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YÜKSEK LİSANS PROGRAMI

ANALYSIS AND EXAMINATION OF FLOATING PHOTOVOLTAIC POWER SYSTEMS ACCORDING TO POWER AND EFFICIENCY PARAMETERS

YÜZER FOTOVOLTAİK GÜÇ SİSTEMLERİN GÜÇ VE VERİMLİLİK PARAMETRELERİ AÇISINDAN INCELENMESİ VE DEĞERLENDİRİLMESİ

YÜKSEK LİSANS TEZİ

ABDULRAHMAN EMARA

Advisor: Assoc.Prof. Dr. A. HAKAN YAVUZ

TOKAT- 2023

TEZ BEYANI

Tez yazım kurallarına uygun olarak hazırlanan bu tezin yazılmasında bilimsel ahlak kurallarına uyulduğunu, başkalarının eserlerinden yararlanılması durumunda bilimsel normlara uygun olarak atıfta bulunulduğunu, tezin içerdiği yenilik ve sonuçların başkabir yerden alınmadığını, kullanılan verilerde herhangi bir tahrifat yapılmadığını, tezinherhangi bir kısmının bu üniversite veya başka bir üniversitedeki başka bir tez çalışması olarak sunulmadığını beyan ederim.

ABDULRAHMAN EMARA

22-August- 2023

JÜRİ KABUL VE ONAY

Abdulrahman Emara tarafından hazırlanan **"Analysis and Examination of Floating Photovoltaic Power Systems According to Power and Efficiency Parameters"** adlı tez çalışmasının savunma sınavı 22/08/2023 tarihinde yapılmış olup aşağıda verilen Jüri tarafindan Oy Birliği ile Tokat Gaziosmanpaşa Universitesi Lisansüstü Eğitim Enstitüsü Elektrik Elektronik Mühendisliği Anabilim Dalı'nda Yüksek Lisans Tezi olarak kabul edilmiştir.

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Lisansüstü Eğitim Enstitüsü Müdürü

PREFACE

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ÖZET

YÜZER FOTOVOLTAİK GÜÇ SİSTEMLERİN GÜÇ VE VERİMLİLİK PARAMETRELERİ AÇISINDAN INCELENMESİ VE DEĞERLENDİRİLMESİ

Emara, Abdulrahman
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Ağustos 2023, IX + 73 sayfa

Teknolojik gelişmeler ve nüfusun hızla artması global olarak enerji ve suya olan talebi artırırken, salgın ve savaş gibi global krizler maliyetlerin de önemli ölçüde artmasına neden oldu. Yüzen fotovoltaik güç sistemleri su yüzeylerine kurulan, suyun buharlaşmasını engelleyerek su tasarrufu sağlayan, yosunlaşmayı engelleyerek su kalitesini artıran, kara tabanlı PV sistemlere göre arazi maliyetlerinin ortadan kalkması ile enerji maliyetini büyük ölçüde düşüren ve negatif sıcaklık katsayısına sahip panellerin verimliliğini suyun soğutucu etkisiyle artıran yenilenebilir enerji tabanlı bir sistemdir. Su yüzeylerine kurulan FPV sistemleri için en uygun yerler hidroelektrik santralleri için kurulan barajlardır. Bu çalışmada yüzer ve kara tabanlı PV sistemlerin güç ve verimlilik açısından karşılaştırılması amacıyla kurulan değişik açı ve soğutma özeliklerine sahip 5 farklı kurulum Almus Baraj Gölü'nde test edildi. Veriler analiz edilerek sıcaklık, güç ve verimlilik açısından değerlendirildi. FPV panel yüzey sıcaklığı kara tabanlı PV panelden 10.3 derece daha düşük ölçüldü. FPV panelin çıkış gücü 5.9 W iken verimliliği kara tabanlı PV panelden %1.77 kadar daha yüksek hesaplandı. FPV sistemlerinin su yüzeylerine kurulması çevresel, ekonomik ve termoelektrik etkileri nedeniyle mevcut PV sistemlere göre önemli bir avantaj sağlamaktadır.

Anahtar Kelimeleri: Fotovoltaik, Güneş, Verimlilik, Yüzer fotovoltaik, Karasal, Soğutma

ABSTRACT

ANALYSIS AND EXAMINATION OF FLOATING PHOTOVOLTAIC POWER SYSTEMS ACCORDING TO POWER AND EFFICIENCY PARAMETERS

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While the technical developments and rapid increase in population have significantly increased the demand for energy and water globally, global crises such as Covid-19 pandemic and the Russian- Ukrainian war have caused costs to increase significantly. Floating photovoltaic power system is a strategy to harvest solar power. Floating photovoltaic power systems are installed on water surfaces, they save water by preventing water evaporation, increase water quality by preventing algae bloom, reduce energy costs by eliminating land costs compared to land-based PV systems, and increase the efficiency of panels with lower temperature coefficient due to the cooling effect of water. The most suitable place for FPV systems to be installed on is dams built for hydroelectric power plants. In this experiment, five different installations at different inclination angles and cooling techniques in the Almus dam lake were installed to compare floating and land-based PV systems in terms of power output and operating temperature. The data was analyzed and evaluated in terms of temperature, power output and efficiency. The FPV panel surface temperature was recorded to be 10.3 degrees lower than the land-based PV panel at the same inclination angle. Output power of FPV panel was 5.9 watts higher than land-based panels at the same inclination angle. The floating panel efficiency was 1.77% higher than the land-based PV panel. The findings of this study firmly establish the superiority of floating photovoltaic panels over land-based systems. The enhanced energy output and efficiency highlight the potential of floating solar solutions in meeting the escalating energy demand while conserving land resources.

Keywords: Photovoltaic, Solar, Efficiency, Floating photovoltaic, Terrestrial, Cooling

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1. INTRODUCTION

The rapid developments in technology and significant increase in the world's population, have increased the need for energy and water globally. Currently, global energy demand is mostly met by fossil fuels. Fossil fuel is a hydrocarbon-containing compound formed naturally on Earth from the remains of dead animals and plants. The main fossil fuels are coal, oil, and natural gas. The combustion of fossil fuels heavily contributes to the global warming crisis, climate change (Omer et al., 2020), and the pollution of the ambient air & water sources.

Fossil fuels are non-renewable, and it has a limited lifespan. It is estimated that it will run out in 2040 (Omer et al., 2020).Meeting the energy demand using fossil fuel and its derivatives has proven to be more damaging than beneficial with all the catastrophic effects it is causing, including the global warming crisis, food shortage due to the use of habitable lands for drilling for oil and building oil refineries, the great negative impact on the environment including waste products and gases produced to the air, water sources and the soil and many more that will be discussed further.

Additionally, foreign dependency on energy and water is one of the largest problems many countries face, forcing a lot of countries to explore and invest in alternative energy sources to grant their energy independence in water and power. Relying on renewable energy and natural resources will reflect positively on the economic, and political situation of any country and will also improve the quality of life of the people and the environment. Due to all the challenges and consequences associated with using fossil fuels as an energy source, countries must come together and commit to increase the share of energy generated from clean and renewable energy to meet the energy demand while trying to conserve the environment and fix the damage caused by years and years of using fossil fuel as a main energy source.

The global energy crisis of 2021-2022, was sparked by the rapid economic rebound in the wake of the COVID-19 pandemic which led to tighter energy supply markets starting in October 2021. The world's energy challenges were exacerbated in February 2022 following the Russian Federation's invasion of Ukraine.

The energy crisis contributed to high inflation and then became a global phenomenon during the year, even if the effects were less visible in Asia and some parts of the world. Throughout 2022, energy prices in Europe and elsewhere skyrocketed to their highest levels since 2008. The International Energy Agency estimates that higher fossil fuel prices accounted for 90% of the increase in electricity prices in 2022, and that fossil gas prices alone accounted for more than half this rise.

In many countries, governments sought alternative fossil fuel sources to restore disruptions to the energy supply or opted to heavily subsidise fossil fuels to shield consumers from price hikes; despite this, the uptake of renewables increased in all sectors. Overall, 2022 was a year marked by energy crisis resulting in high inflation globally, but it also was a year of accelerated deployment of renewables as different sectors found renewable energy sources to be reliable, stable and affordable.

1.1.Renewable Energy in World

According to the 2023 world renewable energy report, the rate of modern renewable energy use worldwide is only 30%. In other words, 70% of the energy demand is still fulfilled by fossil fuels (Figure 1.1). 15.5% of the total energy used is used to meet domestic needs, including heating, cooling, and lighting; the rate of renewable energy used in this sector is 33%. 30% of the energy used supports the public transportation system, with only 4.1% being renewable. The remaining energy (33%) is used thermally for space heating/cooling, and industrial heat processes, with renewable energy contributing only 16.8% (Renewables now, 2023).

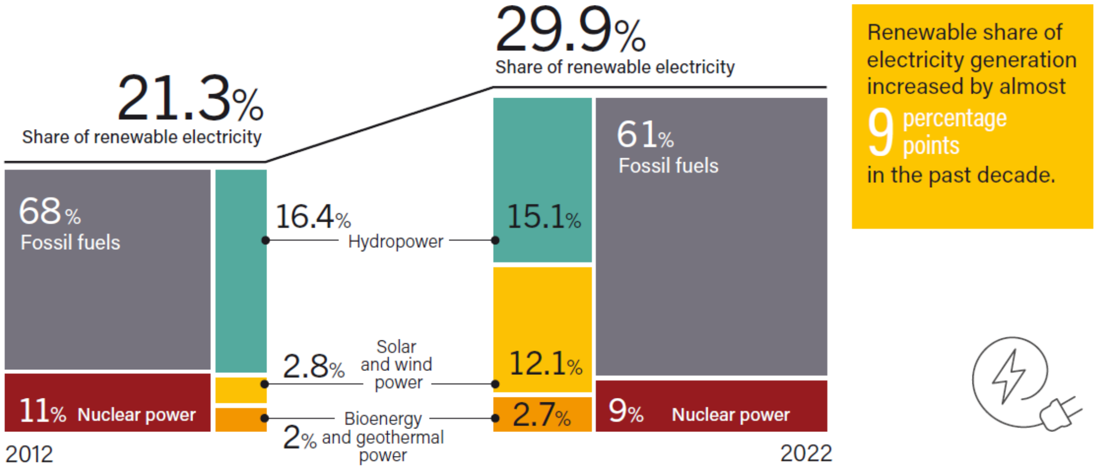

Figure 1. 1 Global Energy Status (Renewables now, 2023).

Those figures highlight the urgent need for sustainable energy sources to prevent further damage and climate change. The use of renewable energy grants this by reducing emissions and protecting water sources. While many countries have made huge efforts to reduce emissions by 2030 within the framework of The Paris Agreement, to achieve renewable energy and protect the planet; major changes must be implemented. The agreement aims to reduce global warming below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels (Bataille et al., 2018).

The energy transition has focused not only on power, but also on a few specific technologies in the power sector. In 2022, solar PV and wind power represented 92% of renewable power capacity (70% solar and 22% wind). In total, 348 GW of renewable power capacity was added in 2022 (up 13% from the 306 GW added in 2021); however, this annual capacity addition would need to be accelerated by as much as 2.5 times to achieve the capacity growth required to achieve the International Energy Agency's (IEA, 2020) scenario for net zero emissions by 2030 (Renewables now, 2023).

1.2.Renewable Energy in Turkey

According to the Republic of Turkey's Ministry of Energy and Natural Resources, Turkey receives enough solar radiation to generate 380 billion kWh of energy annually. This translates to an average of annual sunshine duration of 2766.5 hours/year and an average daily total sunshine time of 7.58 hours/m^2/year, with an average daily radiation intensity of 4.18 kWh/m^2/day.

According to a report published by TSKB Economic Research in 2022 (TSKB Economic Research, 2022), Turkey's total generation capacity had accumulated 99,820 megawatts (MW) by December 2021. In August, 54.4% of the total capacity was generated using renewable energy with solar power accounting for 168 MW of this capacity. According to International Energy Agency (IEA, 2020), Turkey could be ranked fifth in Europe in its renewable energy capacity, that is expected to increase by 22.2 gigawatts by 2025 totalling to 66.8GW (IEA, 2020).

As figure 1.2 shows, solar power accounts for 8.8% of the total capacity, which is a significant portion; however, another golden opportunity to utilise is to build and combine solar power with another form of dominant renewable energy in Turkey to come up with a novel modern approach to produce electricity and that when coupling solar power and hydro power comes into play to give us floating solar photovoltaic power systems. With over 25 rivers in Turkey and hydropower being Turkey's cheapest electricity source (O'Byrne, 2021), the government relies heavily on hydropower to generate energy. Hydropower accounts for 30.9% of the total capacity, and there are more than 700 hydropower plants in Turkey, with about 60 of those having a capacity of 100 MW and over (Hydropower.org, 2023).

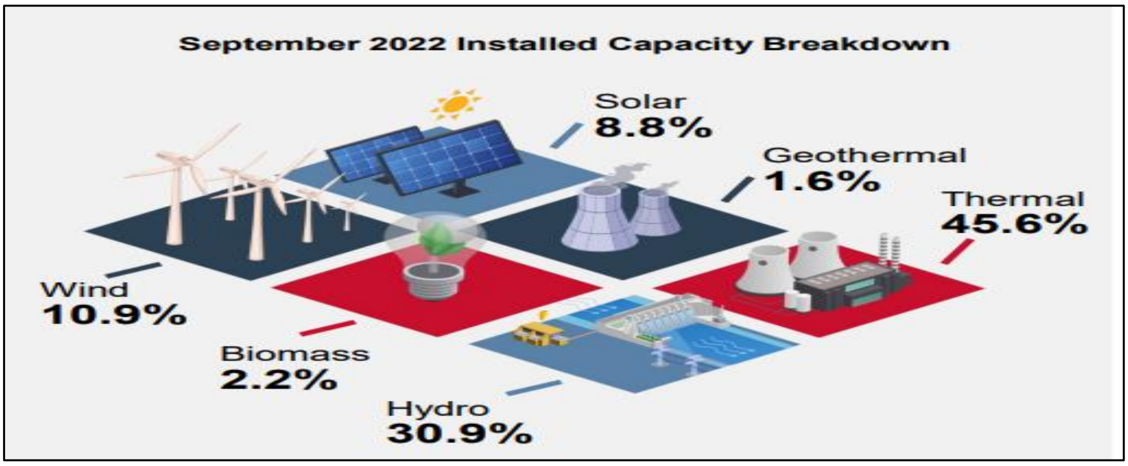

Figure 1. 2 Demonstrates the different type of sustainable energy installed in September 2022 in Turkey. (TSKB, 2022).

1.3.Solar energy

Sun is the centre of all forms of the renewable energies on the earth. The growth of plants, which is considered as biofuel thermal distribution by solar energy through natural convection in the atmosphere and conduction in solids. The pattern in which wind blows is due to the pressure difference generated by the direct uneven heating of the earth's surface by the sun.

PV technology is a semiconductor-based technology that converts the radiation received from the sun directly into electrical energy. A semiconductor solar cell uses only the 300-1000 nm wavelength parts of the radiation it receives from sunlight. Actively used radiation is only 5-20% of the total absorbed energy, and the yield varies between 10% and 20% (Energy.gov, 2020). The reminder of the radiation that is not converted to power, emerges as heat energy, and causes an increase in the cell temperature. An increase in temperature at the junction of positive (p) and negative (n) semiconductors causes a decrease in efficiency and hence a decrease in the electrical power due to the hole and electron mobility. This also reflects negatively on the durability and reduces the expected PV module lifespan (Energy.gov, 2020).

Photovoltaic systems are generally installed in terrestrial areas, thus why significant land needs arise. Accordingly, large-scale PV system installation is complex in places with high population density. Although roof and facade installation are solutions that could partially and temporarily solve this problem of PV systems, they cannot be used all the time due to installation difficulties (Kumar, Niyaz and Gupta, 2021).

In addition, due to the shading factor, which affects the radiation falling on the solar panels adds another layer of complexity to the choice of areas for terrestrial installation. Land selection in renewable energy investment decisions is determined by considering its proximity to the interconnected grid, its integrability to the grid, acre cost of the land, operating cost, and sunshine duration. However, since the cost of the lands close to the residential areas is high, it severely impacts the return time of the investment and sometimes even eliminates the feasibility of the investment entirely. Nevertheless, when the renewable energy investment trends in the world are evaluated, PV systems come to the fore.

As mentioned previously, solar energy is one of the prime solutions for tackling climate change and global warming. Historically, photovoltaic panels installations, whether plants for industrial and large-scale purposes or individual consumption have been placed on rooftops or grounds where the weather allows an adequate number of hours of sun. Studies have shown that using active and passive heat transfer systems to minimise the effect of the temperature coefficient on solar panels' efficiency (Ghadikolaei, 2021) & (Nižetić et al., 2021) would result in higher energy output. PV panel provides a 20.2% power increase using finned heat exchangers, a 3.5% efficiency increase with a heat pipe cooling system, a 6.7% power increase using phase change material, a 38% output power increases the potential of micro-channel water cooling systems (Verma et al., 2021).

Over the years, a rapid surge in the distribution and installation of PV solar systems to increase green energy generation has been observed. However, other significant resources were being overlooked; and those are oceans, seas, and lakes. Taking the advantage of cooling down the panels on their efficiency and the challenges associated with terrestrial PV systems, scientists and engineers continued developing this sector; and came up with what we call now floating photovoltaic panels. Floating photovoltaic (FPV) systems are, as the name suggests, solar panels that are mounted to float on a water body, such as reservoirs, oceans, lakes, or dams.

1.4.Literature Review

In this literature review, a thorough analysis of the literature available about renewable energy sources in general and floating photovoltaics, in particular, was carried out and presented to highlight the primary and vital points. This literature review also covers significant challenges or limitations concerning the above-mentioned topics.

(Hafeez et al., 2022) the paper discussed using water bodies like lakes and canals in urban areas to mount floating photovoltaic systems instead of taking over lands and spaces with traditional on-the-ground photovoltaic systems. On the ground, PV systems could affect land quality and deem them unfit for other purposes, such as residential units. The articles focused on the potential deployment of a floating photovoltaic system on Lake NUST in an urban area in Pakistan. They compared it to a similar on-the-ground photovoltaic system.

The study considered the effect of real-time temperature drop, calculation of water reduction efficiency for FPV systems, and economic parameters such as net present value (NPV) and payback period to evaluate the economic possibility of the floating photovoltaic deployment project. The study was carried out for an entire year under standard temperature conditions. The capacity factor is 0.70% in the floating system, more than in the ground systems. The floating system generated 64 kWh/kW additional energy yield compared to similar ground systems and operated at 10 °C lower. The total power potential for the entire lake was found to be 4.47 MW. In addition to that, the extraction cost of the lake water will go down. The required extraction and cleaning of water costs a one-time extraction rate of $1435 of the lake, while for a floating photovoltaic system, the extraction cost was estimated to be $1.35.

In conclusion, it was established that FPV is favoured over on-the-ground systems, as it saves the cost and procures land. FPV systems also require less maintenance which contributes to even lower costs. All those factors reduce the payback period significantly from beyond 15 years for on-ground systems to only 5.3 years for floating photovoltaic systems, with the net present value remaining positive.

(Ravichandran, Ravichandran, and Panneerselvam, 2022) the paper compared offshore floating photovoltaic systems (OFPV) against pontoon-mounted FPV and ground-mounted systems in the Maldives island, where land availability is scarce and minimal. The successful utilisation of floating photovoltaic systems offshores would be very beneficial to the island as it will allow them to generate ample amounts of energy to suffice the entire island while maintaining its sustainability and environment 5 MW thin-film modules OFPV systems were installed on four offshore locations and their electrical performance was tested and compared against floating photovoltaic systems on a lake and an on-a ground photovoltaic system.

The results showed that the OFPV systems had higher annual energy yield by 13% and 14 % compared to that of pontoon-mounted FPV systems and ground-mounted systems, respectively, due to factors such as the direct contact of the PV system with the water and the absence of any obstacles such as buildings and trees that would shade the sun and prevent the absorbance of the sun.

The performance ratio of OFPV was significantly higher than the other two systems by 87.10 % and an annual energy yield of 8.74 GWh.

Upon conducting a cost evaluation, it was revealed that ground-mounted systems cost 72 % more than floating systems, with the OFPV having a lower carbon footprint than the other two systems. From an environmental point of view, the OFPV saved around 71152 tons of CO_2 making it more environmentally friendly by reducing its carbon emission by 14% less than ground-mounted systems and pontoon-mounted FPVs. Furthermore, the temperature loss in the OPFPV systems was lower than that of FPV and ground-mounted PV systems, with values between 4.13 to 4.79 % without additional cooling systems.

The study also conducted a cost analysis that revealed that ground-mounted PV systems were 75% more expensive than both FPV and OFPV due to the high cost of land procurement and the construction of the facilities. The OFPV system was cheaper than traditional FPV systems due to the thin film modules used; also, fewer mooring lines needed to be installed, contributing to a lower anchor cost overall. In conclusion, the study highlighted the large capacity of energy that could be harnessed from using OFPV systems.

The results emphasised the benefits of utilising the thin film based OFPV systems as an energy production strategy. The Benefits are not just limited to maintaining the environment on the island but also reflect positively on the economy as it reduces the reliance on imported fossil fuel, significantly reducing the cost. The results could also be replicated on several islands with similar climate conditions.

(Pimentel Da Silva & Branco, 2018) paper discussed floating photovoltaic (FPV) systems as a strategy to produce clean energy. However, it highlighted the disadvantages associated with using FPV systems, with FPV mainly emerging to overcome challenges related to land-based photovoltaic systems. The article discussed the challenges associated with FPV systems at all project stages, including planning, construction, operation, and decommissioning.

The following issues were highlighted as the main drawbacks of using FPV to generate power. Disturbance of the ecosystem, with the FPV system covering the water's surface, alters and reduces the amount of sun radiation reaching the water.

The ecosystem operates at an ideal temperature and light from the sun; with reduced sunlight, several bioprocesses such as photosynthesis and reproduction of certain species, hence drastic impact on food chains. With less sunlight and decreased rate of photosynthesis, a chain of reaction could be triggered, including a reduced rate of plant and algae growth resulting in less oxygen in the water.

This could lead to the death of plants and animals. The death of the plants also contributes to the death of the animals, as they represent the primary food source for herbivorous species. The decay of plants and animals also leads to an increase in the nitrogen content of the water and temperature, which in turn depletes the levels of oxygen even further; this could even lead to eutrophication resulting in algae bloom that again affects the ecolife system and could have a destructive effect on any water pipes or cables under the seawater.

The high cost associated with the installation of the system and the inert materials to be used is another challenging aspect of installing an FPV system. The high cost associated with anchoring, mooring, and installing the system usually halts its utilisation to produce clean energy. While it is true that no need for land space saves a lot of money on renting/buying land, the cost of installing the system is considerably higher than land photovoltaic (LPV) systems.

The materials used to make all parts of the systems, including the panels and fixtures, must be inert and safe for aquatic life to prevent the leaching of any toxic trace metals/substances into the water harming aquatic life and polluting the water. This could significantly raise costs and pose another obstacle in designing and installing FPV systems.

Scalability, practicality, and application of FPV systems. FPV systems are only sometimes a good fit for small-scale power generation. Most FPV systems are designed and installed to produce power at a large scale for factories or even meet energy demands for medium to large communities. Even with a water body nearby, it would not be the most efficient and cost-effective solar power solution to power a house or a few properties.

Location and logistics, despite the ample number of water bodies, specific characteristics of the water body, such as the rise and fall of tides, water salinity, depth, underwater terrain, and soil, could affect the design and installation of FPV systems and even halt entire projects. The proximity to main roads, transportation lines, and work sites could also affect the overall cost and render a project profligate.

In conclusion, this paper identified several challenges associated with the FPV system that must be considered before proceeding with the installation of the system. More studies are required to study the effect of the impact between artificial and natural water bodies.

(Elminshawy et al., 2022) A study conducted in Egypt studied the performance of a newly modified FPV system partially submerged in water to harvest solar energy and generate electricity production.

The system used consisted of a partially submerged floating photovoltaic system (PSFPV) in water and was built and placed in the water body taking into consideration the Egyptian outdoor conditions. The submerged section of the PSFPV system acted as a natural cooling system for the PSFPV system as it was in direct contact with the water. The thermal and electrical performance of the PSFPV system at different submerged lengths (ranging between 4 to 24 cm) was compared to a similar ground-mounted photovoltaic system. The results showed that the PSFPV system had operated as efficiently as the ground system, even at a lower operating temperature by 15.1% compared to the ground-mounted PV system.

The natural cooling effect also strongly suggests generating up to 27.31% more electricity than the traditional PV without a cooling system. Furthermore, the PSFPV system operating temperature decreased even further by increasing the submerged ratio of the PSFPV, with the ideal performance achieved when 12% of PSFPV was submerged in water, contributing to the system's overall efficiency. In addition, The PSFPV system generated 20.8% more power than the ground-mounted PV system. The PSFPV system also had lower CO_2 emission by around 49.6 kg/summer season, and a cost analysis of the PSFPV system showed a reduction in the level of energy cost 0.075 to 0.067 ($/kWh) just by increasing the submerged part of the PSFPV from 4 to 24 cm.

In conclusion, this study highlighted how different PSFPV configurations contribute to higher efficiency and more cost-effective strategies to generate power compared to traditional FPV and on-the-ground PV systems.

(Kakoulaki et al., 2023) The paper focused on generating renewable energy sources to reduce carbon footprints and emissions to contain climate change. However, the paper highlighted the ample number of European reservoirs and researched the opportunity to pair FPV with hydropower to produce clean, sustainable energy. The study was conducted in 337 European hydropower sites to utilise the pre-existent facilities. While considering variables such as the estimated annual FPV electricity output, evaporation, water losses, and water savings at the reservoir, regional and national levels, the results revealed the following: Installing FPV systems of equivalent capacity as the hydropower plants would only need to cover 2.3% of the total reservoir area. This could generate 42.31 TWh, making the total annual potential electricity yield of FPV covering 100% of the reservoirs' area around 1386.7 TWh, equating 49% of the total E.U. electricity generation.

Consequently, this reduces the reservoirs' total water losses from 9380 MCM to 8823 MCM. It was estimated that 10% FPV coverage increases power production by 1.5 times and could save up to 1718 MCM of water annually (117 times the water consumption of the Italian population in 2018).

The benefits of using this combination of power-generating sources go beyond eater saving. It also helps tackle other issues, such as limited land availability and high costs associated with land acquisition, in addition to meeting the huge energy demand in Europe. This also puts the E.U. on the right track to producing zero-emission energy and free them from importing fossil fuel.

In conclusion, this paper highlighted the great potential that could be harnessed from coupling hydropower with FPV, especially in countries threatened by water scarcity and drought related to climate change.

(López, Soto and Hernández, 2022) article explored the potential of deploying FPV systems in different regions of Spain. Both freshwater and artificial water bodies were included in this study.

Several factors were considered to calculate the power produced, such as geo-data for the different water bodies, environmental geospatial data, and the water-cooling effect. Three dams were included for the artificial water bodies, and factors such as water level variations and the FPV system's depth restriction were considered to reduce ambiguity.

The study's results were based on only 10% coverage of the fresh water and artificial water bodies with horizontal FPV systems. Then the results were compared against the current electricity demand fulfilled by non-renewable sources. The results revealed that 80 TWh per year could be harvested by covering only 10% of the water bodies. This is equivalent to 31% of Spain's electricity demand.

Regarding the environmental impact, the results have shown that using FPV systems could reduce power produced from non-renewable sources by 81% and reduce greenhouse gas emissions by 6%.

The results have also suggested that artificial water bodies may be more suitable for deployment than freshwater bodies due to their location. Ultimately this would reduce the potential power generated using FPV to 56 TWh/year. However, the sole use of artificial water bodies would still fulfil 22% of Spain's electricity demand and reduce electricity demand from non-renewable sources by 51%.

In conclusion, Spain could benefit significantly from the FPV system to reduce the dependency on energy derived from non-renewable sources, ultimately reflecting positively on their economy. Balancing the electricity demand and production with FPV systems would also reflect positively on the environment and maintain the sustainability of natural sources such as lands and ambient air, aiding Spain to meet the E.U. 2030 Climate Target Plan.

(Sanchez et al., 2021) The paper focused on the potential of pairing floating photovoltaics (FPV) with existing hydropower reservoirs in Africa, where many countries depend on hydropower to generate electricity. While hydropower plants sustainably generate electricity, the frequent droughts in the continent pose a serious issue that threatens the water and energy security of the countries affected.

The paper highlighted the ample amount of solar radiation that hits the continent, which exceeds 2000 kWh/m^2 a year. It evaluated the benefits and potential of combining FPV and hydropower using data from Africa's most significant 146 hydropower reservoirs. Factors such as the amount of electricity produced, evaporation rate reduction, and the potential additional hydroelectricity produced due to evaporation reduction have accounted for uncertainty in the results. The results revealed that covering around 1% only of the water bodies included in the study with FPV systems could increase the power generated from existing hydropower facilities by two folds, with the electricity output increasing by 58%.

This translates to an extra 46.04 TWh of electricity every year. Results have also shown the FPV systems contributed to the evaporation rate reduction, which could save 743 million m^3 of water annually, which ultimately can increase the hydroelectricity production by 170.64 GWh/year.

In conclusion, the paper highlighted that with the existence of hydropower plants and the solar potential in Africa, there is a vast opportunity to offset the hydroelectricity during droughts while still diversifying the renewable energy portfolio in Africa to sustainably generating electricity and mitigate the risk associated with droughts and relieve water scarcity. The additional hydroelectricity produced due to water saving on top of the solar electricity via the FPV systems will positively impact the economy and enhance the African country's ability to tackle climate change. It will also aid in balancing energy sources and fulfilling rising electricity demand due to rapid population growth.

(Nisar et al., 2022) the study focused on studying the optimal temperature for mono and polycrystalline photovoltaic modules used in small Floating Photovoltaic (FPV) and similar On-Ground PV (OPV) in Pakistan to operate at their thermal trends and electrical performance at different weather conditions and tilting angles.

A test bench, including FPV and an OPV system, was built, and results were collected and evaluated. Several performance differences were observed between the two systems despite the similarity in the materials used to build them.

Thermal imaging and electrical performance trends were studied and revealed that FPV systems could operate more efficiently and are less likely to overheat and maintain a uniform temperature across the panel than OPV systems due to the natural water-cooling effect. The average temperature of monocrystalline and polycrystalline FPV modules was 2–4 °C cooler than OPV and 5–11 °C cooler for the back of FPV modules. Studies show that a one-degree temperature increase could cause up to 0.45% drop in efficiency in monocrystalline and polycrystalline PV panels (Choi, 2014); this significantly impacts the performance of OPV systems, reducing their efficiency and eventually lowers the panel's lifespan due to overheating.

Results have also shown that the floating PV system produces anywhere between 1 to 28% more energy than the OPV system depending on the tilt angle; also, with fewer dust particles accumulating on the FPV panels due to their remote location far from urban areas, the FPV systems have shown higher efficiency. The FPV systems also contributed to the reduction of the levels of evaporation by 17% when partially covering the water surface and by 28 % when fully covering the water surface. This reflects positively and contributes to water conservation.

In conclusion, the paper concluded that the FPV system is more efficient than traditional OPV systems. This study is novel as it tested the temperature for both the front and back temperature of the panels, making the data collected more accurate and reflecting real-life scenarios. However, further studies are required to establish a measuring station to transmit data online and replicate the results at a different location over an extended period.

(Uddin, Biswas and Nuruddin., 2022) The study discussed and analysed the techno-economic impacts of a clean energy production strategy using FPV technology to achieve the Bangladeshi government's goal of producing 6000 MW of electricity solely from solar Photovoltaic (PV) modules by 2041.

The paper has suggested an innovative simulation of a photovoltaic-Battery Energy Storage System Coupled System (FPV-BESS) of 1.4 MW capacity to be installed in the country's rural western coastal region.

The simulation considered several factors, such as different levels of desired voltage, current, and power, that could impact the performance of the FPV system and compared it to an experimental Diesel Generator- Battery Energy Storage System (DG/BESS) to ensure accurate results. The FPV/BESS coupled system was addressed as configuration A, and the DG/BESS system was addressed as configuration B.

The simulations were done using MATLAB/Simulink. An in-depth economic evaluation has also been carried out to compare the cost-effectiveness and feasibility of both systems using HOMER Pro software by analysing each system's Net Present Cost (NPC) and Cost of Energy (COE). The Net Present Cost (NPC) is the system's total cost over its entire lifetime. The NPC includes costs like capital, replacement, operational and maintenance, fuel costs, and emission penalties minus the remaining salvage value. Cost of Energy (COE) is the average cost per kWh of valuable electrical energy delivered.

The paper highlighted the enormous amount of area the FPV/BESS system could preserve; as 1 MW traditional PV installation requires around five acres of land, the FPV/BESS system could save up to seven acres of land and utilise the 310 rivers in Bangladesh. This is vital in a country with a heavy population, such as Bangladesh; the government could use all lands available for agricultural and residential

While the study found out that the FPV/BESS system requiring more components might increase the overall cost for the anchoring and the mooring of the system, however, the higher cost of it is significantly offset by the passive cooling effect provided by the water, which improves the performance leading to a higher energy yield overall. The results have also shown that, while FPV/BESS are more expensive to install, they are up to 16% more efficient due to the water-cooling effect that reduces heat losses and extends the component's life cycle. Also, the fuel cost for configuration B is 104 496$ million, which exceeds all other costs for configuration A.

In conclusion, considering all factors, the study suggested that the FBV/BESS coupled system is a hopeful and more cost-effective solution to fulfil the significant energy demand and protect the environment.

The study estimated that configuration A (FBV/BESS) could produce enough electricity for 10000 locals/ 2500 households, 120 EV scooters, 25000L saltwater treatment, and related facilities. In addition, the FPV/BESS coupled system can cut back emissions by 228 metric tons and 466.56 metric tons of CO_2 annually.

(Goswami et al., 2019) paper analysed the increased energy demands in India and solutions to compact it. The study focused on ground-mounted PV systems and issues linked to them, such as ground-mounted PV systems occupying large surface areas of land in urban areas, the high cost of land, and the sharp rise in the electricity tariff.

A techno-economic feasibility investigation of a 10 MW FSPV system was conducted to analyse its economic feasibility and environmental impact compared to traditional ground-mounted PV systems. The results revealed that the FSPV system had produced 10.2% more power than the land-based PV systems while also producing an additional 28.38 million units of energy over the system's life cycle.

Cost-wise, the FSPV system will be more cost-effective as it will eliminate any land costs; the results have shown that FSPV saves, on average, $352 125 in land purchasing and water costs of $ 47600. This reflects positively on the electricity tariff reducing it to $0.026/ kWh, which is 39% less than land-based PV systems.

Comparing the operating temperatures of FPV and ground-mounted PV modules in the pond, the results have shown that the FPV system consistently has a lower operating temperature than the land-based PV system, with a difference of up to 12 °C on the hottest day; this made the FPV system more efficient with a higher power output by 10.2% comparing to similar land-based PV systems.

The study attributed the finding due to the "Heat Islanding" effect. In traditional PV systems, the heat gets trapped between the soil and PV modules. In contrast, the FVP systems are in direct contact with water, eliminating the heat islanding effect and passively cooling down the panels. Regarding the environmental impact of the FSPV system, the results have also shown that the FSPV system contributes to reducing coal dependence and greenhouse gas emissions by 92945 and 340 801 tons, respectively.

In conclusion, this paper highlighted the promising future of the FSPV systems and how they will aid in guaranteeing energy security while maintaining the environment and combating climate change, especially in a country like India where current climate policies are struggling to protect the environment and achieve improvement particularly when it comes to air quality.

(Micheli, L., 2022) analysed a wide range of literature to review the thermal behaviour of floating photovoltaics FPV compared to similar land-based photovoltaic (LPV) systems. The paper focused on and distinguished between air-cooled FPV and water-cooled FPV systems to deliver fairer comparisons and more robust results.

According to the paper, FPV systems are usually anticipated to operate at a lower temperature than land-based photovoltaic (LPV) systems due to the natural cooling effect of water. Lower operating temperature reflects positively on the performance of the FPV systems by increasing the energy yield, decreasing the rate of degradation and heat losses, reducing the cost, and increasing the overall performance of FPV.

While some studies have shown that FPV systems could end up operating at higher temperatures than land-based PV systems, it is essential to take into consideration other affecting factors such as different models of FPV systems, the cooling mechanism (by air V.S. by water), and PV manufacturing material.

The study compared the different factors to reach a conclusion and identify the ultimate design and conditions that result in the least heat loss and most efficient performance. The paper compares land-based PV systems vs. air-cooled and water-cooled FPV systems to find out that water-cooled systems could operate at the lowest temperature out of all three systems due to the higher heat transfer coefficient of water, reducing the thermal transmission and lowering the overall temperature of the system.

The results have shown that water-cooled FPV systems are the most efficient even when water temperature exceeds air. A difference of up to 6 °C has been reported between the temperature of the water and the air. Another study reported 3 °C higher water temperature than air. The ability of water-cooled FPV to operate at lower temperatures, even in conditions of warmer-than-air water temperatures, can be demonstrated by comparing the findings of (Kjeldstad et al., 2021) and (Dörenkämper et al., 2021).

In conclusion, with overheating of the PV cells being the predominant precursor of degradation and damage to the PV system, water-cooled floating photovoltaics is a promising solution to reduce land use for photovoltaics. In addition to needing minimal land space, FPV operating at a lower temperature and having higher efficiencies reflect positively on the cost-effectiveness of the technology and the net energy yield.

1.5. Floating Photovoltaic Power Systems

As clearly outlined in the literature review above, floating PV power systems emerge as an innovative idea to eliminate adverse effects associated with land-based PV systems. Artificial dams established for drinking water, electricity generation and agricultural irrigation, or natural lake surfaces are a solution that can eliminate the need for land. To reduce the temperature of the panel surfaces, water can be used as a transfer medium providing heat removal via passive cooling. This advantage can aid in reducing the effect of the temperature coefficient, increasing the panels' efficiency, and significantly reducing the return times of FPV systems investments.

It can also save water by reducing evaporation in artificial and natural water bodies and preventing algae bloom in water bodies (Haas et al., 2020). Some might argue that FPV may cause deterioration of water quality as it prevents the contact of sun rays with water surfaces. However, in several studies, prototype floating solar energy systems were installed, and the effect on water quality was examined. Depending on the structure of the system. It was determined that there were no adverse effects on water quality and improved nitrate and chlorophyll concentrations.

It has also been stated that the evaporation effect varies according to the installation structure and the area it covers, but a 60% reduction in the rate has been observed. (Soltani et al., 2022) & (Yang et al., 2021). In a study (Kichou, Skandalos, and Wolf, 2022) on the effects of terrestrial and floating-type PV system installation: It has been determined that the albedo effect of the panels in terrestrial installations is 13%, whereas it varies between 5-8% in floating systems.

The albedo effect denotes the ability of a surface to reflect radiation, in this case, sunlight. In terms of solar panels, the lower the value of the albedo effect, the more efficient the panel is.

This means more sunlight will be absorbed instead of reflected in the airspace. In large-scale terrestrial installations, the high albedo effect resulted in an increase in the greenhouse effect by turning visible light into infrared rays.

Utilising inhabitable areas allows more power production at lower prices, with 0% emission and minimal disruption to wildlife. It will also allow more investment in the habitable areas, boosting the countries' economy while providing them with clean, free energy. This reflects positively on the environment; with fewer solar panels needing to be replaced and repaired, less waste is produced as well.

In addition to all the points covered previously about solar panels, solar panels could be utilised and occupy under-utilised lands. Solar panels can be positioned anywhere; with the Earth's surface area of 510 million km^2, only 29% is land, and 71% is the ocean. Out of the 29% land area, 71% of it is habitable, half of it is used for agriculture and about 1-4 % of the land is occupied by infrastructure and buildings (Tomás et al., 2014), (Ritchie & Roser, 2019).

Furthermore, with the advancement of technology in the solar energy field, engineers have been utilising one of Earth's largest and most unusual spaces. Oceans, seas, and any water body harvest solar energy using floating solar panels (Vo, Huh, & Park, 2021). Floating solar panels are a new, robust, cost-effective solution to convert water bodies into solar energy plants (Cao et al., 2019). The principle is the same as standard solar PV panels; however, more space is available for humans and wildlife since they do not use land/roofs. The conserved space could be used in agriculture or infrastructure. The panels also aid in enhancing the quality of the water and decreasing evaporation; in exchange, the water naturally cools down the panels, increasing their efficiency.

Moreover, floating solar panels will not be blocked by obstacles like over-ground solar systems that might prevent the absorption of solar radiation leading to an unnecessary loss of energy (El Hammoumi et al., 2022). While floating solar panels are still a relatively modern technology, they could also eliminate financial and legal issues using international water. In addition, many reservoirs and dams are located near cities, making it easier to feed power into the urban grid than supplying it from remote areas such as deserts (Abbott, 2009).

In summary, floating PV systems are installed on existing water bodies such as lakes, ponds, reservoirs etc., which avoid valuable land surface—increased electricity production. FPVs can be installed easily because they do not need ground level and eliminate interference from surrounding shading.

A typical 30 MW FPV can be installed in only eight weeks. Moreover, FPV can be decommissioned quickly, but detailed data needs to be analysed to support this aspect. They receive their cooling effect passively from the water and ambient air, which increases output power generation. However, PV technology and local climatic conditions always influence increased efficiency or electricity production. More research is considered necessary to prove this aspect of FPV systems. Existing hydro dams also provide a fantastic opportunity to host the FPV systems.

Some studies have recently reported lower capital expenditure for hybrid hydro and FPV systems due to existing grid infrastructure, subject to specific site characteristics, the simplicity of installation and decommissioning. Furthermore, floating PV systems cover water surfaces, avoiding the direct contact of solar radiation with water and reducing evaporation. However, the evaporation reduction capacity of FPV systems depends on the type of floating structure. By blocking direct solar radiation, the photosynthesis rate will also decrease, eventually reducing the algal growth in the water and improving water quality. However, further studies are required on the ecological impact of FPV because blocking solar radiation can threaten aquatic animals' lives.

Some studies claim the lower degradation rate of PV modules on water bodies due to lower module temperature, whereas some reported higher degradation due to highly humid environments; however, more research is necessary to reach any concrete conclusion. Also, water bodies usually have less dust in their atmosphere, which can benefit PV modules, but at the same time, FPV is prone to other forms of dust, such as bird dropping, dust patches, and soil cementation due to high moisture in the air, etc. Higher electricity production with bifacial modules on water bodies.

In the light of the literature review done, it was determined that research on FPV systems were concentrated due to the additional benefits they could add to the solar power systems.

Benefits such as, increasing panel efficiency and prolonging their lifetimes with active and passive cooling techniques bring FPV systems to the fore. For this reason, in this study, 5 different FPV installations were made to obtain the electrical and thermal parameters of the FPV systems experimentally.

The basic parameters of FPV systems and meteorological data were measured. It was evaluated by making comparative analysis with the data obtained from the land-based installation. In the light of the information obtained, Turkey's potential was evaluated, environmental and economic analysis of FPV systems were also made.

2. SOLAR CELLS AND PANELS

A solar cell is an electronic device that converts sunlight into electricity via the photovoltaic effect (Britannica, 2023). Light reflected on a solar cell generates a current and a voltage, producing electricity. This process requires using a conductive material where the sunlight energy is absorbed, causing the electrons to rise to a higher energy state, followed by the flow of the electrons from the solar cell into an external circuit (Britannica, 2023). After the electrons release their energy in the external circuit, the electron returns to the solar cell, and the process repeats if the solar cells are exposed to a bright enough light source. A wide range of materials could be used to manufacture solar cells. However, in real life, the majority of all photovoltaic conversion of energy is achieved with semiconductor components in the form of a p-n junction (Figure 3.1).

Conversion steps in the solar cell are:

1. The formation of high energy electrons, light-generated carriers.
2. The collection and separation of the light-generated carries to produce a current.
3. The production of a high voltage across the solar cell.
4. The dissipation of power in the load and in parasitic resistances.

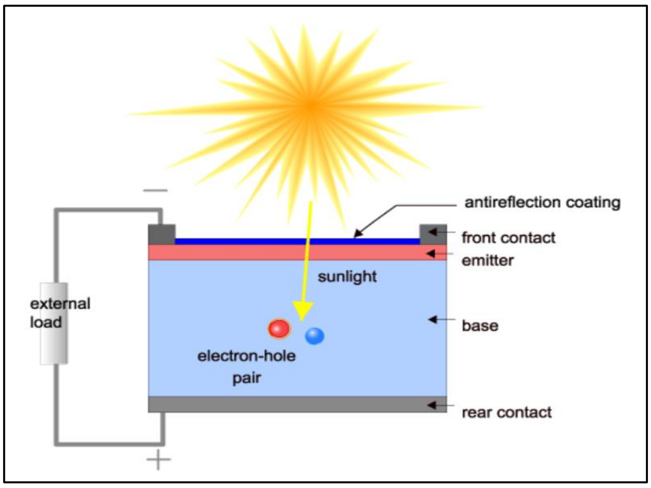

Figure 2.1 Cross section of a solar cell. Emitter and Base represent the layers in a p-n junction. (Pveducation.org, 2023).

The light enters the emitter first. The emitter is usually thin to reduce the depletion region near where the light is absorbed, while the base is usually thick enough to absorb most of the light. This process includes two fundamental processes. The first is the absorption of the photons to form electron-hole pairs, which are the majority of charge carriers.

Electron-hole pairs will be formed in the solar cell when the photon has higher energy than the band gap energy. Most charge carriers allow the flow of electricity in the solar cell. The charge carriers present in small quantities are called minority charge carriers. However, electrons in the p-type layer and holes in the n-type layer are meta-stable and only occur for a long time, like the minority carrier lifetime, before recombining. If the carrier merges again, no electron-hole pair will form, and the light-generated current is lost, meaning no current/power can be produced.

The second process involves the separation of the carriers in the p-n junction due to its spatial electrical field. This process ensures the separation of the electron and the hole; in the p-n junction, the minority carriers are converted into a majority carrier by the same electric field. If the emitter and base of the solar cell are linked together, making a short circuit, the major carriers will flow through the external circuit.

2.1.Quantum Efficiency, Q.E.

The ratio of the number of carriers collected compares the number of photons absorbed by the solar cell. If all photons are absorbed, and all carriers are collected, then the quantum efficiency of that wavelength is unity (1). The quantum efficiency for photons with energy under the band gap is 0. Ideally, we want a unity quantum efficiency with a square curve. However, the quantum efficiency of most solar cells is reduced due to multiple factors. Internal factors that impact quantum efficiency have a similar mechanism to those affecting collection probability, i.e., the recombination of the electron-hole pair. Other factors, such as the surface passivation effect, short diffusion length and device thickness, will lower the collection probability, reducing a solar device's quantum efficiency. This is called internal quantum efficiency, where the reflection/transmission of photons was not considered.

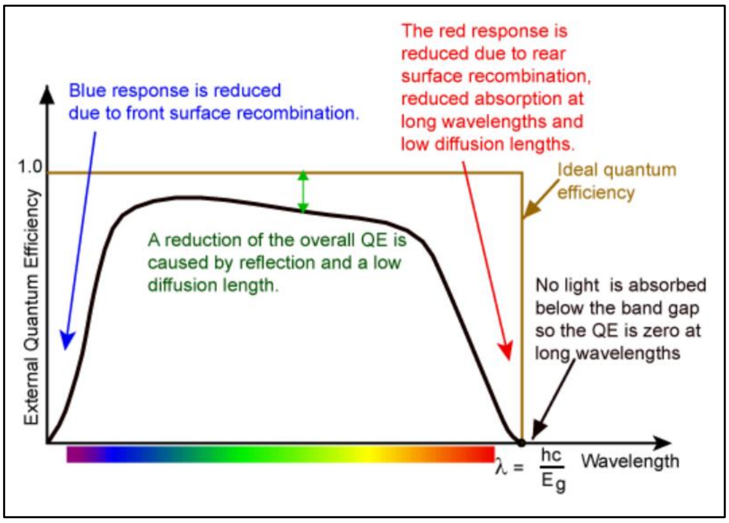

Figure 2.2 Illustrates the ideal quantum efficiency curve by the yellow gold square line. (Pveducation.org, 2023)

The optical losses by a solar device due to transmission and reflection of light are external factors that could lead to a further reduction in quantum efficiency. This is called external quantum efficiency. It is helpful to look at the external quantum efficiency of a device, as the external quantum efficiency curve can help obtain an accurate internal quantum efficiency curve.

2.2.Spectral Response

Similarly, to quantum efficiency, the spectral response is the ratio of the current produced by the solar device compared to the power generated by the solar cell.

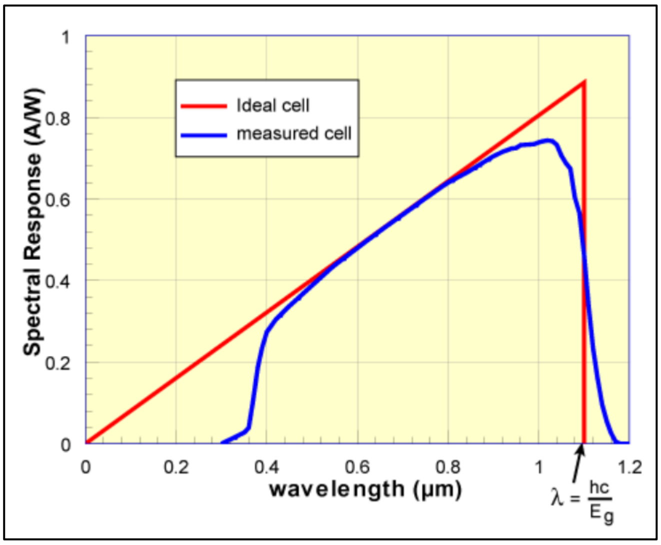

Figure 2.3 Illustrates an ideal spectral response curve Vs a measured cell curve. (Pveducation.org, 2023)

The graph demonstrates the spectral response of a solar cell made from silicon. At short wavelengths under 400 nm, the glass absorbs most of the light, and the cell response is negligible. The cell response is almost perfect at wavelengths between 500 nm and 800 nm. However, at longer wavelengths, the response decreases gradually back to zero. Silicon is an indirect band gap semiconductor, which limits its ability to absorb any photons with energy lower than its band gap of 1.12 eV. Equally, the spectral response of silicon solar devices declines at short photon wavelengths, where photons have high energy.

This is because the ratio of photons to power is much smaller. Moreover, any energy higher than the band gap cannot be utilised by the solar device and heat the solar cell. Between the inability to fully utilise the photons with high energies and the limited absorption ability of light with short wavelength, a substantial power loss occurs in solar devices with a single p-n junction. Depending on the application, the spectral response and/or the quantum efficiency are both used to analyse solar devices. However, while the spectral response uses the light at each wavelength, the quantum efficiency uses the photon fw/m^2.

Converting QE to SR is calculated using the following equation. (Kalogirou, 2017)

$$SR = \frac{q\lambda}{hc} QE \tag{2.1}$$

Where?

- q is the electronic charge.
- λ the wavelength of any wave
- h the Planck's constant
- c the speed of light

This is calculated using the following equation, (Kalogirou, 2017)

$$SR(A/W) = \frac{QE-\lambda(\mu m)}{1.2398} \tag{2.2}$$

$$SR(A/W) = \frac{QE-\lambda(nm)}{1239.8} \tag{2.3}$$

2.3.The photovoltaic Effect

The collection of light-generated carriers only produces a current, which is insufficient to generate power. To produce power, you need both current and voltage. A solar device generates the voltage via the "photovoltaic effect" process. As explained earlier, the collection of light-generated carriers by the p-n junction causes the flow of electrons to the n-side and holes to the p-side of the junction. In short circuits, the charge does not accumulate, as the carriers only exit as light-generated current. To create a voltage within the solar device, the light-generated carriers must be prevented from escaping the solar cell. The build-up of the light-generated carriers increases the number of electrons on the n-side and in holes on the p-side.

The separation of charge creates an opposite electric field at the junction to the existing one at the junction, which reduces the net electric field. With the electric field acting as a barrier to the flow of the forward diffusion current, reducing the electric field enhances the diffusion current. A new equilibrium is established where a voltage exists across the p-n junction. The current of the solar device is the difference between the load current (IL) and the forward bias current. In open circuits, the forward bias of the junction increases to a point where the forward bias diffusion current preciously balances the light-generated current, and the net current is 0. The voltage required to cause these two currents to balance is called the "open-circuit voltage".

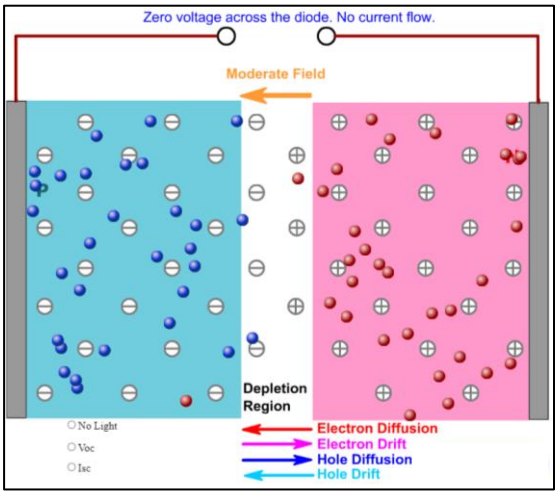

Figure 2.4 Illustrates the carrier flows at short-circuit and open circuit of a solar device. (Pveducation.org, 2023)

2.4.Solar Cell Parameters

2.4.1. Short-circuit current, I_{SC}

Short circuit current is the largest current throughout the solar cell when the voltage across the solar cell is zero. The I_{sc} occurs due to the collection and separation of the light-generated carriers, ideal solar cells and at moderate resistance loss, the I_{sc}, the I_{sc} and the light-generated current are equal. The short-circuit current density J_{SC} can be calculated according to the following equation, (Kalogirou, 2017).

$$J_{SC} = qG (L_n + L_p) \tag{2.4}$$

Where, G is the generation rate, and L_n and L_P are the electron and hole diffusion lengths respectively.

The I_{SC} could then be calculated by multiplying the short-circuit current density by the solar cell surface area (Kalogirou, 2017).

$$I_{SC} = J_{SC} \times A \tag{2.5}$$

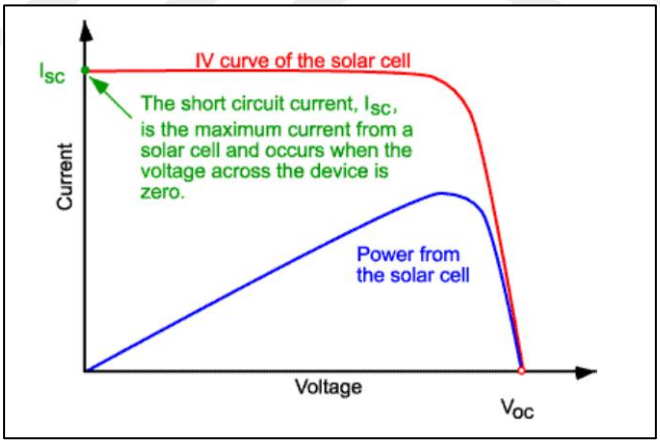

Figure 2.5 Demonstrated the IV curve of a solar cell showing the short-circuit current. (Pveducation.org, 2023).

2.4.2. Open-Circuit voltage; V_{OC}

The maximum voltage of a solar cell, at zero current. The V_{OC} relates to the quantity of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

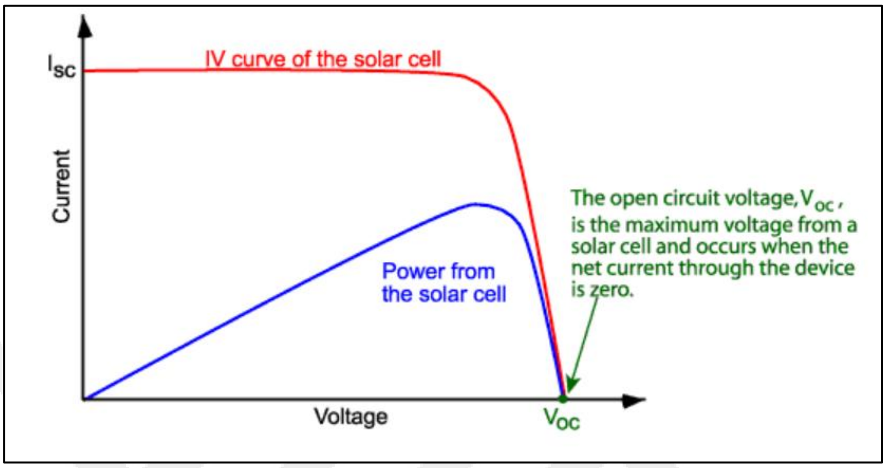

Figure 2.6 Demonstrates the IV curve of the open-circuit voltage. (Pveducation.org, 2023)

V_{oc} is calculated by setting the net current equal to 0, the equation is shown below (Kalogirou, 2017).

$$V_{OC} = \frac{nKT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \quad (2.6)$$

Where;

- I_0 is Dark Saturation Current
- I_L is Light Generated Current
- n is Ideality Factor (1)
- T is Temperature
- V_{OC} is Open Circuit Voltage

2.4.3. Power

Power is measured in Watts, which is equal to a joule of energy/second, it's calculated according to the following equation (Kalogirou, 2017).

$$P = IV \qquad (2.7)$$

Where,

- P is electrical Power (w)
- I is current (A)
- V is voltage (v)

2.4.4. Solar cell current–voltage (IV) curve

The curves equation is calculated according to the following equation (Kalogirou, 2017).

$$I = I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L \qquad (2.8)$$

Where I_L is light generated current. This equation illustrates the state of the solar cell IV curve with no illumination (in the dark) where the solar cell will have the same electrical characteristics of a large diode.

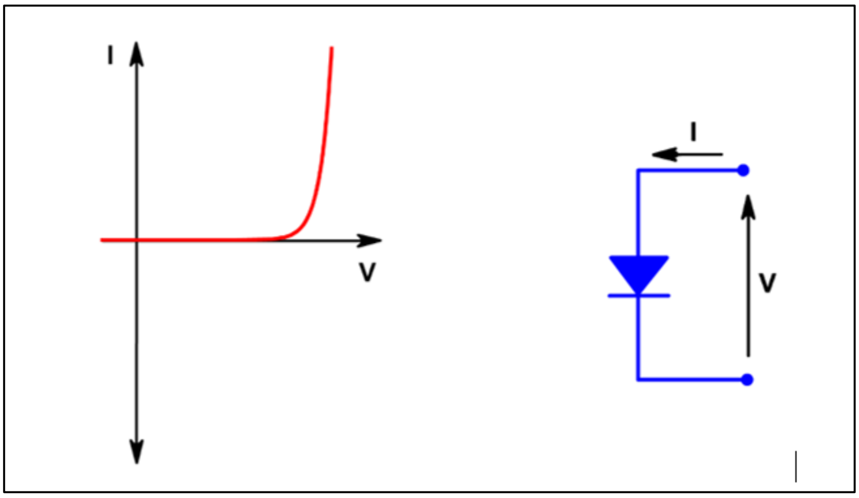

Figure 2.7 . Illustrates the state of the solar cell in the dark. (Pveducation.org, 2023)

When the light shines on the solar cell, it shifts the curve down, the greater the illumination the greater the amount of shift.

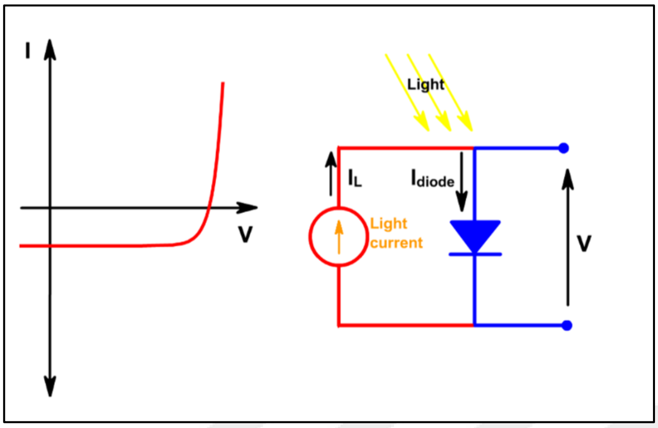

Figure 2.8 Illustrates the state of the IV curve of the solar cell in the 1st quadrant when light shines on the solar cell. (Pveducation.org, 2023)

At the first quadrant, the IV curve equation is the following, (Kalogirou, 2017).

$$I = I_L - I_0 \left[\exp\left(\frac{qV}{nkT}\right)\right] \tag{2.9}$$

Plotting the above equation gives the IV curve below with the relevant points on the curve as the following, generates the diagram below, P_{MP} denotes the maximum power point the cells needs to operate at to obtain the maximum power output of a solar cell.

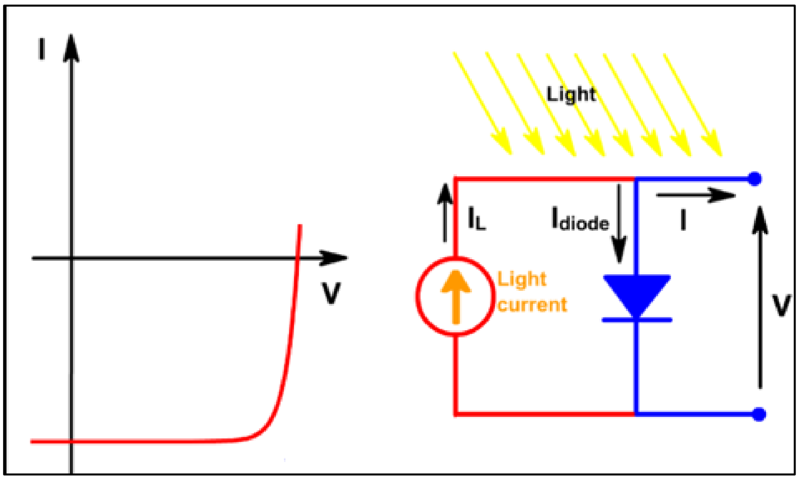

Figure 2.9 Illustrates the state of the IV curve of the solar cell in the 4th quadrant. (Pveducation.org, 2023).

As mentioned earlier the greater the illumination, the greater the amount of shift, once the curve is shifted to the fourth quadrant, power could be generated and extracted from the diode.

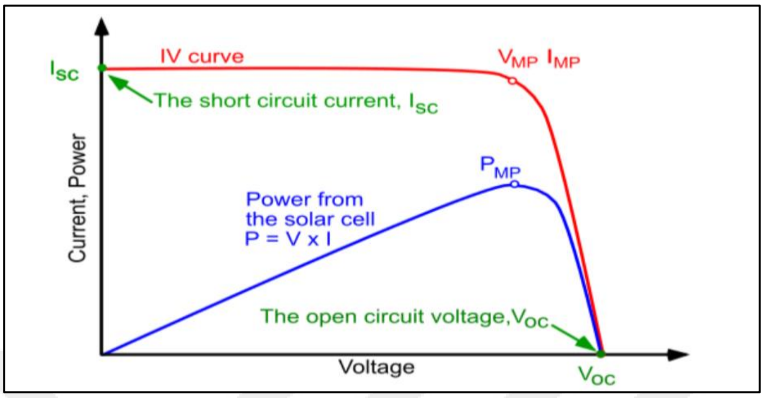

Figure 2.10 Current voltage IV curve of a solar cell showing the maximum power output. (Pveducation.org, 2023)

2.4.5. Fill factor

The fill factor FF is the ratio of the maximum power from the solar cell to the V_{oc} and I_{sc}. The I_{SC} and the V_{OC} are the maximum current and voltage of a solar cell. At both points, the power from the solar cell is zero. The fill factor (FF) is a parameter, together with V_{oc} and I_{sc}, that governs the maximum power generated by a solar cell.

The fill factor could be calculated using the following equation, (Kalogirou, 2017).

$$FF = \frac{P_{mp}}{V_{OC} \times I_{sc}} \tag{2.10}$$

$$FF = \frac{V_{MP} \times I_{mp}}{V_{OC} \times I_{sc}} \tag{2.11}$$

The higher the voltage, the larger the FF value. The maximum theoretical FF from a solar cell can be calculated by differentiating the power of the solar cell in respect to voltage and finding where this is equal to zero. This is illustrated in the equation below, (Kalogirou, 2017).

$$\frac{d(IV)}{dV} = 0 \tag{2.12}$$

$$V_{MP} = V_{OC} - \frac{nKT}{q} \ln\left(\frac{q\,V_{MP}}{nkT} + 1\right) \tag{2.13}$$

2.5.Solar Cell Efficiency

Solar Cell Efficiency is the ratio of the power output from the solar cell to the input energy from sunlight. It is the most used to match the performance of solar cells. Solar Cell Efficiency depends on the solar cell's performance, the spectrum and intensity of the falling sunlight and the temperature of the solar cell. Therefore, to measure efficiency accurately and compare one device to another, the conditions must be precisely controlled under which efficiency is measured and must be carefully controlled to ensure fair testing and accurate findings. Terrestrial solar cells are measured under air mass (AM) of 1.5 and at a temperature of 25°C.

The efficiency of a solar cell is calculated as the fraction of power converted to electricity according to the equations below, (Kalogirou, 2017).

$$P_{max} = V_{OC} \times I_{SC} \times FF \quad (2.14)$$

$$\eta = \frac{V_{OC} \times I_{SC} \times FF}{P_{in}} \quad (2.15)$$

Where;

- V_{oc} is the open circuit voltage.
- I_{sc} is the short-circuit current.
- FF is the fill factor and
- η is the efficiency.
- P_{in} is the input power (1 kW/m^2 or 100 mW/cm^2).

2.6.Characteristic Resistance

Characteristic resistance of solar cell is in Ω is the inverse of the slope of the line of V_{MP} / I_{MP}. (Kalogirou, 2017).

$$R_{CH} = \frac{V_{MP}}{I_{MP}} \approx \frac{V_{OC}}{I_{SC}} \quad (2.16)$$

2.6.1. Series resistance of power loss

$$R_{\mathbf{series}} = f \times R_{CH} \tag{2.17}$$

$$f = \frac{R_{series}}{R_{CH}} \tag{2.18}$$

Where f is the fraction power loss, 0-1 (Kalogirou, 2017).

2.6.2. Shunt resistance and power loss

$$R_{\mathbf{shunt}} = f \times R_{CH} \tag{2.19}$$

$$f = \frac{R_{CH}}{R_{shunt}} \tag{2.20}$$

Where f is the fraction power loss, 0 – 1. (Kalogirou, 2017).

2.6.3. Effect of parasitic resistances

$$R(\acute{\Omega}cm^2) = \frac{V}{J} \text{ ((Kalogirou, 2017).} \tag{2.21}$$

2.6.4. Series Resistance.

$$I = I_L - I_0 \exp\left[\frac{q\ (V+IR_S}{nkT}\right] \text{ (Kalogirou, 2017).} \tag{2.22}$$

Were.

- I am the cell output current.
- I_L is the light generated current.
- V is the voltage
- T is the temperature
- q and k are constants
- n is the Ideality factor
- R_S is the cell series resistance.
- I, on both sides of the equation and requires numerical methods to solve.

2.6.5. The effect of series resistance on the output power of a solar cell.

$$\acute{P}_{MP} = P_{MP}(1 - r_s) \text{ (Kalogirou, 2017).} \quad (2.23)$$

$$\acute{V}_{OC} \times \acute{I}_{SC} \times F\grave{F} = V_{OC}\, I_{SC}\, FF(1 - r_s) \text{ (Kalogirou, 2017).} \quad (2.24)$$

$$F\grave{F} = FF(1 - r_s) \text{ (Kalogirou, 2017).} \quad (2.25)$$

Assuming that the V_{OC} and I_{SC} are not affected by the series resistance allows FF', to be calculated using the below equation, (Kalogirou, 2017).

$$FF_S = FF_0(1 - r_s) \quad (2.26)$$

2.6.6. Shunt resistance

The equation for a solar cell in presence of a shunt resistance is shown below, (Kalogirou, 2017).

$$I = I_L - I_0 \exp\left[\frac{q\,V}{nkT}\right] - \frac{V}{R_{SH}} \quad (2.27)$$

Where,

- I am the cell output current.
- I_L is the light generated current.
- V is the voltage
- T is the temperature
- q and k are constants
- n is the Ideality factor
- R_{SH} is the cell shunt resistance.

2.6.7. The impact of the shunt resistance on the maximum power output

$$\acute{P}_{MP} \approx V_{MP}I_{MP} - \frac{V_{MP}^2}{R_{Sh}} = V_{MP}I_{MP}\left(1 - \frac{V_{MP}}{I_{MP}}\frac{1}{R_{SH}}\right) = P_{MP}\left(1 - \frac{V_{OC}}{I_{SC}}\frac{1}{R_{SH}}\right) \quad (2.28)$$

$$\acute{P}_{MP} = P_{MP}\left(1 - \frac{R_{CH}}{R_S}\right) \text{ (Kalogirou, 2017).} \quad (2.29)$$

Assuming that the V_{OC} and I_{SC} are not affected by the shunt resistance allows FF' (also referred to as FF_{SH}), to be calculated using the below equation, (Kalogirou, 2017).

$$FF_{SH} = FF_0\left(1 - \frac{1}{r_{SH}}\right) \quad (2.30)$$

2.7.Modules and arrays of solar cells

A group of solar cells is called a PV module. A PV module comprises several interconnected solar cells enclosed into one individual, lasting, stable unit, also called a panel. Encapsulating the solar cells is done mainly to prevent their damage and corrosion by rain and water vapour and to protect their wires from harsh surroundings. Solar cells are also relatively thin, so this will protect them from any mechanical damage. There are several types of PV modules; it varies depending on the choice of application. For example, amorphous silicon solar cells that power small gadgets, e.g., portable speakers, solar phone chargers and watches, are encapsulated in a flexible array. In contrast, bulk silicon solar cells for power applications are often very rigid with glass surfaces. The most common modules comprise either 60 cells or 72 cells with three bypass diodes. 60-cell modules are easier to handle in residential applications, while 72-cell modules are heavier and usually used for large utility applications where cranes and hydraulic lifts are involved. The standard for most solar panels' lifespans is 25 to 30 years. The longevity of a solar panel is a direct indication of its robustness and durability. Most PV modules are made of a semiconductive material; silicon is one of the most used materials. Most silicon PV modules are made up of a glass transparent top layer, an EVA (Ethyl Vinyl Acetate) encapsulant, a Tedlar back layer and a frame, as shown below.

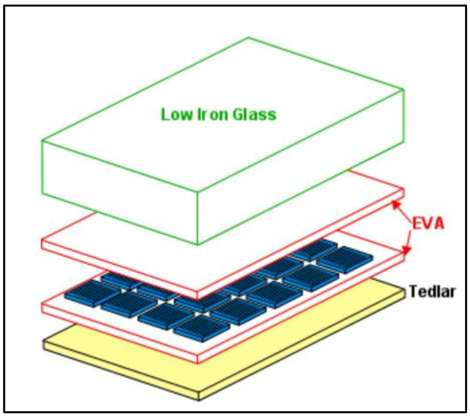

Figure 2.11 Demonstrates a typical silicon PV module material. (Pveducation.org, 2023)

2.7.1. Front surface materials

The front surface provides the mechanical strength and rigidity of the module. The front surface of a PV module must have a low reflection and high wavelength transmission that can be used by solar cells ranging between 350 nm to 1200 nm. The reflection could be reduced by using an anti-reflection coating on the top surface, but those are not strong enough to tolerate the harsh conditions where PV systems are used.

Another strategy to reduce reflection is to texturize the top surface. However, the panels then tend to collect dirt and dust, which affect the amount of power produced due to higher surface soiling, and the modules will not, therefore, be "self-cleaning". Additional top surface properties are water resistance, impact resistance, adequately stable under prolonged UV exposure and low thermal resistivity. Several materials could be used for the top, including acrylic, polymers and low iron-content glass.

2.7.2. Encapsulant

The encapsulant is used to support the adhesion of the solar cells, the top surface, and the rear surface of the PV module together. It must remain stable at high temperatures and prolonged UV exposure. It should also be transparent with low thermal resistance. EVA (Ethyl Vinyl Acetate) is the most used encapsulant material; it is placed in thin sheets between the solar cells and the top & rear, then heated to 150 °C to polymerize the EVA and glue the module together. One of the adverse effects of encapsulating solar cells into PV modules is that the encapsulation changes the heat flow in/out of the PV module. This contributes to the rise of the operating temperature of the PV module.

2.7.3. Rear surface

The rear surface of the PV module must have low thermal resistance that prevents the ingress of water or water vapour. Tedlar, a thin polymer sheet, is usually used in most modules. The rear surface must be optically transparent in bifacial modules that absorb light on both sides.

2.7.4. Frame

The last structural component that frames the module. A typical frame is usually made of aluminium. The frame structure should be free of ridges and projection to prevent water, dust, or other matter lodging.

2.7.5. Packing Density

The packing density of a PV module describes the area of the module that is covered with solar cells compared to that which is not. The packing density influences the power output of the PV module and its operating temperature. Depending on the solar cells' shape, the packing density will vary. For example, single-crystalline solar cells are round or semi-square, while multicrystalline silicon is usually square.

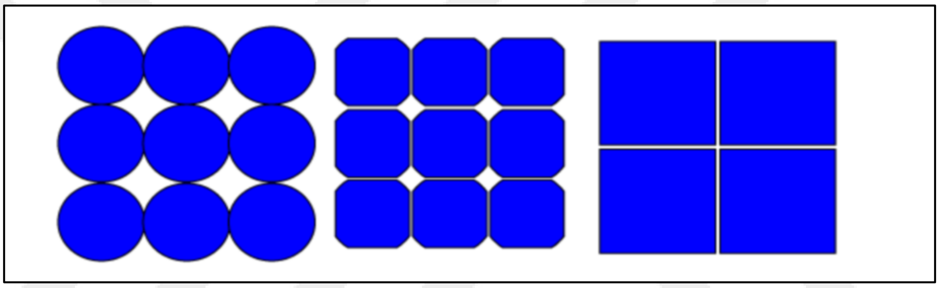

Figure 2.12 Demonstrates the relative packing density with round VS square cells. (Pveducation.org, 2023)

Sparsely packed solar cells in a module with a white back surface could lead to a minimal increase in the amount of energy generated due to the "zero depth concentrator", illustrated below, where some of the light striking areas between the cells, scatters and reflects to the solar cell to be absorbed.

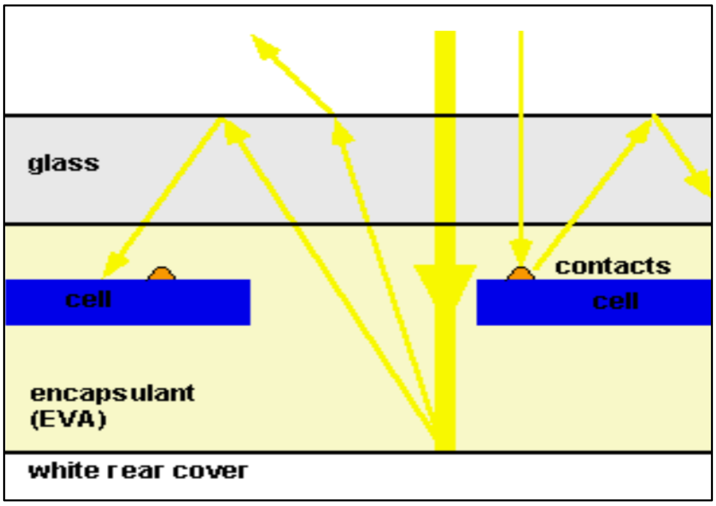

Figure 2.13 Illustrates the zero-depth concentrator. (Pveducation.org, 2023)

2.8.PV Module Temperature

Variation in temperature affects the operation of the PV module by decreasing its voltage, thereby reducing the generated power. Additionally, temperature increases are associated with higher chances of failure and damage to the PV modules. High-temperature degrees elevate stresses associated with thermal expansion and degradation by two folds for each 10°C increase in temperature. The operating temperature of a module is governed by the equilibrium between the heat generated by the PV module, the heat loss to the environment and the ambient operating temperature.

The heat generated by the module is subject to irradiance, the operating point of the module, the optical features of the module and solar cells, and the packing density of the solar cells in the PV module. The heat lost to the environment is released via any of the following three mechanisms; conduction, convection, and radiation; which way it is released depends on the thermal resistance of the materials the module is made from, the emissive properties of the PV module, and the ambient conditions (particularly wind speed) in which the module is installed.

When connecting photovoltaic modules to form a system and produce more power, the maximum voltage is not the specification voltage of the panel by itself, for example, (12V, 24V). However, it combines its open-circuit voltage (V_{OC}) and temperature coefficient. The temperature Coefficient is one of several factors that could alter the performance of a photovoltaic module, causing it to deviate from its ideal values. Other factors that could alter photovoltaic module performance include but are not limited to photovoltaic types. Amount of solar radiation and connected load resistance for maximum power transfer, in addition to the age of the photovoltaic module.

2.8.1. The temperature coefficient

The temperature coefficient of a solar cell is the amount in which the solar cell output voltage, current, and power varies because a change in the ambient temperature of the environment of the photovoltaic module is in, just before the solar cells have begun to heat up.

- β Coefficient of variation of V_{OC} with respect to T, is given by $\partial VOC/\partial T$.
- α Coefficient of variation of I_{SC} with respect to T, given by $\partial ISC/\partial T$.
- δ Coefficient of variation of P_{Max} with respect to T, given by $\partial P_{Max}/\partial T$.

The unit is either in % per degree (%/^{o}C) or volts per degree C, (V/^{o}C). The standard test conditions of solar cells are temperature of 25 ^{o}C, a radiation of 1000 W/m^2 and an air mass of 1.5, the solar panel is supposed to produce a maximum but continuous output power (P_{Max}) of 100W. However, these conditions do not represent the real-life conditions PV panels experience when installed. Nevertheless, the temperature coefficient of any solar cells is observed under those standard conditions and expressed in ± 1 ^{o}C variation in the ambient temperature.

For example, a temperature coefficient of 0.5 %/ ^{o}C indicates that for every 1 ^{o}C variation in the ambient temperature, the panel's power output will change by 0.5%. Theoretically, an increase in the ambient temperature by just one degree over 25 ^{o}C means that the power output will reduce by 0.5%. On the other hand, it also means that for every 1 ^{o}C below 25 degrees, the power output will increase by 0.5%.

Higher temperature will result in lower V_{OC}, meaning less V_{MP} making the PV module less efficient, while in cool weather, higher V_{OC} and greater V_{MP} make the PV module more efficient. The effect of the temperature variation on the PV panel's performance will be explored further in this study; however, determining the ideal temperature the PV panel could operate helps to generate the maximum power output possible. However, it will be based on the location and amount of solar radiation the solar cells receive. The amount of direct current electricity produced by the solar cells will be directly proportional to the amount of solar radiation. Based on the amount of radiation falling on the PV modules, the solar cell will generate a current over a range of voltages from 0V (short-circuit) to its maximum V_{OC} if I_{SC} is not 0 and at a closed circuit.

2.8.2. The effect of temperature coefficient on V_{OC}

An increase in temperature coefficient due to an increase in the ambient temperature will significantly affect the V_{OC} of the solar cell. The increase in temperature will affect the semiconductor material making up the solar cells and reduces the band gap of the semiconductor material. This increases the energy of the electron-hole pair, so they require less energy to break the bond. Breaking the electron-hole pair will result in a 0 I_{SC}, meaning that the solar cells will not generate any current, voltage or power. As mentioned earlier, the standard operating temperature of PV modules is 25°C.

However, this is not an accurate representation of the conditions experienced by PV modules in real-life situations. PV modules are expected to generate a proportional amount of energy to the amount of solar radiation they receive; however, based on research and field experiments, the ideal operating temperature is more of an average range influenced by the factors above. The more regulated and controlled those factors are, the more efficient the PV module is and nearer to its ideal specification.

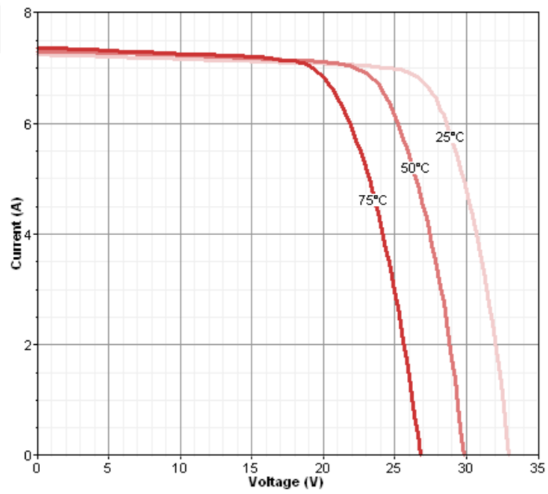

Figure 2.14 shows the current-voltage (IV) curve at different solar cell temperatures.

2.8.3. The effect of temperature coefficient on I_{SC},

It is worth mentioning that the temperature does not just affect the V_{OC}. It could also affect the current depending on the change in the ambient temperature in the environment the PV module is installed. The I_{SC} increases to some extent with temperature increase due to the decrease in the bandgap energy. This slightly increases the photon's energy to create electron-hole pairs. As mentioned earlier, the current is lost if the pair recombined, and no power would be generated. However, this is a minimal effect; the ISC coefficient for silicon solar cells is 0.06% / °C. Variation in I_{SC} in relation to temperature is more dependent on the design of the cell rather than the temperature coefficient or the properties of the semiconductor materials making up the solar cells. Nevertheless, the temperature coefficient for current is usually much lower for the current compared to the voltage; the impact of temperature variation on current is insignificant.

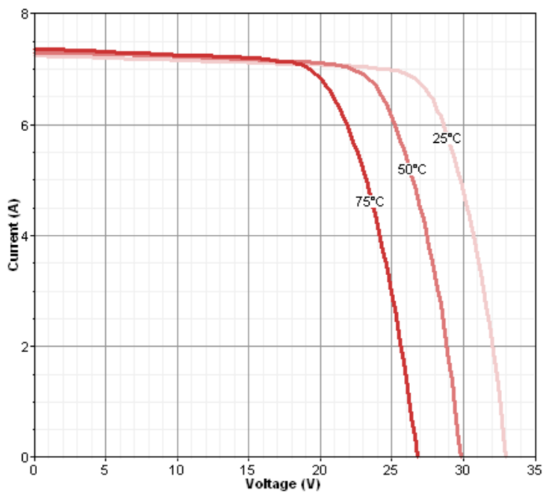

Figure 2.15 shows the current-voltage (IV) curve at different solar cell temperatures.

2.8.4. The effect of temperature coefficient on power.

Since power output is directly proportional to the current and the voltage, the effect of the temperature coefficient on power will be directly proportional to the effect of voltage and current. However, as mentioned earlier, the temperature coefficient significantly affects the open circuit voltage and has minimal effect on the short circuit current. For a significant reduction in the power output, the open circuit voltage must be severely decreased by a significant change in the ambient temperature. Overheating of the PV arrays does not just affect the power output and significantly reduces it. It could also lead to damage to the mechanical component of the solar panels; this will decrease the lifespan of the solar panels, which will reflect negatively on their performance and overall cost.

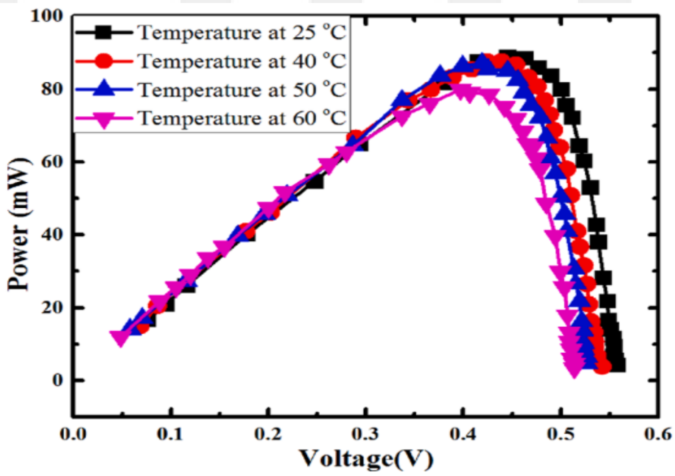

Figure 2.16 shows the P-V characteristics of solar cell at different temperature.

2.9.PV Cooling strategies:

Traditional PV land-based systems are not usually equipped with any cooling mechanism to reduce their temperature, so they cannot withstand the risk of overheating. That is where hybrid solar systems have proven to be revolutionary as it utilises water to cool down the PV modules while still generating power, and that is where cooling strategies become vital to apply for harvesting the maximum potential of solar energy while trying to avoid the challenges associated with overheating (Sooleva, 2023). Five significant ways could be used to cool down a PV solar system, and those include using fans, using water, using ambient air, using liquid nitrogen, and finally, using wind turbines.

1. Cooling with fans could reduce the temperature by 10 degrees resulting in a significant increase in the power output depending on the power coefficient of the PV panel. Fans used are usually installed with a microcontroller and a temperature sensor that measures the temperature of the PV modules. The microcontroller will allow the control of the fans and only activate them when and if needed.
2. Cooling with water could take the form of two strategies: active cooling and passive cooling. Passive cooling uses natural convection to transfer the heat away from the panels, while active cooling requires energy to cool down the solar panels. Water cooling is one of the most common and fundamental strategies to cool down PV modules. Another added advantage to water cooling is that it cleans the panels. For example, when the panels are sprayed with water, it removes any dirt that could be blocking the absorption of the sunlight. The latest systems have even been recycling the hot water from the PV modules for other purposes in the house.
3. Ambient air cooling, this method uses the cooler ambient air to ensure the convective heat transfer from the panels away to the air. The system can be designed with an inlet and outlet to ensure ambient air circulation around the solar modules to transfer the heat away. However, one of the main disadvantages of air cooling is that its weather/location is dependent. So, if you are in a hot country with high ambient air temperature, it will not act as an effective method to cool down the solar system.
4. Cooling with liquid nitrogen is one of the most effective cooling strategies. Nitrogen has a shallow boiling point of -196 °C. When the solar system overheats, the heat is circulated by liquid nitrogen, which significantly cools down the system. The energy can then be converted to electricity, increasing the power output. While liquid nitrogen is a very efficient cooling strategy, it adds to the overall cost of the system, especially for a large-scale solar system.

5. Cooling with wind turbines is an improved air-cooling strategy. It could be used to cool down the solar panels; however, they must be strategically positioned above the PV panels. The rotating wind turbines will allow ambient air circulation around the PV modules and cool them down. The main advantage of cooling with wind turbines is that it allows the potential of complementary hybrid systems, which allow the utilisation of pre-existing infrastructure and results in a significant increase in power output throughout the year.

2.9.1. The effect of cooling on PV solar systems,

Cooling solar panels can positively impact the solar system's performance, longevity and durability, structural and mechanical integrity, and economic sustainability. By maintaining lower operating temperatures, cooling mechanisms boost the efficiency of solar panels, allowing them to convert more sunlight into electricity. This efficiency increase, increases the energy output, potentially raising the return on investment, and lowers the wear and tear caused by excessive heat and damaging PV panels.

Consequently, increasing the panels' lifespan will make solar power systems a cost-efficient project that produces energy with 0 carbon footprints. Besides, cooling solar panels reduces the thermal stresses that can damage the structural and mechanical components of solar panels. From an economic point of view, enhanced energy production and prolonged operational life translate to even more cost savings and less maintenance expenses. Thus, integrating effective cooling strategies provides multiple benefits that ultimately enhance the overall solar panel performance.

2.10. Experimental set up and research methodology

In this study, the following methods will be applied for the evaluation of FPV systems.

1. Experimental setups
    a. Lab
    b. Field
2. Data collection and analysis
3. Impact assessment

To collect data, a two-stage study was carried out as the laboratory experiment and the fieldwork. Based on the methodology discussed earlier, the experiment aimed to evaluate the power and efficiency and how they vary depending on the panel temperatures. For this purpose, the data taken from the field were analysed based on the environment, water, and panel temperatures. Field installations were compared, the data obtained was interpreted, and suggestions were presented. The effects of the study were evaluated and interpreted under four main categories.

1. Evaluation of thermal effects
2. Evaluation of Electrical-Thermal effects
3. Evaluation of environmental impacts
4. The potential and economic evaluation at the scale of Turkey

2.10.1. Experimental setups

2.10.2. Laboratory Setup

A simulation experiment that was carried in the laboratory to compare, analyse, and predict the effect of light intensity on the behaviour of solar modules and on other variables such as temperature, current and voltage is also explained.

The photovoltaic module TS-M364-12 was used from OR.TEC SOLAR with the following specification.

Pmax	**12W**	**Dimensions**	**245x364x25mm**
Power tolerance	**0-5%**	**Series fuse**	**12A**
Open circuit voltage	**24.05V**	**Application class**	**A grade**
Short circuit voltage	**0.64A**	**Min.field wiring(cooper)**	**14 AWG**
Maximum power voltage	**20.6V**	**Structural load**	**45lb/ft^2**
Maximum power current	**0.61A**	**No. of cells**	**36 (4x9)**

Table 2.1 Demonstrates the specification of the photovoltaic module TS-M364-12.

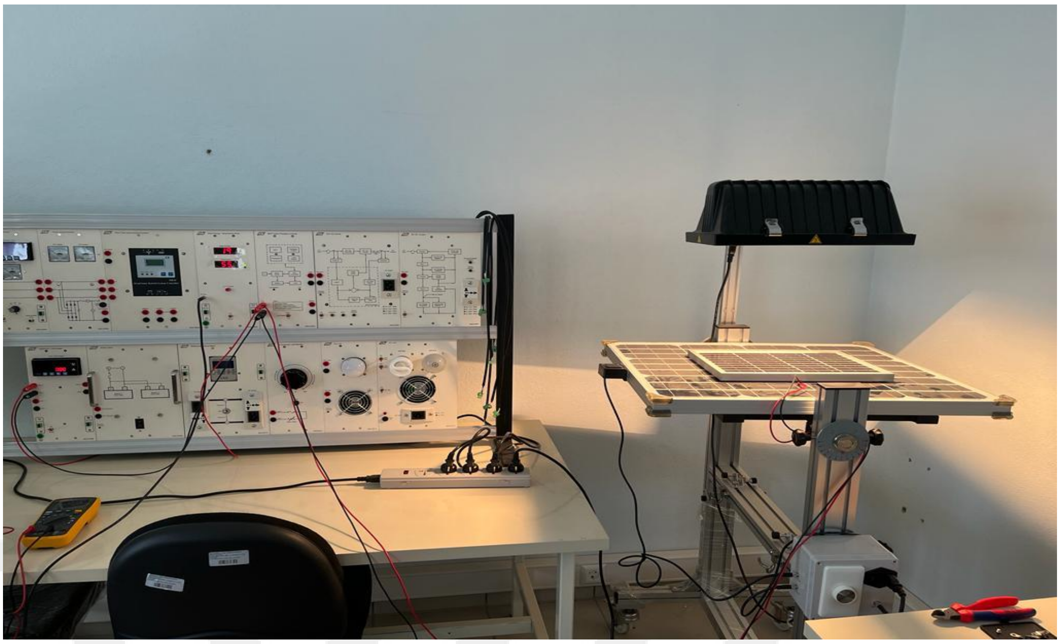

Figure 2.17 Shows the equipment used in the simulation experiments conducted in the laboratory.

The voltage and current were measured using a voltmeter, while the temperature and light intensity were measured and recorded using an electrical board that was directly connected to the solar simulator.

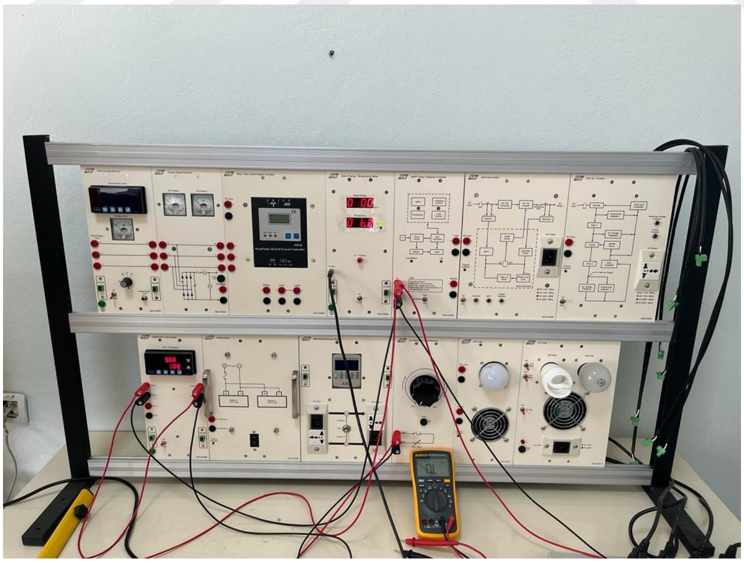

Figure 2.18 Shows the voltameter and electrical board used in the simulation experiments conducted in the laboratory.

2.10.3. Field installations

In this study, a field setup was carried out to evaluate if floating PV systems are more efficient than traditional land-based PV systems. Power characteristics were measured and obtained by performing a series of experiments using 5 identical PV modules that varied between water-cooled / uncooled terrestrial installations and floating solar system installations at different orientations.

PV module 1	**Floating 0°-degree inclined panel with no water contact**
PV module 2	**Floating 21° inclined panel.**
PV module 3	**Floating 0 ° degree inclined panel in direct contact with the water surface.**
PV module 4	**Land-based near the shore panel.**
PV module 5	**Land-based near the shore panel with water-cooling system installation.**

Table 2.2 Shows the different orientation of the panels used in the experiment.

Five identical mono-crystalline silicon diode solar panels were used, with the below specifications,

Pmax	**12W**	**Dimensions**	**245x364x25mm**
Power tolerance	**0-5%**	**Series fuse**	**12A**
Open circuit voltage	**24.05V**	**Application class**	**A grade**
Short circuit voltage	**0.64A**	**Min.field wiring (cooper)**	**14 AWG**
Maximum power voltage	**20.6V**	**Structural load**	**45lb/ft^2**
Maximum power current	**0.61A**	**No. of cells**	**36 (4x9)**

Table 2. 3 Illustrate the electrical specification of the photovoltaic module TS-M364-12.

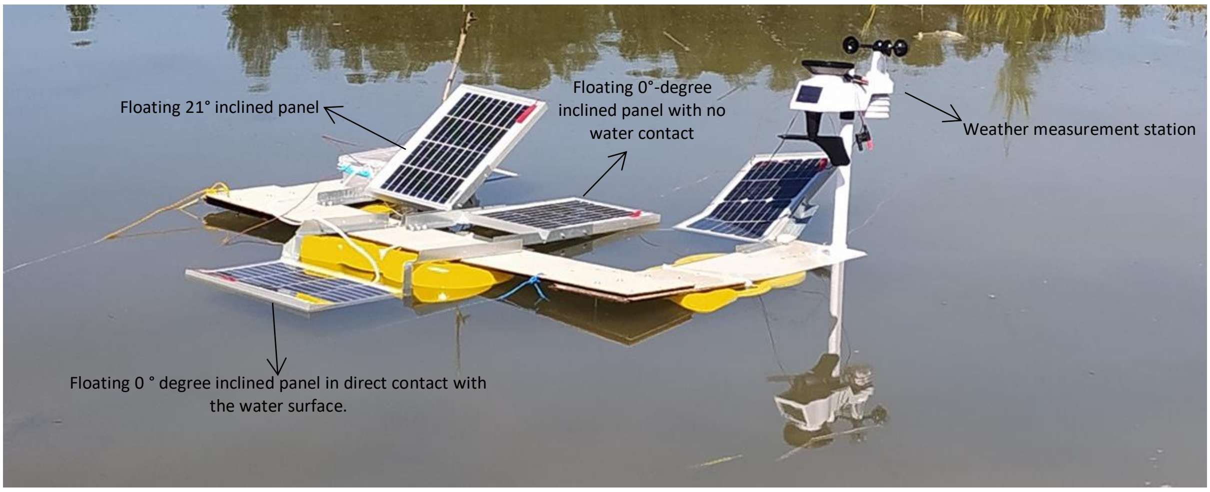

Figure 2.19 Shows the layout and the floating panels used in the experiment.

Figure 2.20 shows the land-based panels used in the experiment.

The weather measurement station measured humidity, ambient temperature, radiation amount, UV index, wind speed, wind direction parameters and transmit them wirelessly. The weather measurement device technical specifications are shown below,

Weather Station Sensor Parameters

Temperature:	[Indoor: 32 to 140°F (0 to 60°C), Outdoor: -40 to 140°F (-40 to 60°C), Accuracy: ±2°F]
Humidity:	[10 to 99 %, Accuracy: ±5%]
Rianfall:	[0 to 9999mm (0 to 393.6 inches), Accuracy: <15mm: ±1 mm, >15mm: ±7%]
Wind Speed:	[0 to 50 m/s (0 to 112 mph), Accuracy: <10 m/s: ±0.3m/s , >10m/s: ±10%]

Wind Direction:	[0 - 360º, Accuracy: ±10º,16 point compass]
UV Index:	[1 to 15, Accuracy: ±1]
Sunlight Index:	[0 to 200klux, Accuracy: ±15%]
Barometric Pressure:	[300 to 1100 hpa (8.86 to 32.5 InHg), Accuracy: ±3 hpa]

Figure 2.21 Shows the parameters that could be measured using the weather station sensor.

Using the basic circuit shown in Figure 3.22, the loaded currents and voltages of the panels were measured with the Fluke 17 B+ digital multimeter shown in Figure 3.23, while the temperatures were measured with the K-type thermocouple reader shown in Figure 3.23. The rheostat shown below in figure 3.22 was used as the load.

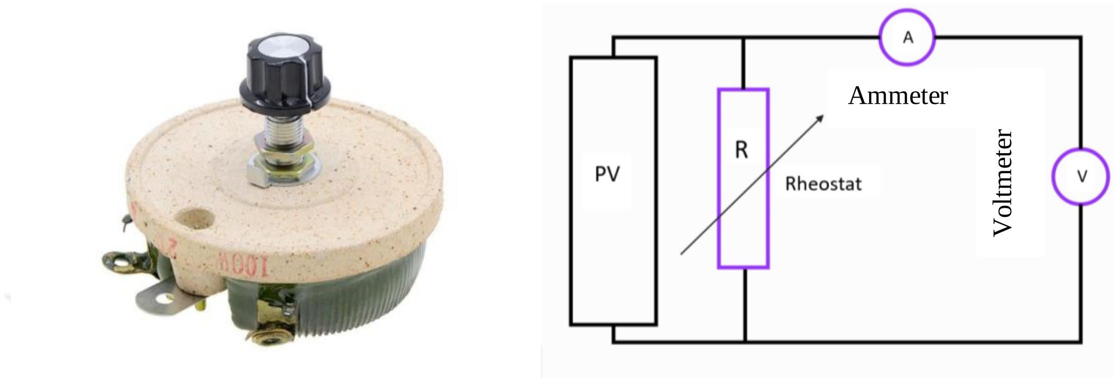

Figure 2.22 Circuit and rheostat

Figure 2.23 Fluke 17B+ Digital Multimeter and LUTRON TM-947SD Thermometer.

3. RESULTS & DISCSSION

A two-stage study collected data from the laboratory experiment and the fieldwork.

3.1.Laboratory experiment

For the experimental evaluation of the effects of solar panels' surface temperatures on power and efficiency, a set of experiments were carried out in the renewable energy laboratory in TOKAT GAZİOSMANPAŞA ÜNİVERSİTESİ/UNIVERSITY.

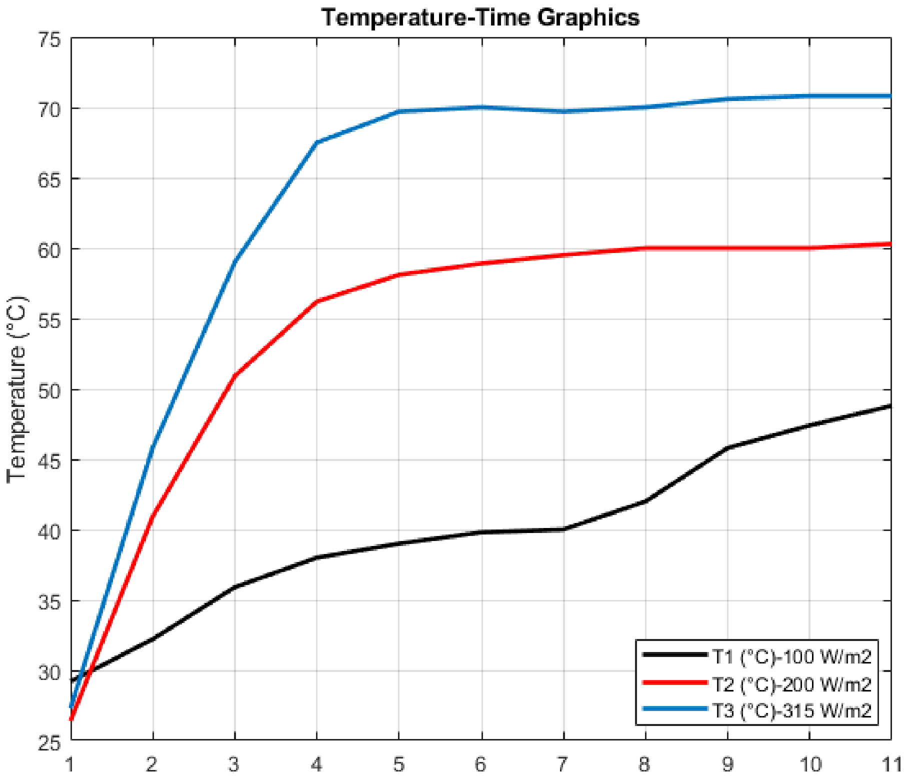

Figure 3. 1 Demonstrates the positive correlation between time and temperature, as more time passed the temperature of the solar panels increased.

Using the equipment in the laboratory, the experiments were carried out under the following light intensities; 100, 200 and 315, as shown in Figure 3.1 above. Under the light intensities, the following parameters were measured; current, voltage and temperature. Based on the measured parameters, the power was calculated. The measurements were taken every 15 minutes; once the solar panels' surface temperatures remained constant at a certain light intensity, the light intensity was changed to explore the effect further.

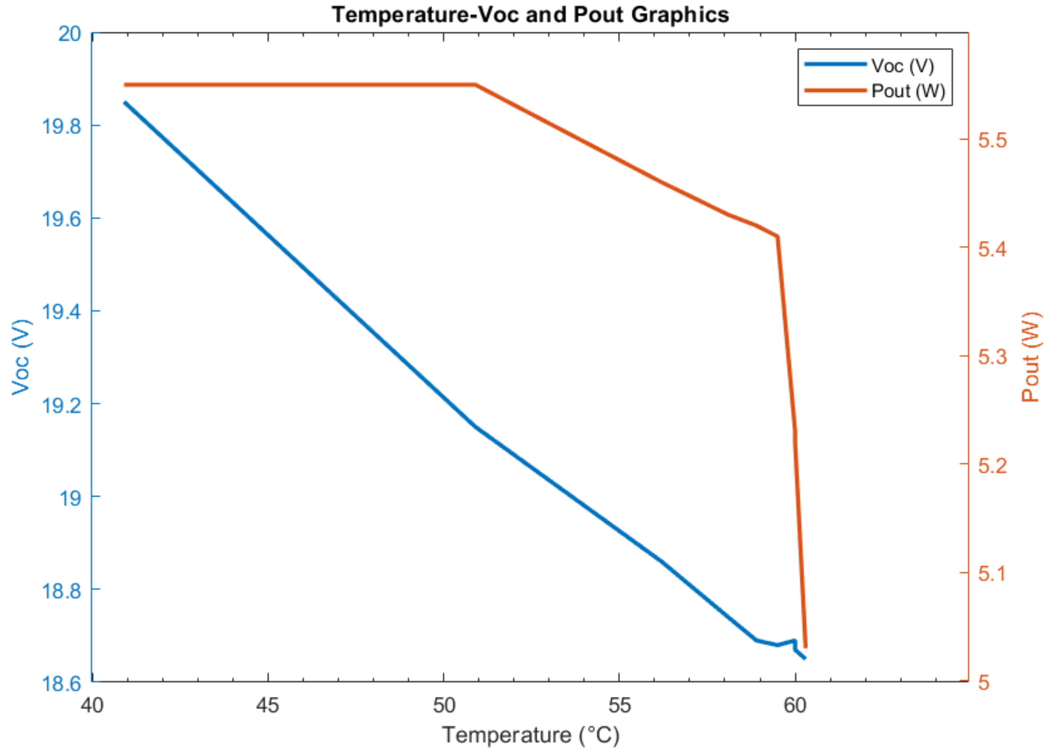

Figure 3. 2 Illustrates the relationship between temperature VS P/V_{OC} at 200 W/m^2

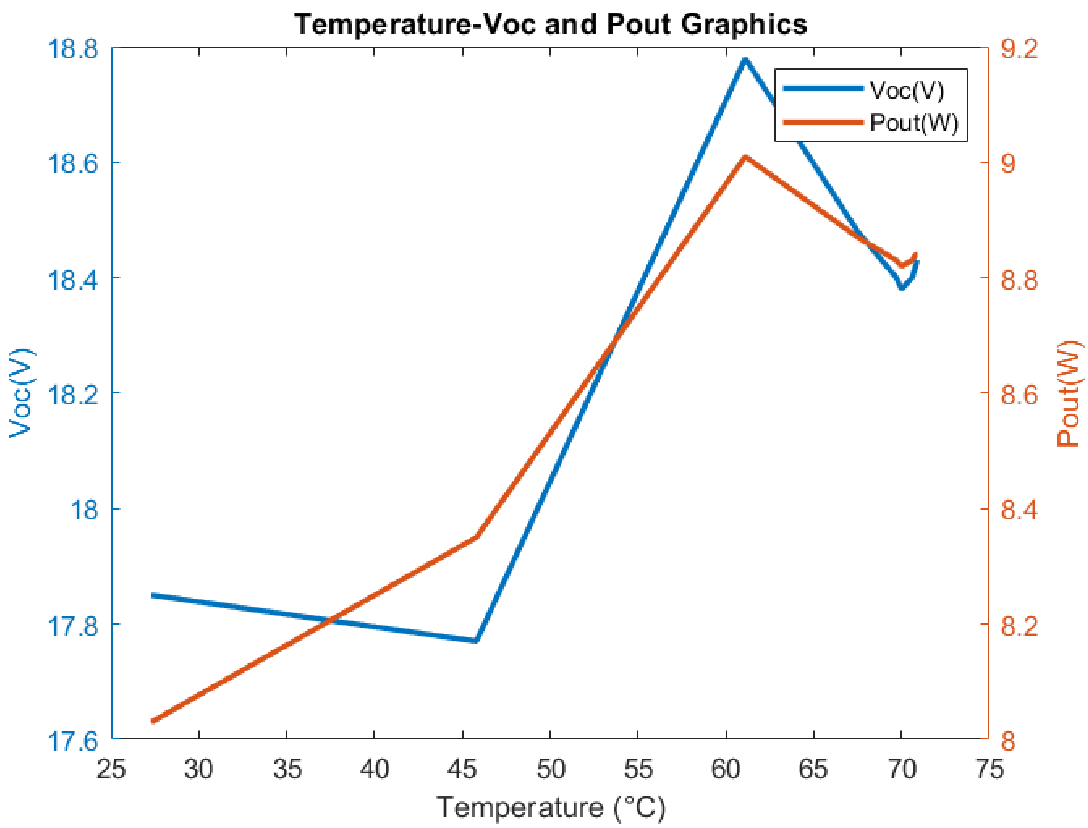

Figure 3. 3 Illustrates the relationship between temperature VS P/V_{OC} at 315 W/m^2

Upon examination of the laboratory study results. At light intensity of 200 W/m^2 and 315 W/m^2 the temperature remained around 50 degrees. While at a light intensity of 100 W/m^2, the temperature remained 48.8 degrees. The plotted results for V_{OC} and power versus temperature at light intensity 200 W/m^2 and 315 W/m^2 are shown in figure 3.2 & 3.3 above.

As observed in the figures above, there is a decrease in both V_{OC} and P values in both cases. For 200 W/m^2 and 315 W/m^2, V_{OC} decreased from 18.85 V to 18.35 V, and from 19.85 to 18.65 V respectively. For power output at 200 W/m^2 light intensity, the power decreased by 0.518W, this corresponds to 9.3% decrease. At 315 W/m^2 light intensity, the power output decreased by 0.361W and this corresponds to 4% decrease. There was no significant change to the short circuit current value.

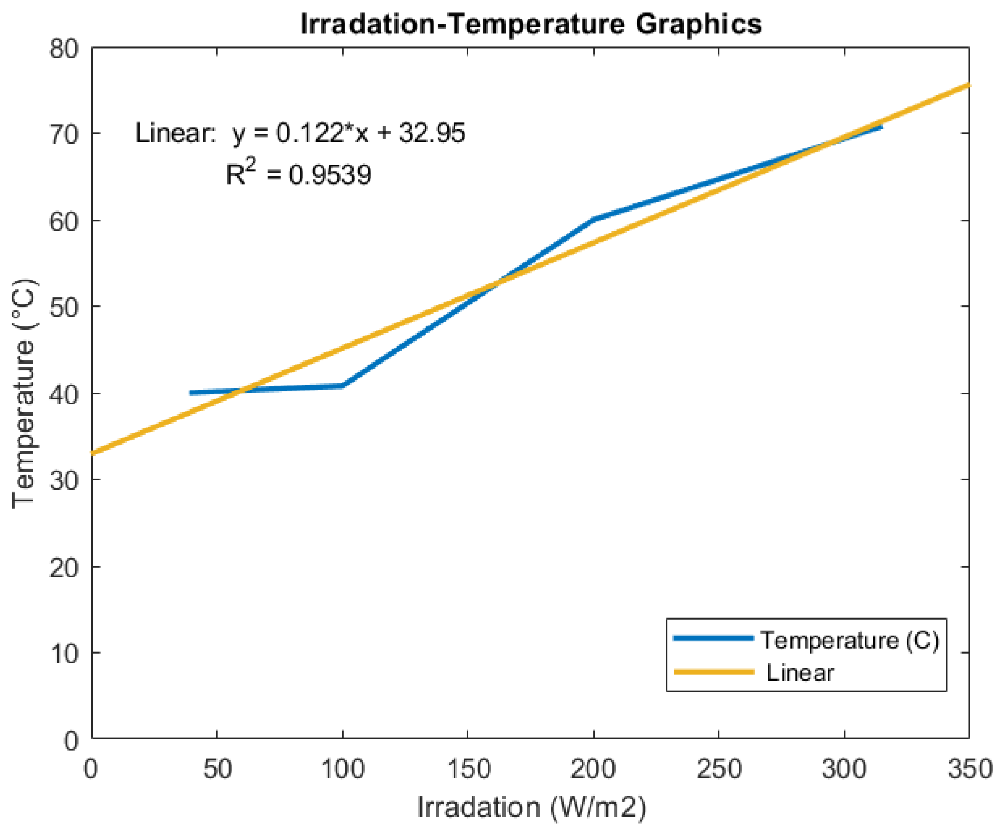

Figure 3. 4 Illustrates the temperature variation of the panel surface at different light intensities.

As observed in the figure 3.4 above, when the light intensity increases, the panel surface's temperature increases exponentially. At a light intensity of 39 W/m^2, the temperature was 40 degrees, however it increased to 71 degrees when the light intensity increased to 315 W/m^2. This means that as the amount of radiation increases, the temperature of the panel increases and therefore the efficiency decreases. This ultimately results in the reduction of the energy produced and efficiency of the solar panels.

3.2.Practical experiment

The study was carried out on the 25th /07/2023 from 8:00am till 17:00 pm and parameters were measured every hour in the Almus Dam Lake, in Tokat Province in the Black Sea region of Turkey which has a surface area of 26650 acres (108 km^2) to determine the potential of floating solar systems in Turkey and investigate their electrical and environmental advantages over terrestrial installations. It will also shed some light on the potential of lands-based systems near the shore of the dam to establish more efficient PV power systems. In this part, the GPS coordinates where the study was carried out is the following, **(40.3781750, 36.9300451)**, the geocoded address is **60900 Almus, Almus Tokat (Merkez) Türkiye.**

In the field experiment, the following parameters were measured every hour.

Parameter	Abbreviation	Instrument	UNIT
Ambient temperature	Ta	Weather station	℃
Temperature of the solar panel	T	Thermometer	℃
Voltage	V	Voltmeter	V
Current	I	Ammeter	A
Maximum power	$P \text{ or } P_{Max}$	-	W
Power	P_m	-	W
Light intensity	Light intensity	Weather station	W/m^2
Humidity	Humidity	Weather station	%
Wind speed	Wind speed	Weather station	m/s
Fill factor	FF	-	-
Efficiency	Η	-	%

Table 3.1 Displays the measured parameters and calculated variables in the field experiment.

The measured parameters and calculated variables are displayed in table 3.2 To table 3.6 below.

Time	Light intensity (W/m^2)	T_1 (°C)	V_{oc1} (V)	I_{sc1} (A)	V_{m1} (V)	I_{m1} (A)	$T1-T_a$ (°C)	FF	P_{m1} (W)	P_1 (W)	Efficiency (%)
8:00	594	18.1	22.1	0.35	12.3	0.31	0.7	0.49	3.625	6.63	7.20
9.00	700	29	21.7	0.46	19.67	0.15	4.8	0.30	3.6765	7.092	4.73
10.00	776	40.2	22.39	0.52	19.5	0.43	5	0.72	3.834	8.3265	12.12
11.00	830	48	22.24	0.52	19.14	0.4	3.1	0.66	2.1086	8.16	10.34
12.00	830	50.9	21.92	0.6	18.14	0.37	2.2	0.51	5.9112	9.8028	9.07
13.00	813	44.7	22	0.51	18.82	0.41	3.5	0.69	6.573	10.0296	10.64
14.00	685	42.4	22.26	0.5	19.9	0.29	-2	0.52	7.1616	9.3093	9.45
15.00	594	41.6	22.22	0.32	22.2	0.15	-3.3	0.47	3.484	7.5968	6.29
16.00	424	38.6	21.85	0.29	21.5	0.14	-2.5	0.48	2.583	6.3477	7.96
17.00	388	34	21	0.23	14	0.15	-0.9	0.43	1.786	4.652	6.07

Table 3.2 Illustrates the parameters for the floating 0 degrees panel with no water contact.

Time	Light intensity (W/m^2)	T_2 (°C)	V_{oc2} (V)	I_{sc2} (A)	V_{m2} (V)	I_{m2} (A)	T_2-T_a (°C)	FF	P_{m2} (W)	P_2 (W)	Efficiency (%)
8:00	594	18.3	22.35	0.42	13.6	0.37	0.9	0.54	5.032	9.387	9.50
9.00	700	32	22.78	0.51	19.7	0.35	13.8	0.59	6.895	11.618	11.05
10.00	776	44.5	22.09	0.53	19.12	0.46	24.8	0.75	8.7952	11.708	12.71
11.00	830	46.5	22	0.49	18.74	0.45	24.8	0.78	8.433	10.780	11.39
12.00	830	54	21.85	0.5	18.25	0.43	30.3	0.72	7.8475	10.925	10.60
13.00	813	49.2	22.93	0.48	18.2	0.43	19.9	0.71	7.826	11.006	10.79
14.00	685	49.4	22.31	0.52	17.8	0.39	20	0.60	6.942	11.601	11.36
15.00	594	44.7	22.21	0.4	16.6	0.35	14.6	0.65	5.81	8.884	10.97
16.00	424	36.1	22	0.35	14.8	0.29	7	0.56	4.292	7.700	11.35
17.00	388	32.6	22	0.25	10.25	0.24	5.6	0.45	2.46	5.5	7.11

Table 3.3 Illustrates the parameters for the floating 21 degrees panel.

Time	Light intensity (W/m^2)	T_3 (°C)	V_{oc3} (V)	I_{sc3} (A)	V_{m3} (V)	I_{m3} (A)	T_3-T_a (°C)	FF	P_{m3} (W)	P_3 (W)	Efficiency (%)
8:00	594	18.1	22.1	0.3	12.5	0.29	0.7	0.55	3.813	7.735	6.84
9.00	700	23	23.64	0.3	19.35	0.19	10.8	0.52	2.950	9.982	5.89
10.00	776	24.7	23.79	0.35	19.17	0.2	20.5	0.46	8.385	11.643	5.54
11.00	830	24.8	24	0.34	16.22	0.13	26.3	0.26	7.656	11.565	2.85
12.00	830	25.9	23.34	0.42	16.42	0.36	27.2	0.60	6.712	13.152	7.99
13.00	813	32.8	23.88	0.42	15.65	0.42	15.4	0.66	7.716	11.22	9.07
14.00	685	27.4	23.87	0.39	22.38	0.32	13	0.77	5.771	11.13	11.72
15.00	594	26.8	23.74	0.32	13.4	0.26	11.5	0.46	3.33	7.110	6.58
16.00	424	26.6	23.51	0.27	12.3	0.21	9.5	0.41	3.01	6.337	6.83
17.00	388	26.1	23.26	0.2	8.93	0.2	7	0.38	2.1	4.83	5.16

Table 3.4 Illustrates the parameters for the floating 0 degrees panel in direct contact with water.

Time	Light intensity (W/m^2)	T_4 (°C)	V_{oc4} (V)	I_{sc4} (A)	V_{m4} (V)	I_{m4} (A)	T_4-T_a (°C)	FF	P_{m4} (W)	P_4 (W)	Efficiency (%)
8:00	594	18	22.3	0.41	13.4	0.32	0.6	0.47	4.288	9.143	8.09
9.00	700	32.9	22.35	0.51	16.9	0.44	14.7	0.65	7.436	11.399	11.91
10.00	776	54.6	22.35	0.5	16.5	0.42	34.9	0.62	6.93	11.175	10.01
11.00	830	56.5	22.22	0.5	19.61	0.4	34.8	0.71	7.844	11.11	10.60
12.00	830	64.3	21.88	0.49	18.79	0.4	40.6	0.70	7.516	10.721	10.15
13.00	813	56.9	22.27	0.49	18.64	0.4	27.6	0.68	7.456	10.912	10.28
14.00	685	53.5	22.25	0.42	17.31	0.37	24.1	0.69	6.405	9.345	10.48
15.00	594	49.8	22.3	0.31	13.91	0.3	19.7	0.60	4.173	6.913	7.88
16.00	424	36.2	22.1	0.26	10.1	0.26	7.1	0.46	2.626	5.746	6.94
17.00	388	33	21.64	0.14	5.85	0.13	6	0.25	0.761	3.030	2.20

Table 3.5 Illustrates the parameters of the land-based panel near the shore.

Time	Light intensity (w/m²)	T_5 (°C)	V_{oc5} (V)	I_{sc5} (A)	V_{m5} (V)	I_{m5} (A)	T_5-T_a (°C)	FF	P_{m5} (W)	P_5 (W)	Efficiency (%)
8:00	594	17.9	22.8	0.52	16.7	0.44	0.5	0.62	7.348	11.856	13.87
9.00	700	25.6	23.39	0.63	20.18	0.56	7.4	0.77	11.301	14.7357	18.10
10.00	776	32.2	23.34	0.59	20.12	0.54	12.5	0.79	10.865	13.7706	15.70
11.00	830	31.5	23.28	0.58	20.54	0.42	9.8	0.64	8.627	13.5024	11.65
12.00	830	33	22.46	0.57	19.36	0.42	9.3	0.64	8.131	12.8022	10.99
13.0	813	32.9	23	0.54	19.2	0.37	3.6	0.57	7.104	12.42	9.80
14.00	685	33	22.82	0.46	18	0.4	3.6	0.69	7.2	10.4972	11.79
15.00	594	32.1	22.67	0.3	12.38	0.27	2	0.49	3.342	6.801	6.31
16.00	424	31.5	21.98	0.26	9.65	0.22	2.4	0.37	2.123	5.7148	5.61
17.00	388	31	21.56	0.12	3.5	0.11	4	0.15	0.385	2.5872	1.11

Table 3.6 Illustrates the parameters of the land-based panel near the shore with water-cooling system.

3.3.Evaluation of The Thermal Effects of The Findings

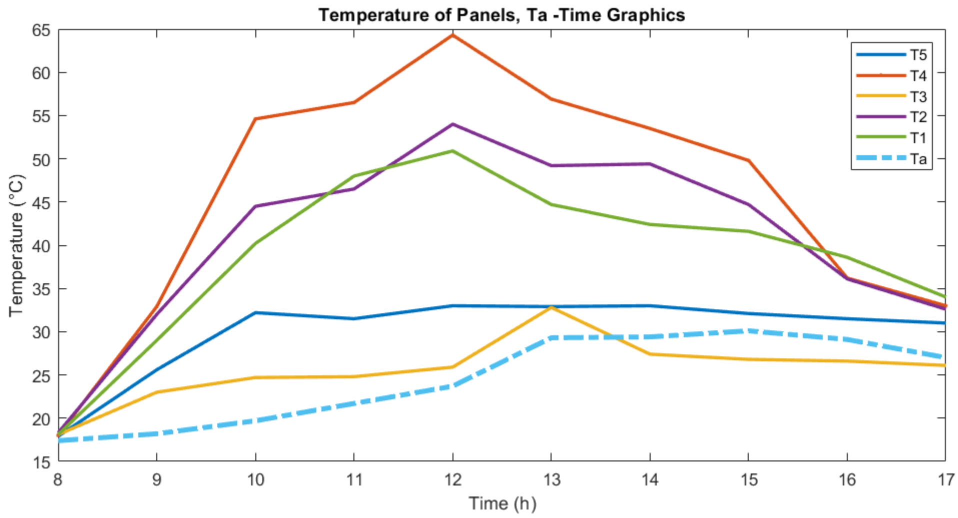

Figure 3. 5 Illustrated the difference between the the ambient temperature and panels' temperature.

In figure 3.5 above, PV modules 2,4 and 5 have the same inclination angle resulting in all three panels receiving the same amount of radiation so they will be compared together in this aspect. Looking at the results and comparing the operating temperature of PV modules 2,4 and 5 to the ambient temperature, PV module 4 had the highest operating temperature and the most significant difference between the operating temperature and the ambient temperature as shown in figure 4.5 above, then PV module 2, followed by PV module 5. Regarding PV module 3 and 1. PV module 3 had significantly lower operating temperature than PV module 1 and operated at a similar temperature to the ambient temperature, while PV module 1 operated at a significantly higher operating temperature.

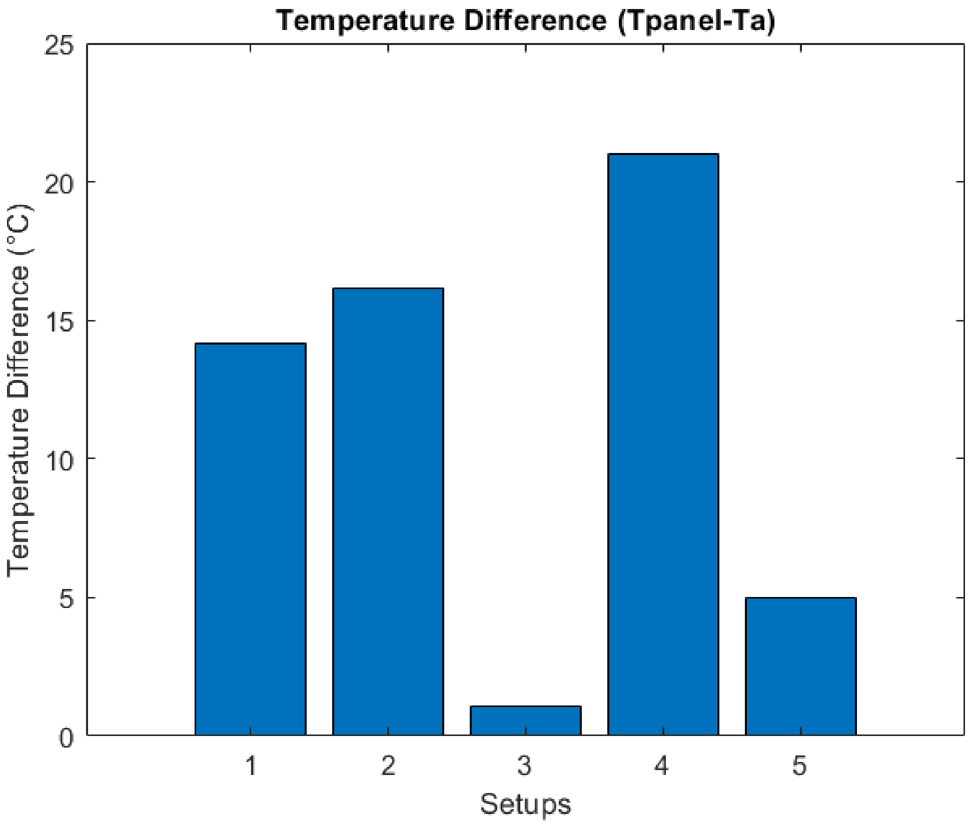

Figure 3. 6 Illustrates the temperature difference between the PV panels' surface temperature and the ambient temperature.

According to figure 3.6 above, the largest difference between the ambient temperature and the panels' surface temperature was for the land-based PV module 4 with a difference of 23.3 °C. The smallest difference was at 1.17°C for PV module 3 when, followed by PV module 5.

3.4.Evaluation of The Thermo-Electrical Effects of The Finding

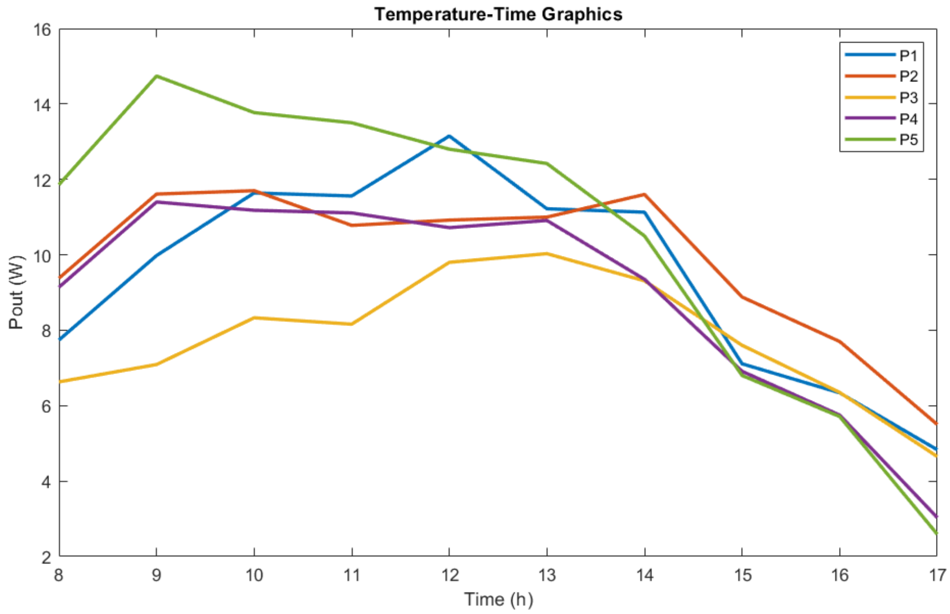

Figure 3. 7 Illustrates the different energy output by the different panels.

As mentioned earlier, PV modules 2,4 and 5 have the same inclination angle resulting in all three panels receiving the same amount of radiation. To obtain accurate results, they will be compared against each other to evaluate their electrical-thermal effect. Regarding the amount of power produced, the results in Figure 4.7 shows that the land-based panel near the shore with the water-cooling system installation (PV module 5) performed the best and had the highest power output of 10.469W/h, second is the floating 21 degrees inclined panel (PV module 2) with 9.911 W/h, and lastly the land-based near the shore panel (PV module 4) with 8.949 W/h.

The power output corresponds with the operating temperature of the panels, as shown in Figure 4.5. PV module 5 has a lower operating temperature than PV modules 2 and 4, resulting in greater power output. Similarly, PV module 2; had a lower operating temperature than PV module 4 and greater power output. Regarding PV modules 1 and 3, while PV module 3 had a lower operating temperature, PV module 1 had a greater power output with 9.470 W/h, comparing to 7.795 W/h for PV module 3.

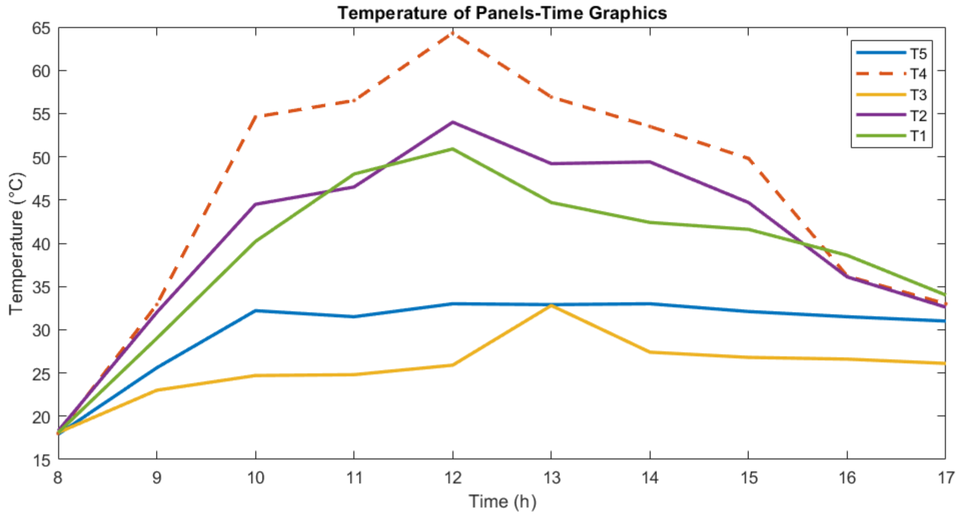

Figure 3. 8 Illustrates the difference between the panels' surface temperature.

When comparing the operating temperature of PV modules 2,4, and 5, as shown in Figure 4.8 above, the result clearly shows that all PV modules 5 and 2 have lower operating temperatures than PV module 4. This translates to a higher power output of 10.469W/h and 9.911 W/h, respectively, as shown in Figure 4.7. PV module 4 had the highest operating temperature resulting in lower power output at 8.949 W/h because as the operating temperature increases, the current increases exponentially, and the voltage reduces linearly, eventually reducing the power output. The results support the proposed theory that floating PV systems are more efficient and generate higher power output than traditional land-based PV systems.

Almost all the floating PV systems evaluated in the study performed better than the traditional land-based PV module. While one could argue that PV module 5 generated the greatest power output of 10.469 W/h, as shown in Table 4.7, and it is technically land-based. However, this installation follows the same principles as floating solar panels. Additionally, the difference was insignificant between PV module 5 and PV module 2, which was passively cooled using tidal movement. The difference was 0.558 W/h; however, this could be easily compensated because no cost or extra installations were required to equip the PV system with a cooling system.

Moreover, while PV module 5 was land-based, it followed the same principle of the floating PV modules with the pump using the lake water to cool down the PV module on land.

Using heat transfer systems to prevent the overheating of the PV system is vital to increasing its efficiency and lifespan. In terms of cooling techniques, active or passive cooling strategies could be used to reduce the temperature of the PV system. PV module 5 was equipped with an active cooling system, unlike PV module 2, that was passively cooled using the tidal movement of the lake, and PV module 4, which represented a traditional PV module without any cooling system.

Other studies have also shown that the PV cell efficiency decreases significantly during the hours when the radiation is the highest, so the cooling process is vital for the performance of a PV module and reflects positively on the amount of power generated by the PV system and its life span, especially in summer and hot areas. PV modules 1 and 3 had a lower operating temperature than PV module 4, as shown in Figure 4.8. However, while PV module 3 had the lowest operating temperature, PV module 1 had a greater power output of 9.470 W/h, compared to 7.795 W/h for PV module 3. Regarding PV module 3, the results were promising but also demonstrated some anomalies.

Comparing PV module 3 to all other PV modules, PV module 3 had the lowest operating temperature, as shown in Figure 4.7. Theoretically, this should translate to PV module 3 having the greatest power output. However, other factors came into play, making PV module 3 come last in the energy generated, as demonstrated by comparing results from the other PV modules. To start with, the PV module had direct contact with water. The tidal movement and water molecules covering the top surface of the PV module could have been a reason that severely impacted the power output.

Typically, the sunlight travels through the air, which has a low density and hits the transparent top surface of the PV module to be absorbed by the solar cells. However, when the light travels through the air and hits the more-dense water molecules, the light speed decreases, and the light rays slow down. The higher density of water molecules also changes the direction of light and causes its refraction. Refraction of the light means there is less light to be absorbed by the solar cells. Less light to be absorbed means smaller power output. Another reason that could have led to PV module 3 having the lowest power output is its orientation.

Studies have shown that the optimum tilt angle changes between 0° and 65° throughout the year in Turkey. Changing the angle of the PV module could have changed the power output dramatically, as the incident angle of sunlight significantly impacts the efficiency of a PV module. The angle at which the light falls on the panel can affect the amount of solar radiation the module can convert into power. When the angle is perpendicular to the panel, the radiation hitting the module is at its maximum. When the angle becomes more oblique, the amount of radiation decreases, which ultimately means less power output. The main factor affecting the power output in PV power systems is the amount of radiation.

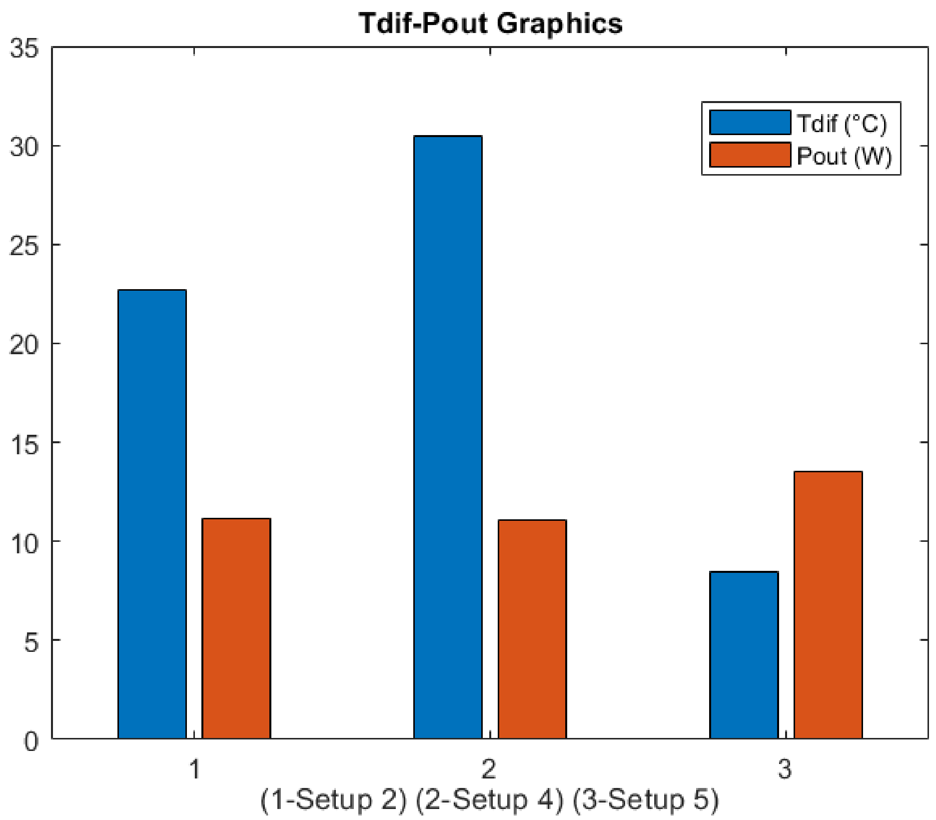

Figure 3. 9 Compares the difference between the average temperature of installation 2,4 and 5 and the ambient temperature VS the average power generated by each panel.

The amount of radiation is expressed in watts per m^2. For radiation to be evaluated correctly and accurately, the angles of the solar panels must be the same. In the PV module installations, installations 2,4 and 5 have the same inclination angle (21 °C) and are exposed to the same amount of radiation.

Therefore, the three installations were compared in Figure 4.9 above, which compares the difference between the average temperature difference of installations 2,4, and 5 and the ambient temperature and the average power generated. The data in figure 4.9 was based on an average light intensity of 700 W/m^2 between 9.00am and 1.00pm as those were the hours with highest solar radiation levels.

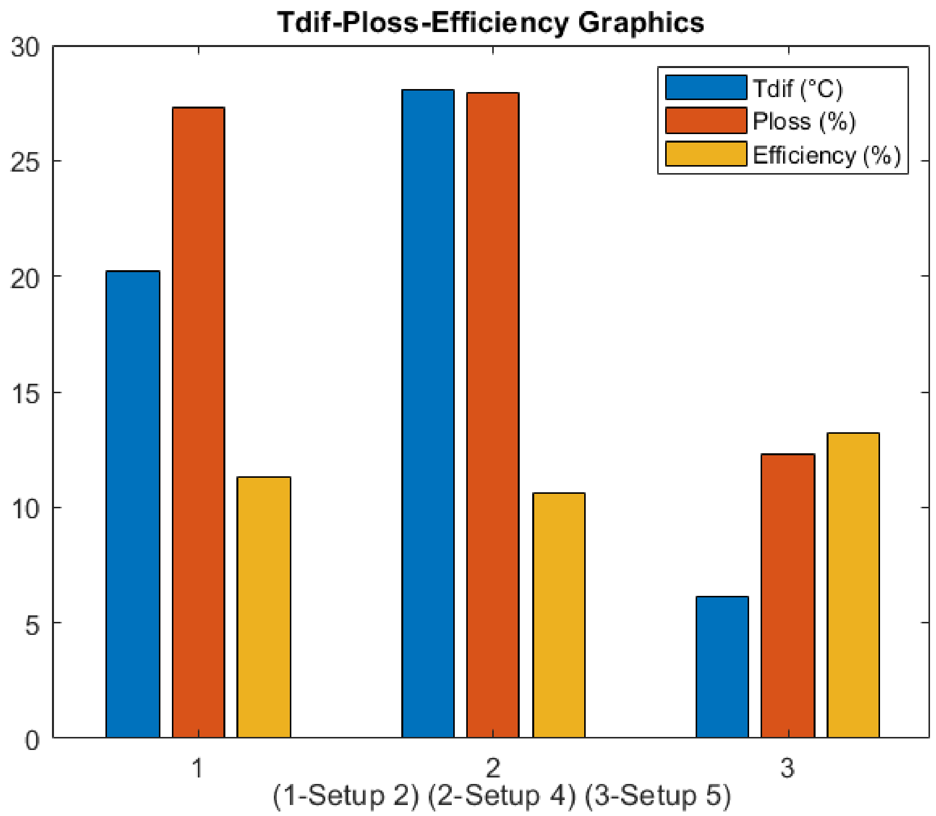

Figure 3. 10 Demonstrates the differences between installations 2,4 and 5 temperature and the standard condition temperature, their efficiency and power loss rates.

To compare the efficiency of the PV panels, the power loss was calculated and compared. As can be seen from the figure 4.10, the efficiency decreases as the temperature difference increases, resulting in a higher power loss rate. For PV module 2, the power loss rate was 0.6% / °C above 45.2 °C. For PV module 4, the power loss rate was 0.5% / °C above 53.1 °C. While for PV module 5, the power loss rate was 0.3% / °C above 31.1 °C.

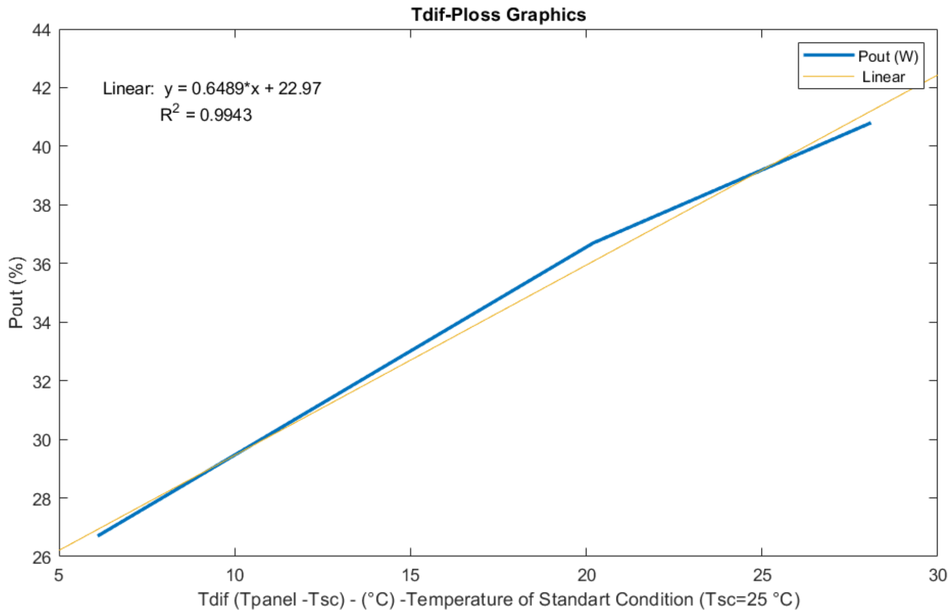

Figure 3. 11 Demonstrates the differences between installations 2,4 and 5 temperature and the standard condition temperature and power loss rate.

The amount of power per m^2 is calculated by P_{out} / FF. Considering the fill factor, the power loss rate per m^2 was also calculated and the results are shown graphically in figure 3.11 above. The output power of P_2 was 89.3 W/m^2, P_4 83.4 W/m^2 and P_5 103.2 W/m^2. According to the panel's datasheet, the maximum power is 140.1 W/m^2. The temperature of the panel under standard conditions (T_{sc}=25 °C) and the difference with the panel surface temperatures was calculated. The graph was sorted from small to large according to these differences and shown in the graph.

All results supported and demonstrated that floating solar modules are more consistent than land-based PV modules and operate closer to the manufacturing standard ideal operation temperature of 25 degrees. The lower the operating temperature of a PV module, the better and more efficient the module is; this means it will generate higher energy output. Also, this reflects positively on the lifespan of the PV modules, as studies have found that panels with high operating temperatures have shorter lifespans and are more susceptible to damage.

3.5.Evaluation of The Environmental/Economical Effects of The Finding

As mentioned throughout this paper, one of the main advantages of FVP is the reduction of evaporation rate in water bodies, according to (Abd-Elhamid et al., 2021). The total evaporation loss in Turkey was 4.1 × 109 m^3/year from lakes and 2.7 × 10^9 m^3/year from reservoirs. There are 57 natural lakes with a total surface area of 8762.52 km^2 and 17 reservoir and dam lakes with a total surface area of 3258 km^2 in Turkey. Building on the finding of (Soltani et al., 2022), a 90% reduction in the evaporation rate could drop the evaporation rate to 4.1 × 10^8 m^3/year in lakes and 2.7 × 10^8 m^3 in reservoirs. While it is not feasible to cover the entirety of water bodies, building on the work of (Sanchez et al., 2021), covering 1% of 29222 km^2 could save 734 million m^3 of water, reflecting that the Turkish situation could result in the saving of 8.2× 10^7 m^3 in reservoir and dam lakes alone. The preserved water could be used for agricultural purposes; it could even be reused as a hydropower source, ultimately increasing the net energy produced. The higher power output associated with floating solar photovoltaics is heavily influenced by multiple factors, such as the passive cooling effect of water which aids in increasing the efficiency of the entire system. The water acts as a transfer medium and dissipates the heat away from the panels, preventing them from overheating, which reflects positively on the power output. The water surrounding the floating panels will also help reduce reflection, as some of the travelled light is diverted into the water, decreasing the amount of light reflected in the atmosphere. There will be more light available to be absorbed by the panels to generate energy. It will also reduce the panel resistance to wind, resulting in higher power output, as the water absorbs some of the wind and dampens the wind, resulting in higher power output. Moreover, floating solar panels can also be installed on water surfaces, giving a significant advantage over land-based solar panels. Firstly, because those areas are not used for residential/agricultural purposes, generating energy by utilising them will not compete with other sectors or exacerbate existing issues such as food security and lack of land/space associated with land-based solar panels. Secondly, water surfaces such as lakes and dams are usually close to the national grid network. This will help cut back on transportation costs and infrastructure building. Furthermore, floating solar systems are more flexible and can be easily adjusted to a more suitable orientation, allowing them to absorb more sunlight and ultimately generate more power.

3.6. Evaluation of The Findings on Turkey's Potential for Floating Photovoltaic Solar Systems

Our study findings propose a promising opportunity for Turkey to reform its clean energy market by implementing floating solar panels. Turkey can significantly increase its power output from renewable sources by harnessing the vast potential of its abundant dams and ample natural lakes. To put things in perspective, utilising about 3% of the Atatürk Lake and Dam in Turkey could match the dam's hydropower capacity (The world bank, 2019), which has a total installed power capacity of 2,400 MW and generates 8,900 GW/h electricity annually (Verdict Media Limited, 2017).

The average consumption per person is 216 L a day (Özbaş et al., 2021), while Turkey's annual water consumption is 54 billion m^3. According to (Abd-Elhamid et al., 2021), the total evaporation loss in Turkey was 2.7×10^9 m^3 /year from reservoirs and 4.1×10^9 m^3 /year from lakes. If 90% of the amount evaporated were to be conserved, this would save 6.12×10^9 m^3 of water per year. This represents 11.3% of Turkey's annual water consumption.

Floating PV modules can be strategically installed atop these water bodies to absorb solar energy while minimising land usage and increasing the net amount of energy produced. This approach utilises the existing infrastructure and increases energy generation efficiency due to the cooling effect of the water and free energy production from season/weather restrictions. Moreover, this novel approach aligns with Turkey's commitment to reducing greenhouse gas emissions and achieving sustainable development goals.

By embracing FPV technology, Turkey can diversify its renewable energy portfolio, reduce reliance on fossil fuels, and ultimately lead towards a cleaner, more sustainable energy future.

3.7.Study limitations

Regarding the limitation of this study, the study was conducted on a small scale with only 5 PV modules due to time and cost constraints; a larger sample size could be beneficial to obtain more accurate results and also design more variation and installation at different orientations to study the effect of other variables on the power output.

4. CONCLUSIONS

The findings obtained in this study are data obtained as a result of experiments carried out under real operating conditions.

The main findings of the following parameters PV Panel Temperatures – Efficiency - Output Power are listed below,

- The surface temperature of the land-based installation is always higher than that of the panels in floating installations.
- When the surface temperatures of three panels placed at the same angle (21 degrees) were compared, the highest value was measured in the land-based installation, was 30.5 °C above the average ambient temperature.
- As seen in Figure 3.11, the variation between temperature difference and power loss is linear and the correlation coefficient is 0.9943.
- The floating panel produced approximately 20% more power per square meter.

Potential of Turkey

- The surface area of dams built for electricity generation in Turkey is 3258 km^2.
- According to the global solar atlas data, the annual horizontal irradiance is 1908.2 kWh/m^2 and annual PV area factor is 1624 kWh/kWp.
- The capacity is calculated as 1332 TWh/year if the suitable areas are assumed to be 100%.

The findings from this study exhibited comparable and reliable trends and results to the published literature, providing the mutual conclusion that floating solar photovoltaic systems are more efficient than land-based photovoltaic systems. The literature supports the results obtained in this study, as several other studies have found that floating solar panels operate at lower temperatures while generating a higher energy output.

Floating solar systems were also found to be more stable at higher temperatures and could maintain a lower operating temperature than land-based solar panels.

There is a significant gap in the literature and a need for more research studies on this topic, especially the effect of light intensity on the power output of PV modules, so optimistically, this research will mark the beginning of more research on the subject. Additionally, the literature lacks sources that focus on the net power production solely by floating photovoltaic; whether no studies have not been conducted just yet or it has been combined with the net power produced by the traditional terrestrial solar photovoltaic system is highly recommended to be addressed and discussed hopefully in the near future.

In conclusion, this study determined that floating PV modules are more sustainable than PV land-based systems as they are more efficient in producing clean energy. They could also tackle issues associated with PV land-based systems, such as land space and high costs associated with procuring land. Land-based PV systems run the risk of very high operating temperatures due to the reflective effects of sun rays, causing the temperatures of the panels to increase significantly; also, shading risks significantly affect the amount of power generated. Furthermore, this study has shown promising potential for improving the performance of existing and future PV systems by installing a cooling system.

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