. Photovoltaic modules currently available in the market range from 3 W to 400 W. The rechargeable battery plays a crucial role in protecting against deep discharge and overcharging, ensuring the efficient operation of the system (kodirov et al., 2020).



Solar energy is a renewable energy source that harnesses the power of the sun to produce electricity. This alternative energy source is distinct from traditional biofuels. Solar energy has a wide range of applications, including generating electricity. One of the main challenges in using solar energy for electricity production was the ability to store the energy for use during periods without sunlight, such as at night or during inclement weather. To address this challenge, innovative devices like solar panels, solar heating systems, and solar cells were developed. These technologies have made it possible to capture and store solar energy effectively. Solar power applications can be utilized as long as there is sunlight available, making it a versatile energy source for personal, domestic, and industrial purposes. Advancements in battery technology now allow for the storage of solar energy generated by solar panels, enabling the use of solar electricity independently of traditional utility grids. Recent experiments have shown that solar energy can even be stored in salt beds to support solar heating (Das et al., 2015). kodirov et al. (2020) recommended that: State support for the use of solar panels includes various key initiatives:

- Encouraging local production of solar panels and collectors to boost the domestic market.
- Ensuring the availability of high-quality and efficient solar devices for consumers.
- Implementing tax incentives for individuals using solar, wind, and other renewable energy sources, such as reducing property taxes by 50%.
- Facilitating access to bank loans at favorable rates, not exceeding the refinancing rate, to promote the adoption of solar panels.
- Updating legislation to regulate the individual, joint, and public-private partnership use of solar energy.
- Establishing a service infrastructure, providing skilled personnel, and organizing support services to facilitate the use of solar energy.

There are two primary categories of solar power plants (SPP) (Pliusnin, 2017):

1. Stand-alone systems: These systems operate independently and typically include batteries and a charge controller in addition to PV panels. For

systems that supply alternative current and voltage of 220/380V, an inverter is also incorporated to convert DC to AC.

2. Grid-tied systems: These systems work in parallel with the grid and do not require batteries. They directly feed excess energy back into the grid.

One notable drawback of stand-alone SPPs is the loss of excess energy during low-load periods. Typically, when batteries are fully charged, the controller switches off the PV panels. Although excess energy can be utilized for auxiliary purposes such as water or air heating, this does not entirely address the issue (Pliusnin, 2017).

A significant challenge with stand-alone SPPs is the reliance on batteries, which need to operate in a cyclic mode. Lead-acid batteries, commonly used in such systems, have a limited number of working cycles, necessitating frequent replacement. While commercial batteries with longer lifetimes, such as nickel-cadmium and lithium-ion batteries, offer a solution, they come at a higher cost (Pliusnin, 2017). A typical layout of a stand-alone solar power supply system is depicted in Figure 3.1.

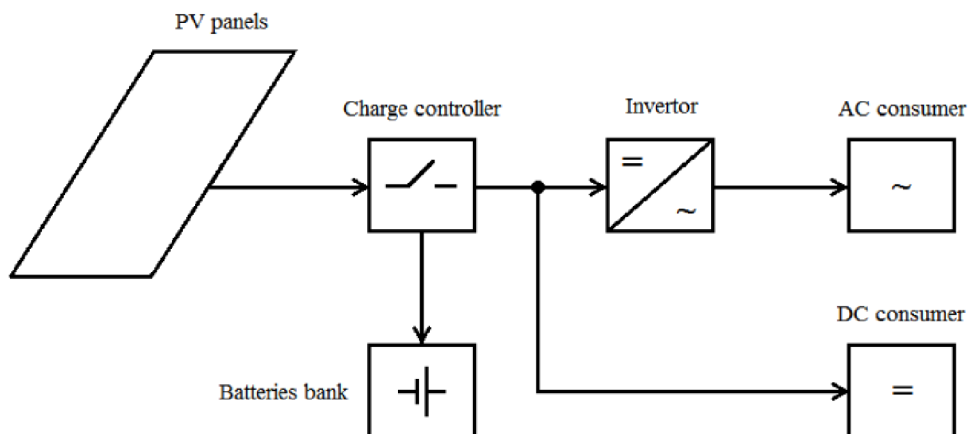


Figure 3.1: typical layout of a stand-alone solar power supply system. Source: Pliusnin, (2017).

Grid-connected solar power plants (SPPs) are categorized into two main types: those with and without batteries. The most prevalent configuration in practice is the battery-less system, known for its high reliability and minimal maintenance requirements. These systems utilize inverters that rely on the external grid for reference voltage, enabling them to synchronize with the grid and operate accordingly (Pliusnin, 2017).

However, in the event of an external grid outage, a local blackout occurs, leading to a halt in electricity supply to consumers. This is due to the grid inverters requiring the presence of the external grid to function properly, as they generate a voltage identical to that of the grid. While this reliance on the external grid presents a significant drawback, it serves as a safety measure to prevent the connection of AC power to lines undergoing repair or maintenance (Pliusnin, 2017). The block diagram of a grid-connected SPP is illustrated in Figure 3.2.

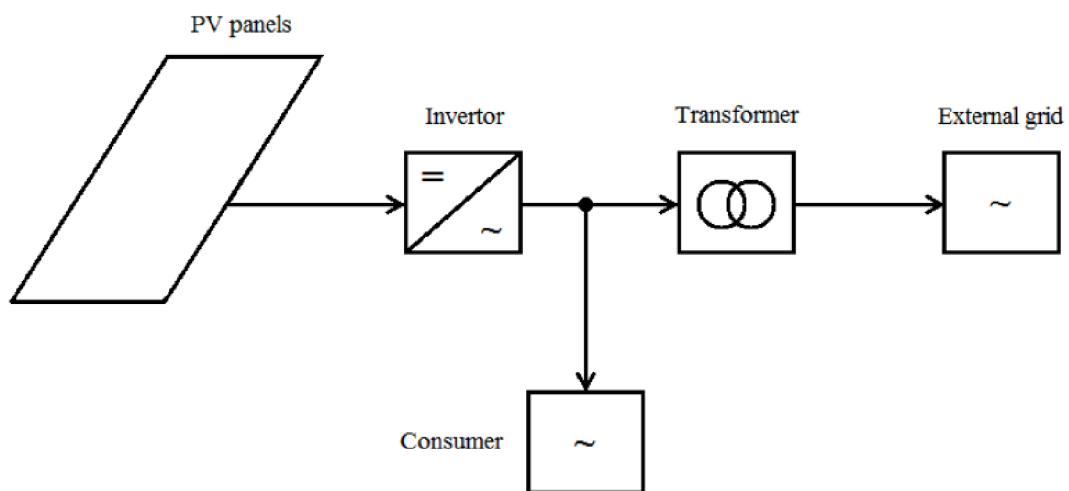


Figure 3.2: diagram of a grid-connected SPP, source: Pliusnin, (2017).

the type of grid operation model is expected to have significant impacts, such as alleviating pressure on the power grid, reducing household peak demand, smoothing out load patterns, and decreasing electricity demand during peak hours. From a cost optimization standpoint, this model is projected to minimize electricity purchases from the grid during morning peak hours, while its impact on afternoon peak hours is anticipated to be less pronounced. Despite these optimizations, there remains a substantial disparity between peak and average load demands throughout the day, resulting from variations in grid electricity usage during peak and non-peak hours. In terms of grid operation efficiency, the differences in hourly electricity purchases from the national grid by households are minimal, thereby ensuring consistent monthly savings. While household peak demand decreases significantly compared to cost optimization scenarios, the reduction in electricity purchases during peak hours is substantial. However, achieving these reductions necessitates a substantial increase in

storage system capacity, leading to higher investment costs and diminished economic efficiency (Van et al., 2023).

Increased reliance on the intensified utilization of natural resources like gas and coal for electricity generation, leading to the depletion of mines and greater dependence on energy imports (Olczak et al., 2021). Incorporating renewable energy sources, eco-friendly technologies, and implementing green management practices are essential for businesses aiming to remain competitive and sustainable in the market. Additionally, adopting green management practices allows companies to reduce their environmental footprint and cut costs by minimizing energy and resource consumption. (Bednárová et al, 2023). Governments across the globe have integrated measures to promote the adoption of micro renewable energy systems in residential settings as a key component of their energy policies focused on addressing climate change. Various support mechanisms, such as Feed-in Tariffs (FiT), point-of-sale rebates like Renewable Energy Certificates (REC), and tax incentives, have been utilized to drive the achievement of renewable energy targets. These strategies have proven effective in boosting the installation rates of residential solar photovoltaic systems in nations such as the US, Australia, and the UK (Chesser et al, 2018).

According to Sekisov et al., (2020). Solar panels have a wide range of applications, including:

1. Integration into new construction projects: Companies can offer the installation of solar power plants during the initial construction phase of houses and apartments. This not only enhances the property value but also boosts the company's reputation for sustainable practices.

2. Retrofitting solar panels in existing buildings: With the trend of renovating old properties into high-end luxury residences, incorporating solar panels during the renovation process can add value and appeal to potential buyers.

3. Solar panel installation in country houses: Building country cottages has become a popular construction trend. Instead of investing in costly and time-consuming electrical grid extensions, installing solar panels on the roofs of these houses can provide electricity and potentially heat, depending on the panel's capacity.

Throughout the day, a 12V-rated solar panel experiences a voltage potential that rises from 0V to a maximum of 18V and then returns to 0V as sunlight transitions from sunrise to sunset. Concurrently, the current rating fluctuates in response to sunlight intensity. To manage these fluctuations and regulate battery charging, a controller is essential (Acharya and Aitha, 2020). In addition, Secondary batteries, also known as rechargeable batteries, are highly favored for their versatility and reusability compared to primary disposable batteries. Despite their lower energy-to-weight and energy-to-volume ratios, secondary batteries excel in supplying high surge currents, resulting in a significant power-to-weight ratio. Their cost-effectiveness and ability to meet high current demands make them ideal for applications such as powering motor vehicles and solar panel systems (Ashiquzzaman et al., 2011).

One of the key challenges in the solar energy sector revolves around selecting the most suitable solar panel technology to effectively harness solar power. Recent scientific advancements in this domain have yielded promising outcomes in enhancing solar cell technologies. Apart from harnessing solar energy, photovoltaic (PV) systems offer numerous advantages. These include a long operational lifespan of approximately 20 years, ease of installation and operation, suitability for deployment in rugged terrains and remote areas, compatibility with mobile applications, straightforward maintenance requirements, independence from centralized power grids, and seamless integration with grid-connected setups. Moreover, PV modules facilitate the conversion of solar energy into electricity without generating pollution, noise, or voltage fluctuations. However, due to their low energy density, PV modules necessitate a large surface area to produce substantial energy outputs. Ongoing industrial advancements and technological progressions in PV cell manufacturing are expected to drive enhanced productivity and broader adoption of these systems (Mehr et al., 2022).

Solar energy has been valued since ancient times for its importance and advantages. Plants utilize sunlight for photosynthesis, generating food. Solar power, a free energy source, allowed people to preserve food before the invention of refrigerators. It was also used to disinfect clothes and provide essential vitamin D for bone health. In modern times, solar energy is increasingly recognized as a cost-effective method for electricity production, leading to evolving practices in its utilization systems, further expanding the potential applications of this sustainable energy source (Das et al., 2015).

Given the pressing environmental concerns such as pollution and the escalating threat of global warming, photovoltaic (PV) solar energy emerges as a compelling solution, especially in regions abundant with solar resources (Rodríguez-Urrego and Rodríguez-Urrego, 2018). The growing adoption and utilization of renewable energy sources as a sustainable method for generating and preserving clean energy is globally recognized as a pivotal technological remedy in the battle against climate change. (Attia, 2021).

The SCC's primary function is to manage the power transfer from the solar panels to the battery, ensuring swift recharging without overloading, thereby prolonging battery lifespan. The controller serves as an electronic tool responsible for managing the flow of direct current between the battery and the load. It ensures that the battery is not overcharged, preventing excessive charging when the battery is already full, and regulates the voltage from the solar panel or solar cell. Overvoltage and overcharging can significantly diminish the lifespan of the battery (Faizal et al., 2022). Several techniques exist for charge controllers, facilitating the conversion of solar energy into a suitable format for storage devices. Of these, the widely favored options include PWM-based controllers and those utilizing MPPT technology (Acharya and Aitha, 2020).

Three key factors influence the extraction of maximum power from a PV panel: (i) Irradiance: Alters the PV panel's current operating point. (ii) Temperature: Alters the PV panel's voltage operating point. (iii) Load: Serves as a reference for both current and voltage (Majaw et al., 2018). To enhance the effectiveness of a solar panel, the utilization of MPPT, a power electronic device, becomes essential. MPPT enables the system to operate at its Maximum Power Point (MPP), allowing it to generate its highest power output by detecting the peak solar radiation incident on the PV module. (Hamid et al., 2016).

### **3.1.2 Controllers types in solar system**

To harness solar energy from solar panels and convert it into usable electrical energy, the inclusion of a Solar Charger Controller (SCC) is essential. The SCC serves the crucial role of safeguarding and regulating the battery charging voltage to prevent it from surpassing the threshold that could potentially damage the battery cells (Putra et

al., 2022). Extending the lifespan of batteries can be achieved by carefully managing their charge levels, which helps regulate the chemical reactions within the battery. By controlling the cover charge of batteries, the rate of these reactions can be slowed down, leading to a potential increase in battery longevity of around 5%. It is essential to interrupt the charging process to allow the batteries to store charge and reach their maximum voltage. Effectively utilizing this Storage Control Charge (SCC) method can significantly enhance the lifespan of batteries like lead-acid batteries, despite their inherent limitations and the need for careful management to optimize their performance and durability (Ashiquzzaman et al., 2011). The Solar Charge Controller fulfills three primary functions (Thounaojam et al., 2014):

1. Regulating the voltage from the solar panel to prevent battery overcharging.
2. Preventing deep discharge of the battery while DC loads are in use.
3. Providing appropriate voltage levels for various DC loads to ensure efficient operation.

Solar power is a renewable energy source that utilizes sunlight to generate electricity, distinguishing it from traditional biofuels. It has various applications, including electricity production. A significant challenge faced in solar energy utilization is storing the energy for use when sunlight is unavailable. Innovative technologies like solar panels and cells have been developed to effectively capture and store solar energy. Solar power can be harnessed as long as there is sunlight, making it versatile for personal, domestic, and industrial use. Advances in battery technology enable the storage of solar energy from panels, allowing independent use of solar electricity. Recent experiments have demonstrated storing solar energy in salt beds to support solar heating systems, expanding its potential applications. Signal microcontrollers are commonly used to control non-digital electronic systems by integrating necessary analog components. For example, The ATmega 8 microcontroller is specifically effective to manage the direction of DC Gear motors (Das et al., 2015). Different types of charge controllers are available in the market, each offering unique features and benefits. Analog charge controllers use operational amplifiers and LED indicators to display the battery status through glowing LEDs. ON/OFF charge

controllers control the flow of current to the battery by switching a controlling element like a MOSFET on and off (Thounaojam et al., 2014).

The SCC's primary function is to manage the power transfer from the solar panels to the battery, ensuring swift recharging without overloading, thereby prolonging battery lifespan (Faizal et al., 2022). To ensure efficient charging of the battery backup, the solar energy is elevated to 14V using a boost converter until the solar voltage reaches this threshold. During this phase, the input current experiences a significant reduction. Once the solar energy surpasses 14V, a buck converter steps in to decrease the voltage back to 14V by boosting the current. This process ensures that the energy from the solar panel is harnessed throughout the day for charging the battery backup, rather than allowing the solar voltage to fluctuate between 14V and 18V (Acharya and Aitha, 2020). The programmed algorithm developed by Ashiquzzaman et al. (2011) focuses on enhancing battery efficiency through specific control actions. The key operational guidelines can be summarized as follows:

1. When the battery voltage falls below 10V, the controller initiates the battery charging process.
2. If the battery voltage drops below 12V, the load (for a 12V load) is disconnected from the battery.
3. If the battery voltage exceeds 15V, the controller ceases the battery charging operation.
4. When the battery voltage surpasses or equals 12V, the load (for a 12V load) can be connected to the battery as per normal operation.

A Solar Charge Controller (SCC) is a crucial device that regulates the flow of energy between the battery, load, and solar panel using a micro-controller. Its primary function is to prevent overcharging, ensure efficient charging and discharging, and block reverse charging, all while optimizing the utilization of renewable energy sources (Ashiquzzaman et al., 2011). To harness solar energy from solar panels and convert it into usable electrical energy, the inclusion of a Solar Charge Controller (SCC) is essential. The SCC serves the crucial role of safeguarding and regulating the battery charging voltage to prevent it from surpassing the threshold that could potentially



damage the battery cells (Putra, et al., 2022). The charging requirements of the battery backup vary based on the stored energy levels, necessitating specific voltage and current inputs ranging from 12V to 14V and maximum input current to zero amps, respectively. This disparity between incoming solar energy and battery needs underscores the importance of a charge controller. Acting as a mediator, the controller adjusts the incoming solar energy to align with the battery backup requirements. During periods of low battery levels, the controller maximizes solar energy extraction. Conversely, as the battery approaches full capacity, the controller regulates the incoming energy to prevent overcharging. Upon reaching full charge, the controller shifts focus to monitoring the battery voltage rather than actively charging it (Acharya and Aitha, 2020).

### **3.2 microcontrollers in solar system**

Solar energy is rapidly gaining prominence as a crucial source of power for the future, with solar-powered devices becoming increasingly integrated into various aspects of daily life. To store the energy harnessed during daylight hours for use when sunlight is unavailable, a reliable storage solution such as a Smart Solar Charge Controller is essential. This component of a solar power system is specifically designed to efficiently recharge solar batteries while preventing over-discharge, thereby extending the battery's lifespan. Once the battery reaches full capacity, the charge controller employs a logic system to maintain a trickle charge to ensure optimal performance. Additionally, the controller incorporates a smart battery management system to oversee deep discharge protection and automatically cut off the load when the battery reaches a predetermined level of discharge (Thounaojam et al., 2014). Solar power plants necessitate auxiliary equipment beyond just solar panels, such as Solar Charger Controllers (SCCs), which facilitate the charging of batteries with electricity generated by the solar panels. The batteries themselves serve as reservoirs for storing the generated electrical energy. Hence, the presence of additional supporting equipment is crucial for the effective operation of solar power generation systems. In the process of charging batteries using solar panels, a Solar Charger Controller (SCC) is indispensable as the charging intermediary. SCCs come in two types: Maximum Power Point Tracker (MPPT) and Pulse Width Modulation (PWM) (Putra et al., 2022).

The Solar Charge Controller serves as the central control unit in Solar Home Systems and certain photovoltaic hybrid systems, managing the flow of energy throughout the system. This essential component, typically a compact box housing solid-state circuitry on a PCB, is positioned between the solar panel and the battery. Its primary role is to oversee and regulate the flow of charge from the panel to the battery bank to prevent overcharging (Thounaojam et al., 2014). By adjusting the voltage level at the battery terminal through the micro-controller, the Solar Charge Controller (SCC) regulates the charging process from the solar panel, thereby enhancing the longevity of the battery. Additionally, it safeguards against over-discharging by disconnecting the load from the battery once the voltage level hits a critical threshold determined by the micro-controller (Ashiquzzaman et al., 2011). The study by Tarik et al. (2013) presents a charger system where a microcontroller is connected to an NPN transistor. When the output battery is fully charged, the zener diode cuts off the supply and lights up the corresponding LED. The same process is followed for the system battery, with the LED glowing after the zener diode cuts off. Once both tasks are completed, the supply is returned to the input point. This system demonstrates an effective way to manage charging processes and ensure that batteries are charged optimally without overcharging, thus enhancing the overall efficiency and longevity of the batteries.

The microcontroller is designed to monitor the battery's charging status and determine when it should receive power from the solar panel and when it should be disconnected once it reaches near full capacity. By utilizing programmed algorithms, the microcontroller can effectively manage the charging process to ensure optimal battery performance and longevity (Ashiquzzaman et al., 2011). Many contemporary charge controllers integrate PWM and MPPT functionalities. These controllers are engineered to facilitate rapid recharging of the solar battery while preventing over-discharge, thereby extending the battery's lifespan (Majaw et al., 2018). The MPPT and PWM types of solar charge controllers exhibit distinct characteristics. MPPT controllers are adept at maximizing both voltage and current from the solar panel, nearly reaching its maximum power point. Consequently, when charging, the current and voltage supplied to the battery surpass those of PWM controllers. On the other hand, PWM controllers provide a voltage and current output slightly higher than the battery's nominal values but fall short of reaching the solar panel's maximum power point. The irradiation level significantly influences the output voltage and current of

solar panels connected to both MPPT and PWM controllers. During low irradiation conditions, the output voltage and current decrease, while they increase with higher irradiation levels.

The microcontroller plays a crucial role in preventing overcharging of the battery by instructing the optocoupler to isolate the battery from the solar panel when necessary. This decision is based on the battery's charge level and the power requirements of the connected loads. Once the stored charge in the battery is deemed sufficient to power the permitted loads, the system is primed for smooth operation (Ashiquzzaman et al., 2011). Microcontrollers are cost-effective computing devices that offer a wide range of advantages. Their capability to store and execute custom programs makes them highly adaptable. By programming a microcontroller, one can enable it to make decisions based on specific conditions and choices. Additionally, the mathematical and logical functions it can perform allow it to replicate complex logic and electronic circuits effectively (Das et al., 2015).

The primary role of the solar charge controller is to manage the flow of charge from the solar PV module to the battery bank, preventing overcharging. Its functions include regulating solar panel voltage to prevent battery overcharge, preventing battery discharge when DC loads are in use, and facilitating the use of various DC loads. (Thounaojam et al., 2014). In contemporary solar setups, pulse width modulation (PWM) and maximum power point tracking (MPPT) charge controllers are widely employed. They serve as efficient options for charging batteries in off-grid solar systems. The primary function of an MPPT controller is to optimize power extraction from the PV module by adjusting the output to match the battery voltage, thereby maximizing charging efficiency. Additionally, it acts as a DC-to-DC converter, modifying input from the PV module to align with battery requirements. PWM controllers regulate high current and voltage when the battery is fully charged, ensuring optimal control in such scenarios (Majaw et al., 2018).

### **3.2.1 Pulse Width Modulation microcontroller**

The primary function of pulse width modulation (PWM) in solar system controllers is to regulate the power devices by maintaining a constant voltage during battery charging. PWM technology is utilized in modern charge controllers to reduce the amount of power supplied to batteries as they approach full charge. This approach

ensures that batteries are fully charged with minimal stress, thereby extending their lifespan. (Majaw et al., 2018). The Pulse Width Modulation (PWM) charge controller is a popular choice for managing the transfer of solar panel energy to battery backup. It utilizes a switching circuit to route the solar energy to the battery, controlled by an oscillator that adjusts the pulse width based on the battery's energy level (Acharya and Aitha, 2020).

The operation principle of a PWM controller involves monitoring the voltage generated by solar cells through a voltage indicator. Based on this measurement, the controller adjusts the voltage to ensure efficient charging of the batteries connected to the solar panels (Swarnakar and Datta, 2016). Figure 3.3 clarify the Mechanism of Pulse Width Modulation (PWM) charge controller.

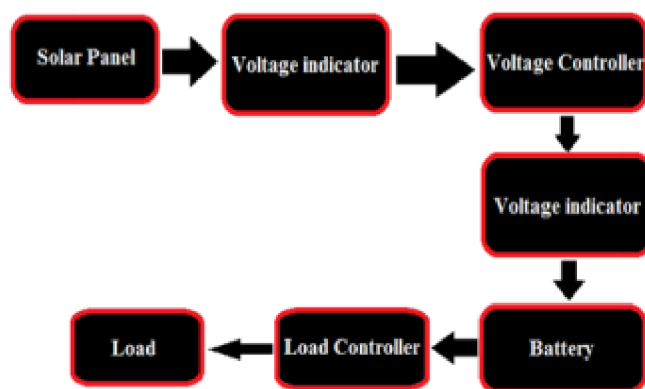


Figure 3.3: Flowchart of Pulse Width Modulation (PWM) charge controller, source: (Majaw et al., 2018).

The charger controller utilizes pulse width modulation (PWM) technology to manage the battery charging process and regulate the flow of current to and from the battery for the load. Its key functions include controlling the charging current to prevent overcharging and overvoltage, managing the discharge current to avoid complete battery depletion and overloading, and monitoring battery temperature for optimal operation. When purchasing a charger controller, factors to consider include the voltage rating (e.g., 12 Volt DC / 24 Volt DC), the controller's current capacity (e.g., 5 Ampere, 10 Ampere, etc.), and features such as full charge and low voltage cut-off capabilities (Faizal et al., 2022). A PWM controller functions as a switch rather than a DC-DC

transformer. When the switch is closed, it connects the solar panel directly to the battery. Consequently, both the panel and the battery will maintain nearly identical voltages. As the battery's state of charge increases, the voltage will rise accordingly. (Swarnakar and Datta, 2016).

Pulse Width Modulation (PWM) is a highly effective method utilized in numerous control systems. This technique finds application across various fields, including speed regulation, power management, and communication. PWM entails manipulating a square wave, adjusting its duty cycle to achieve a desired output voltage, represented by the waveform's average value. Essentially, PWM involves rapidly switching a DC motor on and off, with precise control over the duration of each on and off period (Faizal et al., 2022).

The study by Ashiquzzaman et al. (2011) highlights the importance of a cost-effective solar charge controller (SCC) designed and implemented using a PIC microcontroller to improve the efficiency and prolong the battery lifetime. The findings suggest that this SCC could be instrumental in addressing the energy crisis in Bangladesh by optimizing the utilization of solar energy resources. By effectively managing the charging process and ensuring the longevity of the battery, such a system can contribute significantly to enhancing the overall energy sustainability and reliability in the region. However, Thounaojam et al., (2014) suggest that PWM (pulse-width modulated) charge controllers charge the battery with either constant voltage or constant current by toggling a power device such as a MOSFET. They offer higher efficiency compared to analog and ON/OFF controllers, enabling improved battery performance and longevity. PWM controllers have the capability to enhance battery capacity and charge acceptance, ultimately extending the battery's lifespan and reducing costs. Moreover, According to Faizal et al., (2022) Pulse Width Modulation (PWM) is a highly effective method utilized in numerous control systems. This technique finds application across various fields, including speed regulation, power management, and communication. PWM entails manipulating a square wave, adjusting its duty cycle to achieve a desired output voltage, represented by the waveform's average value. Essentially, PWM involves rapidly switching a DC motor on and off, with precise control over the duration of each on and off period.

Rural consumers often struggle to cover the extra expenses associated with purchasing a costly Solar Charge Controller (SCC) for their solar energy systems. Despite the benefits of extending battery life, the affordability of SCCs remains a significant challenge for these individuals (Ashiquzzaman et al., 2011). An efficient charger controller typically incorporates a battery capacity detection feature, which enables it to cease charging once the battery reaches full capacity. This detection process is facilitated through monitoring the voltage level of the battery. The controller charges the battery until it reaches a predetermined voltage level, and then stops charging until the voltage drops, indicating the need for recharging. Charger controllers typically comprise three main components: an input (with two terminals) connected to the solar cell output, an output (also with two terminals) linked to the battery, and another output (with two terminals) connected to the load (Faizal et al., 2022). The main objective of solar charge controllers is to manage the flow of DC energy to meet the needs of the battery backup, thereby extending the battery's lifespan. In PWM solar charge controllers, the pulse width varies based on the battery voltage, controlled by an oscillating circuit. When the battery voltage is low, the pulse width increases, allowing maximum solar energy input for battery charging. Conversely, as the battery voltage rises, the pulse width decreases, reducing solar energy input. Once the battery is fully charged, the pulse width decreases to a minimum, and the controller focuses on monitoring battery voltage. This controller's primary advantage is its ability to prolong battery life. Another common type is the MPPT controller, which adjusts input voltage to optimize energy storage efficiency by increasing voltage during low-demand periods and decreasing it during peak hours to maximize input current for battery charging (Acharya and Aitha, 2020).

The PWM (Pulse Width Modulation) charge controller serves as a charging regulator designed to charge batteries from solar panels by employing pulse modulation to manage the charging process. As the battery nears full capacity, the PWM mechanism gradually reduces the power supplied to the battery to alleviate strain on the battery (Faizal et al., 2022). When the energy stored in the battery backup is insufficient to match the pulse width, the high state will be extended, resulting in a notable duration, while the pulse width of the low state will be brief, akin to a single spike. The output signal from the PWM oscillator is directed to a switching circuit responsible for regulating the battery charging process. Typically, during a significant

portion of the pulse cycle, the switch remains in the on position, allowing solar energy to be transferred to the battery backup. As the battery backup nears full capacity, the duration of the on stage of the pulse width decreases, while the off stage increases. Likewise, the pulse width of the PWM oscillator adjusts so that the pulse predominantly remains in a low state, with occasional spikes occurring in the high state when the battery storage backup reaches full capacity. This spike is solely intended to monitor the level of the battery backup (Acharya and Aitha, 2020).

Acharya and Aitha, (2020) provided some detail about the mechanism of PWM micro controller: When the battery backup has insufficient energy, the duration of the pulse width in the high state increases significantly, while the pulse width in the low state becomes a brief spike. This pattern of pulses during periods of intense charging is depicted in Figure 3.4:

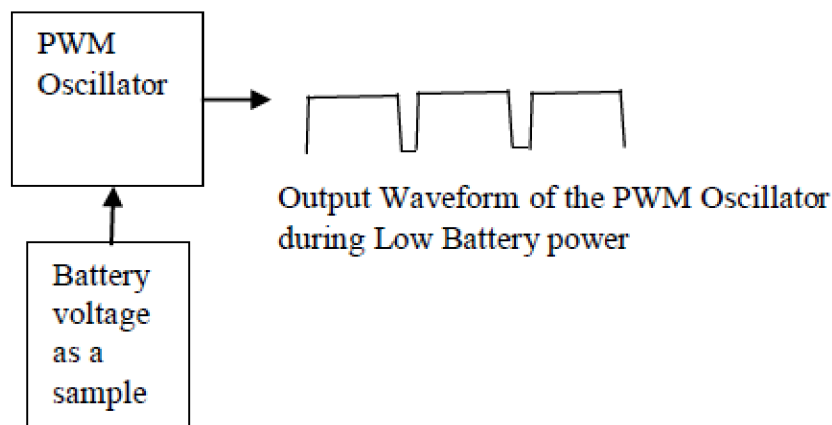


Figure 3.4: The output of PWM oscillator during low battery storage, source: Acharya and Aitha, (2020).

The PWM oscillator's output is subsequently linked to a switching circuit responsible for managing battery charging. During the majority of the pulse cycle, the switch remains in the "on" position, allowing solar energy to be stored in the battery backup. As the battery backup approaches full capacity, the duration of the "on" stage of the pulse width decreases, while the duration of the "off" stage increases. The pulse pattern during the stage when the battery is 50% charged is illustrated in Figure 3.5

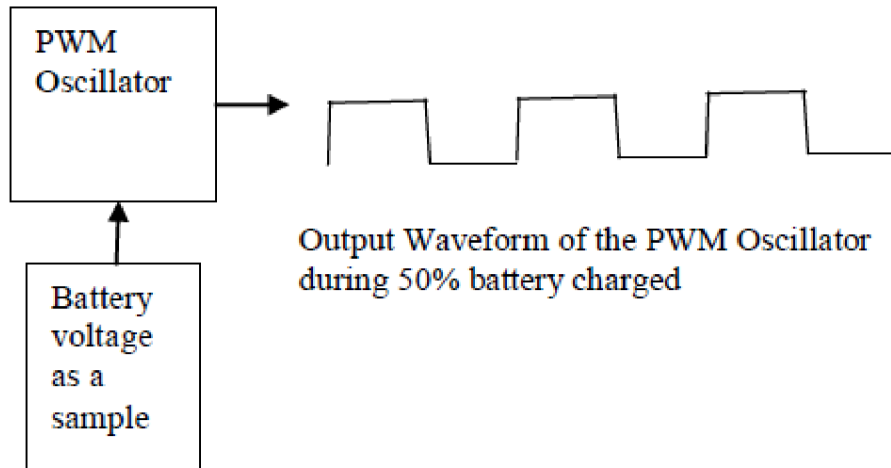


Figure 3.5: The output of PWM oscillator during 50% battery storage, source: Acharya and Aitha, (2020).

Likewise, the pulse width of the PWM oscillator adjusts to predominantly maintain a low state for most of the time, with occasional spikes occurring in the high state when the battery backup is fully charged. This condition serves as a means to monitor the level of the battery backup. The pulse width of the PWM oscillator during the charged state of the battery is depicted in Figure 3.6.

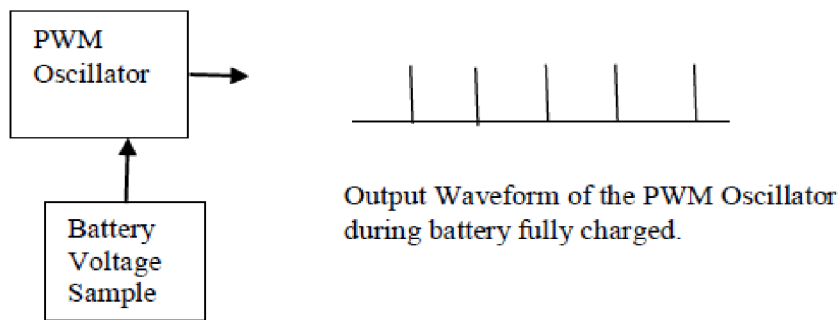


Figure 3.6: The output of the PWM oscillator during fully charged battery. Source: Acharya and Aitha, (2020).

Pulse Width Modulation (PWM) stands out as the most efficient method for maintaining a consistent voltage during battery charging, replacing traditional solar system control mechanisms. In PWM regulation, the solar array's current adjusts based on the battery's condition and charging needs. PWM solar chargers utilize advanced technology akin to contemporary high-quality battery chargers. As the battery voltage nears the predetermined set-point, the PWM algorithm gradually reduces the charging



current to prevent battery overheating and gas formation, while ensuring maximum energy transfer to the battery in the shortest time possible. This approach yields enhanced charging efficiency, rapid recharging, and optimal battery capacity (Faizal et al., 2022). The introduction of pulse width modulated controllers revolutionized the charging process from a PV array by enabling efficient three-stage charging or trickle charging. This system charges batteries using high-frequency electrical pulses, allowing for continuous adjustment of the amperage being delivered. When the batteries are discharged, the PWM controller detects this based on the battery bank voltage and remains active to provide maximum current, known as the bulk charging stage. As the batteries near full charge, the absorption stage begins, during which the controller maintains a constant battery bank voltage for a specific duration while gradually reducing the current by increasing the "off" time of the pulses. Once the batteries reach full capacity, the float charging stage, also known as trickle charging, takes place to maintain the batteries at their optimal level without overcharging (Thounaojam et al., 2014).

PWM chargers are readily accessible in the market and are cost-effective, available in different sizes to cater to diverse needs. However, they have constraints such as requiring the charger voltage to align with the battery bank voltage and typically having a maximum capacity of 60 amperes for the Maximum Power Point Tracker (Faizal et al., 2022). Pulse width modulation (PWM) facilitates efficient battery charging, prolongs battery lifespan, and maximizes the storage of solar-generated power. By ensuring that batteries retain more energy on average, PWM enables the use of smaller battery sizes or fewer batteries in a battery bank, thereby reducing overall system expenses. (Majaw et al., 2018).

### **3.2.2 Maximum Power Point Tracking microcontroller**

MPPT, or maximum power point tracking, is a crucial feature in inverters that ensures optimal performance of a PV array by continuously adjusting to the ever-changing MPP. The IV characteristic curve of PV modules illustrates key points such as the short-circuit current ( $I_{sc}$ ) and open-circuit voltage ( $V_{oc}$ ), with the MPP representing the peak power output. Factors like cell temperature and sun irradiance influence module performance, impacting both current and voltage. As these environmental conditions fluctuate, the array's MPP shifts accordingly. An effective MPPT feature enables the inverter to adapt to these variations, ensuring compliance

with grid standards and regulations throughout operation (Aribisala, 2013). In the study conducted by Putra et al. (2022), a comparison was made between the SCC (Solar Charger Controller) types MPPT (Maximum Power Point Tracker) and PWM (Pulse Width Modulation) using Simulink/Matlab. Their analysis revealed that MPPT outperformed PWM in terms of current input stability, exhibiting more consistent performance. Both controllers experienced fluctuations in voltage, with MPPT generally demonstrating greater stability. However, under conditions of high irradiance, PWM exhibited superiority over MPPT (Putra, et al., 2022). Figure 3.7 shows the MPP for a module at full sun at various temperature conditions.

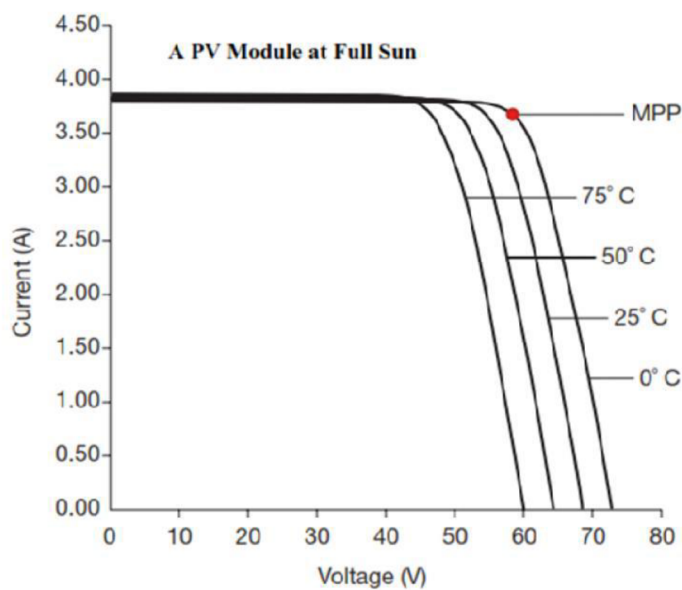


Figure 3.7: the MPP for a module at full sun at various temperature conditions, source: Aribisala, (2013).

MPPT controllers play a crucial role in maximizing the power extracted from solar panels, irrespective of weather fluctuations. Their significance has spurred numerous research endeavors aimed at enhancing PV system efficiency through the integration of MPPT controllers employing various algorithms, including fuzzy logic, neural networks, swarm algorithms, and the perturb and observe algorithm (P&O). These efforts seek to optimize PV system performance by minimizing oscillations, ensuring maximum power output even during sudden changes in irradiation, operating temperature, and instances of partial shading on solar modules (Robles-Algarín et al., 2022).

In their study, Fianti et al., (2021) found that the MPPT Solar Charger Controller (SCC) outperformed the PWM SCC in terms of power output (P), voltage (V), and current (I). Specifically, the MPPT SCC exhibited higher values in all three parameters compared to the PWM SCC, with differences of 0.07 watts, 0.09 volts, and 4.2 milliamps, respectively. Moreover, the average efficiency of the MPPT SCC was 177%, while that of the PWM SCC was 172%. These results indicate that the MPPT SCC is better suited for solar power generation systems due to its superior performance characteristics. In the same context, Faizal et al. (2022) found that the efficiency of MPPT solar charge controllers (SCCs) surpassed that of PWM SCCs. Specifically, the MPPT SCC exhibited an efficiency of 84.623%, whereas the PWM SCC showed a lower efficiency of 80.935%.

To optimize the use of solar panels, it is essential to implement a Maximum Power Point Tracking (MPPT) system along with a specialized inverter that includes battery voltage control. This setup allows for excess solar power to be efficiently utilized, ensuring that even when the batteries are fully charged, the surplus energy can be directed to power the load or stored in the batteries. By effectively managing the energy flow, the system can reduce reliance on the grid and maximize the utilization of solar-generated electricity (Pliusnin, 2017). An essential role of the software and monitoring component of the system is to manage the MPPT functionality, adjusting the DC voltage and current levels as necessary to effectively track the varying Maximum Power Point (MPP) of the PV array in real-time. Additionally, the software is responsible for activating the contactor to connect the inverter to the grid during daylight hours and disconnect it at nightfall when solar power generation ceases (Aribisala, 2013). In specific scenarios, MPPT charge controllers are employed to extract the utmost available power from PV modules, ensuring that the voltage generated by the PV module achieves its maximum power output, known as the 'maximum power point'. This point varies based on factors such as solar radiation, ambient temperature, and solar cell temperature. The implementation of maximum power point tracking (MPPT) techniques serves to enhance the efficiency of solar panels (Hamid et al., 2016).

MPPT solar charge controllers enable the utilization of PV modules with higher voltage outputs than the operating voltage of the battery system. However, due to their larger physical size, MPPT units tend to be more expensive compared to PWM

controllers. (Majaw et al., 2018). MPPT, or Maximum Power Point Tracking, is a technology integrated into battery charging regulators aimed at enhancing the efficiency of solar arrays and battery banks. It functions by transforming the high voltage DC output from solar panels into the lower voltage needed by the battery or battery bank, while simultaneously boosting the DC current supplied to the battery or battery bank (Faizal et al., 2022). The primary objective of an MPPT system is to analyze the output of PV cells and adjust the resistance accordingly to achieve maximum power output regardless of environmental conditions. The maximum power point (MPP) is determined by the product of the MPP voltage ( $V_{mpp}$ ) and the MPP current ( $I_{mpp}$ ) (Majaw et al., 2018). The MPPT solar charge controller functions as a DC-DC transformer, converting power from a higher voltage to a lower voltage level. When the output voltage decreases compared to the input voltage, the output current increases to maintain a constant product of power ( $P=V*I$ ). This relationship indicates that variations in power lead to adjustments in voltage and current levels (Islam, 2015).

MPPT (Maximum Power Point Tracking) charge controllers are a more recent innovation and are considered a premium option in the market. While they come at a higher cost, they are ideal for larger systems where the investment can lead to quick returns. MPPT controllers ensure efficient charging of the battery at full power, maintaining an efficiency level of around 90% to 93%. Despite their higher cost, MPPT controllers stand out for their exceptional efficiency compared to other types of charge controllers (Thounaojam et al., 2014). In the study of Plusnin (2017), the focus was on assessing the performance of the ECO MPPT Pro 200/100 controller, which is manufactured by MicroART company and specifically tailored for use in photovoltaic (PV) systems. This controller is capable of effectively managing PV systems with a capacity of up to 11kW. It is crucial to note that the total power output of the PV panels connected to the controller must not exceed its maximum power handling capacity.

Given the swift expansion of PV energy, there's a pressing need for research aimed at enhancing the effectiveness of PV system components, including solar modules, inverters, controllers, and batteries. In PV setups, various methods exist to boost performance, with notable options such as solar trackers, hybrid systems, and maximum power point controllers (MPPT) (Robles-Algarín et al., 2022). The Maximum Power Point Tracker (MPPT) plays a crucial role in optimizing the performance of solar cells

by ensuring they operate at their maximum power point. Among the various algorithms employed, one notable approach is the Incremental Conductance (INC) method. Typically, an MPPT system comprises a DC-DC converter and a microcontroller. There are two primary types of MPPT systems: dynamic and static. Dynamic MPPT systems incorporate mechanical trackers that adjust the orientation of solar panels to align with the sunlight direction, aiming to maximize power output. However, the drawback of dynamic MPPT lies in the energy consumption of the mechanical tracker's drive motor, potentially resulting in energy wastage if the light sensor sensitivity is too high. On the other hand, static MPPT systems utilize a different approach to optimize solar cell output. They leverage the current-voltage characteristic curve to identify the maximum power point. Static MPPT employs a DC-DC converter to condition the output voltage of solar panels, aiming to elevate the working voltage to the maximum power point for enhanced efficiency (Faizal et al., 2022). This system optimizes the solar panel output by ensuring it operates at its maximum power point, achieved either by increasing voltage while decreasing current or vice versa. Typically, solar panel output voltage ranges from 0 to 18V, whereas the voltage required for battery backup (typically 12V) falls between 12V to 14V. Any solar output voltage outside this range is wasted. The MPPT technology rectifies this issue by converting the solar output voltage to the required range for charging the battery backup. Thus, regardless of the fluctuating solar voltage due to sunlight variations, the MPPT controller ensures the battery backup receives charging by adjusting the current, effectively converting any voltage from 0V to 18V to the optimal 14V range (Acharya and Aitha, 2020).

From 2010 to 2021, there has been a remarkable enhancement in the competitiveness of photovoltaic (PV) systems, marked by an impressive 88% reduction in the average levelized cost of electricity for large-scale PV initiatives (Robles-Algarín et al., 2022). there is a growing demand for DC electricity, especially with the increasing focus on renewable energy sources like solar power. Solar energy, in particular, has emerged as a highly efficient alternative to conventional fuel-based power generation methods. To optimize the power output of solar panels, the Maximum Power Point Tracker (MPPT) system is employed. This system utilizes the perturb and observe algorithm, which aims to identify the maximum power point (MPP) by detecting zero  $dP/dV$ , indicating the peak of the MPP curve. Additionally, to further enhance system efficiency, solar panels are moved using a DC motor gearbox to ensure they remain perpendicular to the sun's

direction, thereby maximizing voltage, current, and power values. In another approach, static control with the MPPT method employs the Incremental Conductance algorithm to condition solar panel operations. This involves using a buck converter to adjust the operating voltage of the solar panels. Experimental setups typically involve a 6 V battery and a resistive load, with solar panels capable of delivering a peak power of 50 watts (Faizal et al., 2022).

### **3.2.3 A comparison between PWM and MPPT microcontrollers**

PWM charge controllers incorporate advanced technologies found in modern high-quality battery chargers. These controllers offer several distinct advantages, including the ability to detect and address lost battery capacity, enhance battery charge acceptance, accommodate high average battery capacities, equalize drifting battery cells, minimize battery heating and gassing, adapt to battery aging, and regulate voltage drops and temperature fluctuations in solar systems. (Hiwale et al., 2014). The PWM controller utilizes pulse width modulation to achieve the desired output voltage. Conversely, the MPPT controller focuses on a specific point known as the Maximum Power Point (MPP). At this point, the solar cell generates its maximum voltage and electric current (Fianti et al., 2021).

In Putra et al., (2022) study, a comparison of MPPT and PWM performance yielded the following findings: At 25°C, the PWM charger controller exhibited higher current output compared to MPPT, while at 30°C, MPPT surpassed PWM. However, at 35°C, both controllers showed similar values under 600 W/m<sup>2</sup> irradiance. Under 800 W/m<sup>2</sup> irradiance, MPPT demonstrated superior current output over PWM, although it decreased at 30°C. Overall, MPPT exhibited better performance across various temperature ranges compared to PWM, albeit with slight variations. In terms of input voltage at 400 irradiances, PWM experienced a decrease at 35°C, while MPPT showed an increase. MPPT performed better at lower temperatures under this irradiance condition, while PWM showed superiority at higher temperatures. Across different temperature ranges, MPPT generally outperformed PWM, except when the irradiance was high, where both controllers exhibited stable performance. Notably, MPPT showed increased output voltage compared to PWM, except under high irradiance conditions, where their performance was comparable.

The Solar Charger Controller (SCC) served as an electronic component responsible for regulating the current, acting as both a current regulator for the current flowing from the solar cell to the battery and the output load. Furthermore, the SCC played a role in preventing battery overcharging, and thus extending the battery's lifespan (Fianti et al., 2021). Solar radiation levels can fluctuate throughout the day due to factors like cloud cover, varying sun intensity, seasonal weather patterns, and local atmospheric conditions like fog. These fluctuations impact the output power of solar cells, making it less consistent and optimal. To address this issue, a control device known as a Solar Charge Controller (SCC) is employed to stabilize the energy output from solar cells (Faizal et al., 2022). The primary function of PWM charge controllers is to align the voltage of the panel with the battery voltage, effectively reducing the panel output voltage. In contrast, MPPT technology is designed to maximize the output from solar panels by operating based on the panel voltage and converting any excess voltage into current, thereby boosting the overall output of the solar system. (Majaw et al., 2018).

Majaw et al., (2018) provide a corporation between the advantages and disadvantages of PWM and MPPT as Table 3.1 and Table 3.2 shows:

Table 3.1: Advantages of PWM and MPPT

MPPT	PWM
MPPT solar charge controllers can enhance efficiency by up to 30%.	PWM controllers are constructed using a well-established technology with a proven track record.
these controllers enable the possibility of utilizing an array with a higher input voltage than the battery bank.	These controllers come at a low cost.
They are employed to rectify the detection of variations in the I-V characteristics of solar cells.	<ul style="list-style-type: none"> <li>▪ PWM controllers are offered in sizes ranging up to 60 amps</li> </ul>

It compels the PV module to operate at a voltage proximate to the maximum power point in order to extract the maximum available power.	PWM controllers typically boast durability, often featuring passive heat sink-style cooling mechanisms for efficient heat dissipation.
It simplifies the system while ensuring highly efficient output.	PWM controllers are known for their extended lifespan, providing reliable operation over a longer period of time.

Table 3.2: Disadvantages of PWM and MPPT

MPPT	PWM
MPPT controllers typically come at a higher cost compared to PWM controllers.	The nominal voltage of the solar input must align with the nominal voltage of the battery bank when employing PWM controllers.
MPPT units tend to have larger physical dimensions.	Currently, there are no controllers available exceeding 60 amps DC in size.
Determining the suitable size for a solar array can pose challenges without guidance from MPPT controller manufacturers.	PWM controllers have restricted capacity for expanding the system.
The use of an MPPT controller necessitates the solar array to consist of similar photovoltaic modules in similar strings.	They are not suitable for efficient use with 60A panels.

Positioned between the solar panel and the battery bank, the charge controller acts as a safeguard against battery overcharging. The efficiency of battery charging and solar



panel utilization depends on the algorithm or control strategy used by the charge controller, which directly influences the system's ability to meet load demands and extend battery lifespan (Faizal et al., 2022). Renewable energy options offer economical solutions, high performance, and simplified installation processes. By optimizing the utilization of charge controllers, lighting system efficiency can be enhanced. These controllers play a vital role in averting reverse current flow. In instances where solar panels are inactive, there's a risk of electricity backflowing from the batteries through the panels. However, the controller detects the absence of solar panel energy and promptly disconnects them, effectively halting reverse current flow. A comparative analysis between the two controller types underscores the superior performance of MPPT over PWM. (Majaw et al., 2018).

## **4 Practical Part**

### **4.1 Materials and Methods**

This research starts with building two medium size commercial solar system with installed capacity of 4kwp and total photovoltaic power output of 6.426 Mwh per year. the two systems differ in charge controller. According to many researches, the most popular charge controllers are PWM based as well as MPPT technology based, where These charge controllers are designed such that the solar battery gets recharged quickly and does not get over discharged, thereby ensuring the prolonged lifespan of the battery. (Majaw et al., 2018; Acharya and Aitha, 2020). Thus the first system depends on PWM microcontroller and the second system depends on MPPT microcontroller.

Next step in this research is to measure the power obtained from two systems. To do this the study adopt the method used by Robles-Algarín et al., (2022). where this study uses the Irradiation of the Tartus city in Syria ( $2045 \text{ kw/m}^2$ ). The Irradiation data of syria is obtained from The World Bank, Global Solar Atlas 2.0 in 2024. Figure 4.1 shows The Irradiation data of syria.

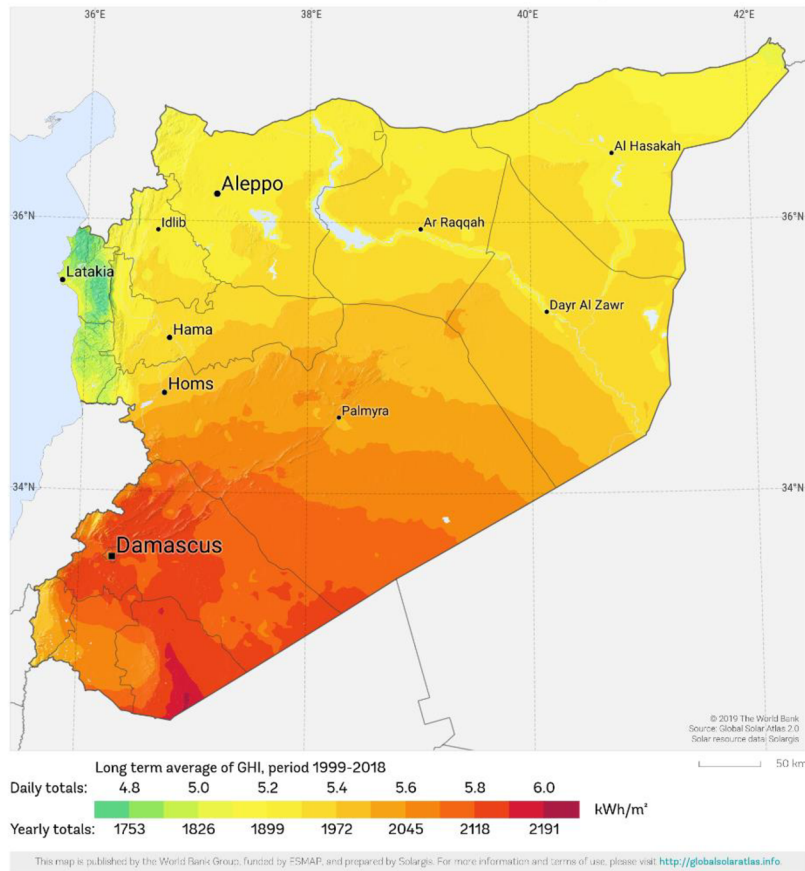


Figure 4.1: The Irradiation data of Syria. (source: World Bank, Global Solar Atlas 2024).

In order to predict the monthly energy output of the solar system, the study utilized data specific to Tarus city in Syria. This data was obtained from the Solar Atlas of Syria, which offers detailed information on monthly average of total photovoltaic power output from a medium size commercial solar system. The corresponding data is presented in figure 4.2.

## Monthly averages

Total photovoltaic power output

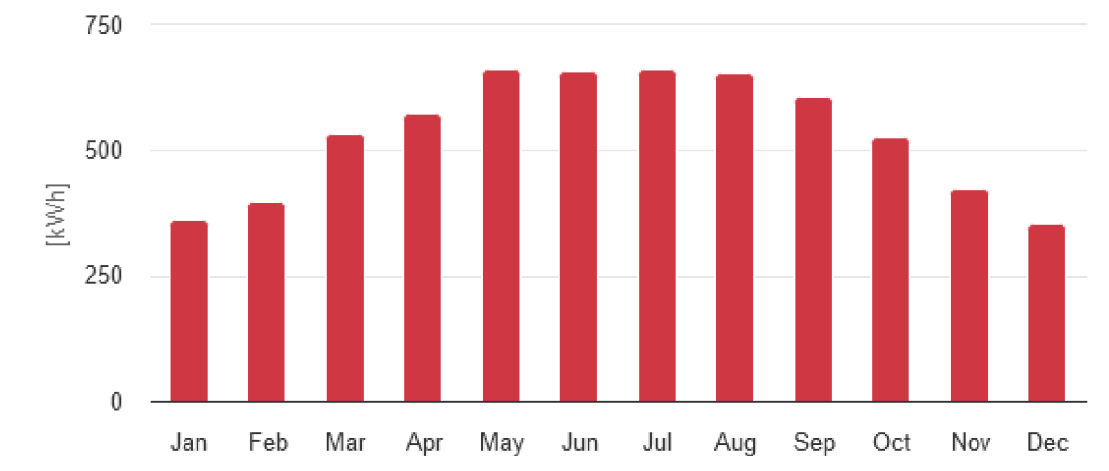


Figure 4.2: monthly average of total photovoltaic power output in Tartus city. (source: Global Solar Atlas, 2024).

In their investigation, Robles-Algarín et al. (2022) discovered that a solar system employing an MPPT microcontroller exhibited an efficiency of 97.74% when compared to a solar system utilizing a PWM microcontroller 68.20%, based on theoretical estimations. This study utilizes this outcome to shed light on the performance of the two solar systems.

### 4.1.1 Solar system based on PWM microcontroller

Solar system has four main elements: solar panels, batteries, charge controller and inverter. There are various types of solar modules available on the Syria market. Solar cells typically produce a potential difference of approximately 0.5 volts. To attain the 14 to 18 volts required to charge a standard 12-volt battery, multiple solar cells need to be connected in series. Solar panels are then created by connecting these cells together. By connecting multiple panels both in parallel and in series, higher current and voltage outputs can be achieved, respectively (Pliusnin, 2017).

The utilization of batteries addresses the challenge posed by fluctuations in solar panel energy generation and the inconsistency in energy quality. Typically, deep discharge lead acid batteries are employed for this purpose. These batteries are characterized by a substantial number of charge-discharge cycles, which is crucial in

terms of their longevity and the frequency of replacements required over time. To decrease charging currents, batteries are connected in series, while connecting them in parallel enhances the overall capacity of the battery bank (Pliusnin, 2017). The battery sets commonly found in the Syrian market are predominantly available in either 6-volt or 12-volt configurations. This study utilizes 12-volt batteries.

In order to convert the DC power generated by the solar system into AC power, an inverter must be installed. In stand-alone systems, the inverter is directly linked to the battery bank. This arrangement ensures that the DC output from the batteries is first converted into AC before being supplied to the load. (Pliusnin, 2017).

The Solar Charge Controller (SCC) is an essential component responsible for managing the energy flow among the battery, load, and solar panel through the use of a micro-controller. Its key role includes preventing overcharging, facilitating effective charging and discharging, and blocking reverse charging. Moreover, the SCC plays a pivotal role in optimizing the utilization of the solar system (Ashiquzzaman et al., 2011).

The primary objective of Pulse Width Modulation (PWM) is to control the power devices of the solar system controller by implementing constant voltage battery charging. Modern charge controllers utilize PWM to regulate the power supplied to the batteries, especially when they are nearing full charge. By employing PWM, the battery can be fully charged while minimizing stress, thereby extending its lifespan. (Majaw et al., 2018).

The Pulse Width Modulation (PWM) charge controller stands out as one of the most commonly used controllers for storing solar panel energy in battery backup systems. In this setup, the solar energy input undergoes switching through a circuit before being stored in the battery backup. This switching process is governed by an oscillator, which adjusts its pulse width based on the level of energy stored in the battery backup. The block diagram illustrating the solar PWM charge controller is depicted in the figure 4.3.

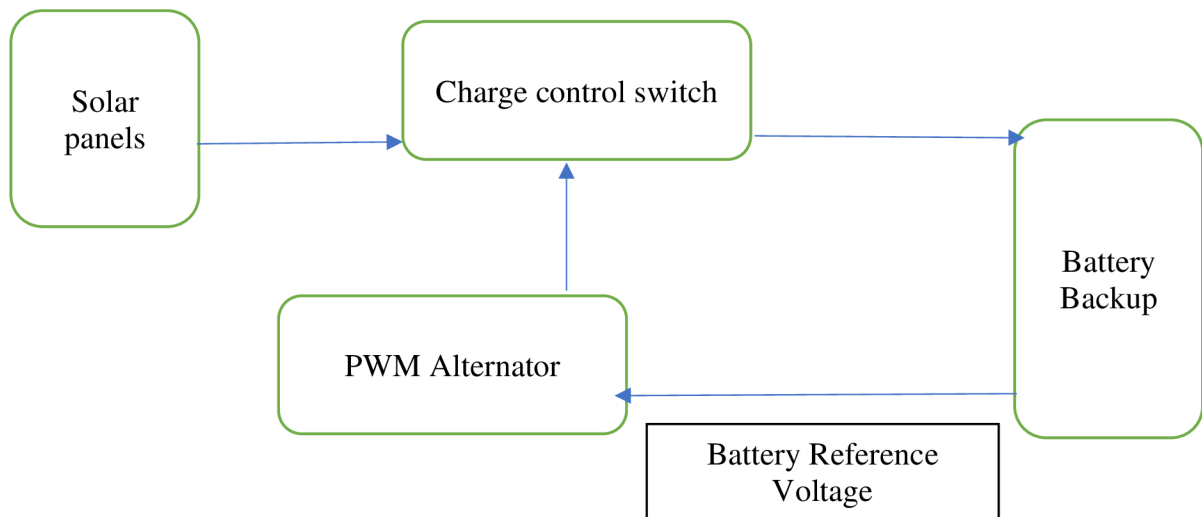


figure 4.3: Conceptual model of solar PWM charge controller.

#### 4.1.2 Solar system based on MPPT microcontroller

This study uses PV panel, battery and inverter with the same specifications in Solar system based on PWM to ensure accuracy. A newer and more efficient type of charge controller that has gained popularity recently is the MPPT (Maximum Power Point Tracking) charge controller. This system is designed to optimize the output of solar panels by tracking the maximum power point. This is achieved by adjusting either the voltage or the current output of the solar panel to ensure that it operates at its maximum power point.. The MPPT technology effectively converts the solar output voltage to the required charging voltage for the battery backup. This means that even when the solar voltage varies due to changes in sunlight intensity, the MPPT controller ensures that the battery backup receives charging within the optimal voltage range. The conceptual model of an MPPT charger is depicted in Figure 4.4.

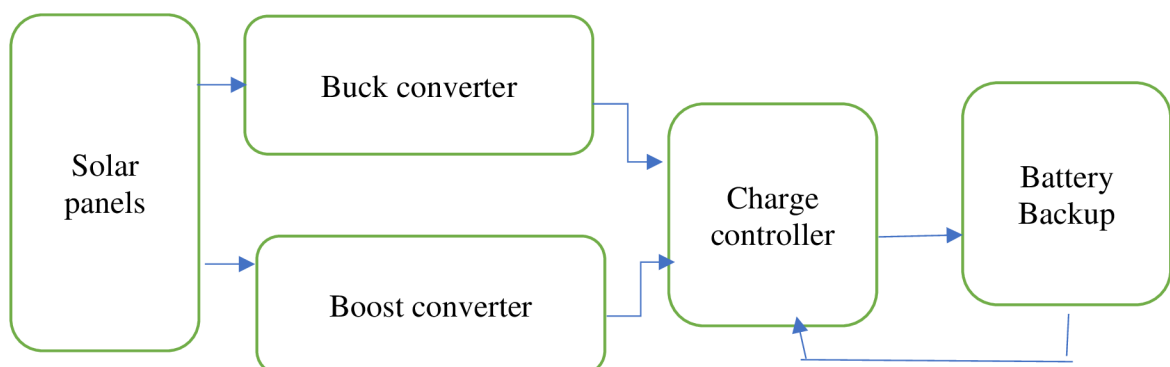


figure 4.4: Conceptual model of solar MPPT charge controller.

Solar energy undergoes a boosting process using a boost converter to elevate its voltage to 14V until the solar voltage reaches this threshold. During this phase, the input current experiences a notable decrease. Upon surpassing 14V, a buck converter steps in to lower the voltage back to 14V while simultaneously increasing the current. This ensures that energy from the solar panel is effectively utilized throughout the day for charging the battery backup, rather than allowing the solar voltage to remain in the range of 14V to 18V.

## **4.2 Economic efficiency measure**

Following the determination of the average energy output of the solar system in both PWM and MPPT microcontroller systems, the study evaluates economic efficiency in accordance with existing literature, which commonly assesses economic efficiency using the payback period. The prices associated with solar system equipment were acquired from the Syrian market. Then the payback period was calculated for each of the two types of solar energy systems based on local Syrian electricity prices. Where The comparison was conducted between the cost of installing the solar energy system and its equivalent in local electricity expenses.

# **5 Results and Discussion**

## **5.1 Power obtained from PV system**

Based on the data collected from (Global Solar Atlas) regarding the theoretical outputs of medium size commercial solar system in the city of Tatus, Syria, along with the efficiency metrics for both MPPT and PWM controllers, table 5.1 can be derived.

Table 5.1: Power obtained from solar systems based on microcontrollers (kwh).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Theoretical power	362.2	398.8	535.9	576.2	660.6	658.4	661.6	655.8	607.6	528.3	424.9	355.5	6426
Power based on PWM 68.20%	247.02	271.98	365.48	392.96	450.52	449.02	451.21	441.38	360.30	289.78	242.45	242.45	4382.53
Power based on MPPT 97.74%	354.01	389.78	523.78	563.17	645.67	643.52	646.64	640.97	593.86	516.36	415.29	347.46	6280.77

The study utilizes this data to calculate the saving cost for both the solar energy system based on PWM micro-controller and MPPT micro-controller.

## **5.2 Economic efficiency of solar system based on PWM and MPPT microcontrollers**

For the installation of a 6.426 MWh solar system, the requirements include 10 solar panels, 4 batteries, 1 charge controller (MPPT or PWM), and 1 inverter. In addition to mounting hardware and labor costs. Table 5.2 and table 5.3 presents the installation costs for solar system based different microcontroller derived from the Syrian market prices in 2024.

Table 5.2: the installation costs for solar system based on PWM microcontroller

Item	Quantity	Price per unit	Total price
Solar panel	10	240 \$	2400 \$
Battery	4	1500 \$	6000 \$
Charge controller (PWM)	1	50 \$	50 \$
Inverter	1	1000 \$	1000\$
Mounting hardware		500 \$	500 \$
Labor costs		700 \$	700 \$
Total			10650 \$

Table 5.3: the installation costs for solar system based on MPPT microcontroller

Item	Quantity	Price per unit	Total price
Solar panel	10	240 \$	2400 \$
Battery	4	1500 \$	6000 \$
Charge controller (MPPT)	1	600 \$	600 \$
Inverter	1	1000 \$	1000\$
Mounting hardware		500 \$	500 \$
Labor costs		700 \$	700 \$
Total			11200 \$



For commercial consumption, the Syrian Ministry of Electricity has set the price of the kilowatt at \$0.12. based on the annual power generated by solar systems based on microcontrollers (PWM, MPPT) (Table 5.1), we can calculate the saving cost from equation (1):

$$\begin{aligned} \text{saving cost} &= \text{Power generated from solar system} \\ &* \text{the govermental electricy price for KW (1)} \end{aligned}$$

Saving cost of solar system based on PWM microcontroller = 4382.53 \* 0.12 \$= 525,90 \$.

Saving cost of solar system based on MPPT microcontroller = 6280.77\* 0.12 \$= 753.69 \$.

To calculate the economic efficiency of solar system based on microcontrollers, we use the payback method as equation 2 illustrates:

$$\text{Payback period} = \frac{\text{cost of solar system}}{\text{saving cost}} \quad (2)$$

Payback period for solar system based on PWM microcontroller:

$$\text{Payback period} = \frac{10650}{525.90} \simeq 20 \text{ year}$$

Payback period for solar system based on MPPT microcontroller:

$$\text{Payback period} = \frac{11200}{753.69} \simeq 15 \text{ year}$$

This study found that the cost of solar energy based on a charge controller relying on PWM microcontroller is lower cost than its counterpart relying on MPPT microcontroller in the Syrian markets. However, the higher efficiency of MPPT microcontroller makes it more economically efficient. Where The results of this study indicate that the payback period for the solar energy system utilizing MPPT microcontroller is 15 years, which is shorter than the payback period for the solar energy system relying on PWM microcontroller, which is 20 years.

## 6 Conclusion

This study aimed to investigate the economic efficiency of solar energy based on two types of microcontrollers in solar system, namely Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT), in the city of Tartus in Syria. These two cities share commonalities in terms of Irradiation ( $2045 \text{ kw}/m^2$ ). To achieve this, the outputs of medium size commercial solar energy systems with installed capacity of 4kwp and total photovoltaic power output of 6.426 Mwh per year were measured for both types of microcontrollers, followed by an assessment of the costs associated with each of these systems. Finally, this research measured the economic efficiency through the payback period. According to the findings of this research, it was observed that the solar energy system employing an MPPT microcontroller demonstrates superior economic efficiency. Specifically, the payback period for the MPPT-based system is 15 years, representing a shorter duration compared to the 20 years payback period for the PWM-based system. These findings assist investors and other stakeholders in making economically efficient choices regarding investment in solar energy systems.

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