



**T.R.
BATMAN UNIVERSITY
GRADUATE EDUCATION INSTITUTE
DEPARTMENT OF MECHANICAL ENGINEERING**

DOCTORAL THESIS

**EVAPORATIVE COOLING SYSTEMS WITH UNDERGROUND
COOLING FOR PHOTOVOLTAIC PANELS IN HOT AND ARID
CLIMATES**

Mazlum CENGİZ

**October-2025
BATMAN**

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Advisors

**Prof. Dr. Hüseyin AYDIN
Assoc. Prof. İsmail KAYRI**

Jury Members

**Prof. Dr. Zeki ARGUNHAN Prof. Dr. Bahattin İŞCAN Assoc. Prof. Faruk ORAL
Assoc. Prof. Mehmet Zerrakki IŞIK**

**October-2025
BATMAN**

THESIS ACCEPTANCE AND APPROVAL

The thesis entitled “Evaporative Cooling Systems with Underground Cooling for Photovoltaic Panels in Hot and Arid Climates” prepared by Mazlum Cengiz, was unanimously accepted as a Doctoral Thesis by the jury listed below in the Department of Mechanical Engineering, Graduate Education Institute of Batman University, on 08/10/2025.

Jury Members

Signature

Chair

Prof. Dr. Zeki ARGUNHAN

.....

Advisor

Prof. Dr. Hüseyin AYDIN

.....

Co-Advisor

Assoc. Prof. İsmail KAYRI

.....

Member

Prof. Dr. Bahattin İŞCAN

.....

Member

Assoc. Prof. Faruk ORAL

.....

Member

Assoc. Prof. Mehmet Zerrakki IŞIK

.....

I approve the above result.

Assist. Prof. Dr. Ömer Murat ÖTER
Director of Institute of the Graduate Education

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ETİK BEYANI

Bu tezdeki bütün bilgilerin etik davranış ve akademik kurallar çerçevesinde elde edildiğini ve tez yazım kurallarına uygun olarak hazırlanan bu çalışmada bana ait olmayan her türlü ifade ve bilginin kaynağına eksiksiz atıf yapıldığını beyan eder, aksinin ortaya çıkması durumunda her türlü yasal sorumluluğu kabullendiğimi bildiririm.

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I declare that all the information in this thesis has been obtained within the framework of ethical behavior and academic rules, and that the source of any statements and information that do not belong to me in this study prepared in accordance with the thesis writing rules has been fully cited, and I declare that I accept all kinds of legal responsibility in case of any contrary situation.

Signature
Mazlum CENGİZ
08/10/2025

ABSTRACT

DOCTORAL THESIS

EVAPORATIVE COOLING SYSTEMS WITH UNDERGROUND COOLING FOR PHOTOVOLTAIC PANELS IN HOT AND ARID CLIMATES

Mazlum CENGİZ

Batman University Graduate Education Institute

Mechanical Engineering Department of Science

**Advisors: Prof. Dr. Hüseyin AYDIN
Assoc. Prof. İsmail KAYRI**

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Solar energy can be mainly harnessed through heat, electricity, and photosynthesis. The utilization of solar energy is globally adopted because it is abundantly available and cost-effective compared to other renewable energy sources. Solar energy possesses light and heat, both of which can be directly converted into electricity. The main application of solar energy is electricity generation through photovoltaic (PV) systems, which include PV panels, a charge controller, batteries or other storage units, and inverters. PV panels consist of multiple solar cells that convert incident solar radiation into direct current electricity. Nonetheless, most of the solar radiation reaching solar cells is converted into heat energy rather than electricity, as solar cells cannot convert all irradiance spectral wavelength into electrical energy. This leads to an increase in the cell operation temperature. The elevated temperature worsens bandgap energy, thereby reducing open circuit voltage and fill factor. Consequently, higher temperatures diminish the conversion efficiency of the cells, and thus the overall efficiency of PV panels. For instance, for every 1 °C rise in the temperature of a crystalline silicon solar cell, the cell voltage decreases by 2.2 mV, causing an estimate 0.5% drop in electrical power output. Furthermore, excessive heating can cause hotspot formation and material degradation, leading to a shortened lifetime of PV panels. Hence, it is essential to dissipate the surplus heat from solar cells by applying the optimal cooling technique to recover the efficiency of PV panels. Among the various cooling methods, evaporative cooling is a simple, sustainable, cost-effective, efficient, eco-friendly, and energy-saving technique. It is particularly effective in hot and arid climates. In this thesis study, evaporative cooling systems incorporating underground cooling were designed, and set up to prevent PV panels from experiencing a reduction in power output in hot and arid climates due to overheating. The evaporative cooling systems included three open-water-based systems: one utilizing a cellulose pad, another employing cotton wicks, and the third using hemp ropes as porous materials. The effects of these cooling systems and their configurations on PV panel temperature, electrical energy output, and efficiency were experimentally evaluated and compared with those of a reference panel without cooling. The findings indicated that the evaporative cooling approaches proved effective in arid and intensely hot climates. The cooling implementations continuously and uniformly lowered the PV panel surface temperature, thereby enhancing efficiency, energy output, and I-V characteristics. As a result, the evaporative cooling configuration with the cotton wicks, hemp ropes and cellulose pad achieved temperature reductions of up to 22.7 °C, 22.1 °C, and 10.3 °C, respectively; efficiency improvements of 9.77%, 9.57%, and 5.38%; and cumulative energy enhancements of 10.4%, 9.56%, and 5.46%, respectively.

Keywords: PV panel, Evaporative cooling, Cotton wicks, Hemp ropes, Cellulose pad.

ÖZET

DOKTORA TEZİ

SICAK VE KURAK İKLİMLERDE FOTOVOLTAİK PANELLER İÇİN YERALTI SOĞUTMALI BUHARLAŞTIRMALI SOĞUTMA SİSTEMLERİ

Mazlum CENGİZ

Batman Üniversitesi Lisansüstü Eğitim Enstitüsü

Makine Mühendisliği Ana Bilim Dalı

Danışmanlar: Prof. Dr. Hüseyin AYDIN
Doç. Dr. İsmail KAYRI

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Güneş enerjisi temel olarak ısı, elektrik ve fotosentez yoluyla kullanılabilir. Güneş enerjisinin kullanımı, bol miktarda bulunması ve diğer yenilenebilir enerji kaynaklarına kıyasla maliyet açısından uygun olması nedeniyle dünya genelinde benimsenmiştir. Güneş enerjisi hem ışık hem de ısı içerir ve her ikisi de doğrudan elektriğe dönüştürülebilir. Güneş enerjisinin temel uygulaması, fotovoltaik (PV) sistemler aracılığıyla elektrik üretimidir; bu sistemler PV panelleri, bir şarj kontrol cihazını, bataryaları veya diğer depolama birimlerini ve eviricileri içerir. PV paneller, gelen güneş ışınımını doğru akım elektriğine dönüştüren çok sayıda güneş hücresinden oluşur. Bununla birlikte, güneş hücrelerine ulaşan güneş ışınımının büyük bir kısmı elektrik yerine ısı enerjisine dönüşür, çünkü güneş hücreleri tüm ışınım spektrum dalga boylarını elektrik enerjisine dönüştüremez. Bu durum, hücre çalışma sıcaklığının artmasına yol açar. Artan sıcaklık, yasak enerji aralığını (band aralığı enerjisini) kötüleştirerek açık devre gerilimini ve dolayısıyla PV panellerin genel verimliliğini düşürür. Örneğin, kristal silikon güneş hücresinin sıcaklığındaki her 1 °C'lik artış, hücre geriliminde 2,2 mV azalmaya neden olur ve bu da elektriksel güç çıkışında yaklaşık %0,5 oranında bir düşüşe yol açar. Ayrıca, aşırı ısınma sıcak nokta oluşumuna ve malzeme bozulmasına neden olabilir, bu da PV panellerin ömrünün kısalmasına yol açar. Bu nedenle, PV panellerin verimliliğini geri kazanmak için güneş hücrelerinden fazla ısının uygun soğutma tekniğiyle uzaklaştırılması gereklidir. Çeşitli soğutma yöntemleri arasında buharlaşmalı soğutma, basit, sürdürülebilir, maliyet açısından uygun, verimli, çevre dostu ve enerji tasarruflu bir tekniktir. Özellikle sıcak ve kurak iklimlerde etkilidir. Bu tez çalışmasında, PV panellerin aşırı ısınma nedeniyle sıcak ve kurak iklimlerde güç çıkışında azalma yaşamalarını önlemek amacıyla yer altı soğutmalı buharlaşmalı soğutma sistemleri tasarlanmış ve kurulmuştur. Buharlaşmalı soğutma sistemleri, üç açık su bazlı sistemden oluşmaktadır: biri selüloz ped, diğeri pamuk fitil ve üçüncüsü kenevir ipli kullanarak gözenekli malzeme olarak tasarlanmıştır. Bu soğutma sistemlerinin ve konfigürasyonlarının PV panel sıcaklığı, elektriksel enerji çıkışı ve verimlilik üzerindeki etkileri deneysel olarak değerlendirilmiş ve soğutmasız bir referans panel ile karşılaştırılmıştır. Bulgular, buharlaşmalı soğutma yaklaşımlarının kurak ve aşırı sıcak iklimlerde etkili olduğunu göstermiştir. Soğutma uygulamaları PV panel yüzey sıcaklığını sürekli ve homojen biçimde düşürerek verimliliği, enerji çıkışını ve I-V karakteristiklerini artırmıştır. Sonuç olarak, pamuk fitilli, kenevir ipli ve selüloz pedli buharlaşmalı soğutma konfigürasyonları sırasıyla 22,7 °C, 22,1 °C ve 10,3 °C'ye kadar sıcaklık düşüşü; %9,77, %9,57 ve %5,38 verim artışı; ve sırasıyla %10,4, %9,56 ve %5,46 kümülatif enerji artışı sağlamıştır.

Anahtar Kelimeler: PV panel, Buharlaşmalı soğutma, Pamuk fitiller, Kendir ipleri, Selüloz ped.

PREFACE

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Mazlum CENGİZ
BATMAN-2025

ÖN SÖZ

Danışmanlarım Prof. Dr. Hüseyin AYDIN ve Doç. Dr. İsmail KAYRI'ye, seçkin birer rol model oldukları için içtenlikle minnettarım. Onların uzmanlığı, teknik desteği, yol gösterici katkıları ve yapıcı geri bildirimleri, bu çalışmanın kalitesinin artmasında ve akademik gelişimin ilerlemesinde kritik bir rol oynamıştır.

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Son olarak, bitmeyen sevgi ve destekleri için anne ve babama ve kardeşlerime derin minnettarlığımı ifade ederim.

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SYMBOLS AND ABBREVIATIONS

Symbols

A	: Amper
Al ₂ O ₃	: Aluminum Oxide
As	: Arsenic
CaTiO ₃	: Calcium Titanate
CdSeTe	: Cadmium Selenide Telluride
CdTe	: Cadmium Telluride
CIGS	: Copper Indium Gallium Selenide
CuInSe ₂	: Copper Indium Diselenide
CuO	: Copper Oxide
E	: Solar Radiation
E _E	: Energy Output
eV	: Electronvolt
g/s	: Grams per Second
Ga	: Gallium
GaAs	: Gallium Arsenide
I	: Current (A)
k	: Power Validation Coefficient
kg	: Kilogram
L	: Liter
m ²	: Square Meter
m/s	: Meters per Second
mm	: Millimeter
Mo	: Molybdenum
MoSe ₂	: Molybdenum Diselenide
P	: Power
Seconds	: s
Si	: Silicon
Si ₃ N ₄	: Silicon Nitride
SiO ₂	: Silicon Dioxide
T	: Temperature

TiO_2	: Titanium Dioxide
V	: Voltage
V_{mpp}	: Maximum Power Point Voltage
V_{oc}	: Open Circuit Voltage
W	: Watt
WS	: Wind Speed
η	: Efficiency
η_{cell}	: Overall Solar Cell Efficiency
η_{panel}	: Panel Efficiency
$\eta_{\text{panel}, T_{\text{ref}}}$	: Panel Power Conversion Efficiency at Reference Temperature
β_{ref}	: Temperature Coefficient
μm	: Micrometer
$^{\circ}\text{C}$	: degree Celsius

Abbreviations

AC	: Alternating Current
A_{cell}	: Overall Solar Cell Area
Ah	: Ampere Hours
AM	: Air Mass
AOI	: Angle of Incidence
A_{panel}	: Panel Surface Area
a-Si	: Amorphous Silicon
CEP	: Cumulative Energy Production
CP	: Cellulose Pad
CPV	: Concentrated/Concentrating Photovoltaic
CR	: Concentration Ratio
c-Si	: Crystalline Silicon
CSP	: Concentrated Solar Power
CWs	: Cotton Wicks
DC	: Direct Current
DNI	: Direct Normal Irradiance

DSR	: Direct Solar Radiation
DSSCs	: Dye-Sensitized Solar Cells
EC	: Evaporative Cooling
EDS	: Electro-Dynamic Screens
FF	: Fill Factor
FTCC	: Floating Tracking Concentrating Cooling
HRs	: Hemp Ropes
I	: Current
I_{mpp}	: Maximum Power Point Current
I_{sc}	: Short Circuit Current
IR	: Infrared Radiation
LCPV/T	: Low concentration PV/Thermal
LFR	: Linear Fresnel Reflector
m_{evp}	: Total Water Mass Evaporated
min	: Minute
MPP	: Maximum Power Point
MPPT	: Maximum Power Point Tracking
mV	: Millivolt
MW	: Megawatt
mW	: Milliwatt
PCE	: Power Conversion Efficiency
PCM	: Phase Change Material
PDS	: Parabolic Dish Systems
P_{in}	: Power In
P_{mpp}	: Maximum Power Point Power
P_{out}	: Power Out
PTC	: Parabolic Trough Collector
PR	: Performance Ratio
PV/T	: PV/Thermal
PV	: Photovoltaic
PVs	: Photovoltaics
QDs	: Quantum Dots
RAFs	: Rectangular Aluminum Fins

SEG	: Specific Energy Gain
SOC	: State of Charge
SPT	: Solar Power Tower
STC	: Standard Test Conditions
T	: Temperature
T _{amb}	: Ambient Temperature
T _c	: Solar Cell Temperature
TCO	: Transparent Conductive Oxide
T _{panel}	: Panel Temperature
T _{ref}	: Reference Temperature
UV	: Ultraviolet
V	: Volt
Wh	: Watt hour
W/m ²	: Watts per Square Meter

1. INTRODUCTION

Energy can be perceived as the capacity to lead changes (Cengel & Boles, 2015). It is not a distinct entity itself but rather an asset of a system or object. All elements in the universe possess a form of energy. However, people did not explore and sufficiently use the power of energy until the development of industry. For example, hydraulic energy was employed to perform different mechanical tasks and wind power started to be harnessed with the invention of windmills after the 12th century. The first coal extraction began in British mines between the 12th and 13th centuries, encouraging people to consider transforming heat energy into mechanical energy. In this context, Thomas Savery innovated the first steam engine in 1698. Subsequently, Nikola Tesla founded the alternative current, leading to the development of electrical engines. As a consequence of these advancements, the generation of electricity experienced rapid growth (Bilen & Erdoğan, 2023; Mousavi et al., 2021).

Energy has been one of the most fundamental and important necessities for humans throughout their existence. It deeply affects technology and overall development, so daily life. Varying types of energy sources have been used to harness energy. Energy sources are classified into two primary groups: nonrenewable and renewable sources (Bilen & Erdoğan, 2023).

Nonrenewable energy sources, also called fossil fuels (coal, petroleum, natural gas, and nuclear energy), formed from the decomposition of ancient organisms exposed to high pressure and heat throughout millions of years within the world's crust. Renewable energy, often referred to as sustainable energy (hydraulic, wind, geothermal, solar, and biomass), is extracted from natural elements, can be replaced at a rate faster than its depletion, and use natural processes for its generation (Bilen & Erdoğan, 2023; Mahdavi et al., 2022).

The increasing population, advancements in technology, developing industry, urbanization, and enhancements in living conditions all over the world have increased energy demand and accelerated depletion of fossil fuels, leading to environmental challenges such as climate change and global warming (Kandeal et al., 2020; Peinado Gonzalo et al., 2020; Salameh et al., 2021; Shafique et al., 2020; Şirin et al., 2023;

Sripadmanabhan Indira et al., 2020). Since energy holds a key role in advancement and growth of a country, and reducing greenhouse gas emissions requires global collaboration, countries seek new ways to use energy more efficiently and to produce it from clean sources (Kandeal et al., 2020; Li et al., 2023; Nižetić et al., 2021; Ridha et al., 2021; Salameh et al., 2021; Siah Chehreh Ghadikolaei, 2021; Tembhare et al., 2022; Vaziri Rad et al., 2020; B. Wang et al., 2024). Therefore, in 1992, the Rio Convention on Climate Change initiated a framework for actions focused on decreasing fossil fuels usage and constraining the resultant emissions. In 1997, countries signed the Kyoto protocol expressing a target of reducing greenhouse gas emissions to keep global warming below 2 °C. Subsequently, in 2015, more than 190 countries committed to an agreement at the Paris Climate Conference to maintain global temperature rise less than 1.5 °C (Herrando et al., 2023; Sheikholeslami et al., 2021). Furthermore, the European Union has established a goal of generating a minimum of 32% of its energy from renewable sources by 2030. Likewise, China targets to produce 35% of its electricity from sources other than fossil fuels by 2030 (LazaroIU et al., 2023). As a result, to achieve these objectives, nations have begun to adopt alternative renewable energy sources such as solar, wind, geothermal, biomass and tidal (El-Nagar et al., 2025; Kazem et al., 2020; Tang et al., 2023). Among them, solar energy is a key renewable energy and holds a tremendous potential (Dada & Popoola, 2023; Kazem et al., 2023; Mahdavi et al., 2022; Salameh et al., 2021; Sheikholeslami & Al-Bujasim, 2025; Tang et al., 2023).

Solar energy contains both light and heat, both of which have the potential to be directly transformed into electricity (Tang et al., 2023). The production of electric energy via photovoltaic (PV) systems is the main application of solar energy (Siecker et al., 2017; Tang et al., 2023). A PV system includes solar PV panels, storage units and inverters/chargers (Siah Chehreh Ghadikolaei, 2021). Solar panels equipped with PV cells that use solar energy by converting solar irradiance into direct current (DC) electricity (Deshmukh et al., 2022; Gao et al., 2023; Kazem et al., 2023; Khoshnazm et al., 2023; Tang et al., 2023). The majority of solar irradiance reaching a PV cell is not converted into electrical energy, but rather into heat energy, causing the cell temperature to rise. Increased temperature reduces conversion efficiency, and lifetime of the cell (Drabiniok & Neyer, 2019; Dwivedi et al., 2020; Elnozahy et al., 2015; Spertino et al., 2016). Therefore, it is important to extract unwanted heat from solar cells with cooling techniques because the performance of solar panels is significantly impacted by the operational temperature of PV cells (Bahaidarah et al., 2016). For instance, for each 1 °C

increase in surface temperature of a PV panel, there is a corresponding reduction in efficiency of 5% (Siecker et al., 2017).

Innovative cooling methods for PV panels have been researched and implemented to reduce the temperature of PV cells to recover the electrical efficiency of them and prolong their lifetime. The cooling methods are generally categorized into three groups: active cooling, passive cooling, and combination of passive and active cooling (Hamzat et al., 2021; Mahdavi et al., 2022). Floating tracking concentrating cooling (FTCC), water spraying cooling (jet impingement, water film cooling, hydraulic cooling), cooling with heat sink and spreader, forced water circulation cooling, cooling with phase change material (PCM), water immersion cooling, transparent cooling (photonic crystal cooling), forced air circulation cooling, air based natural convection cooling (natural air cooling with fins or heat sinks), air collector, thermoelectrical cooling, cooling with microchannels, combined microchannel-jet impingement cooling, dielectric cooling by direct immersion, nanofluid cooling, nano-enhanced PCM cooling, ground coupled-central panel cooling, centralized air conditioning cooling, decentralized air conditioning cooling, selective spectral cooling (spectral filter), radiative cooling, ground water cooling (Earth-water heat exchanger), water pipes and cooling channel, solar chimney, and evaporative cooling (EC) are the cooling techniques reported in literature (Akrouh et al., 2023; Bahaidarah et al., 2016; Bhakre et al., 2021; Kandeal et al., 2021; Nižetić et al., 2017; Sahay et al., 2015; Siecker et al., 2017).

EC has been employed in different residential and industrial applications. It is a well-known concept, sustainable, cost-effective, efficient, and environmentally friendly cooling method. It is efficient in hot and arid climates (Haidar et al., 2018; Poddar et al., 2022; Walsh et al., 2013; Y. Yang et al., 2019; Zheng et al., 2020). Therefore, it holds a significant promise for regulating the temperature of PV panels installed in hot and dry environments (Akrouh et al., 2023; Haidar et al., 2018). EC cooling methods for PV systems reported in the literature are EC with absorbent pads, EC with synthetic clay, EC with zeolite, porous layer cooling, EC with co-current configuration, droplet EC, EC with heat pipe thermosiphon, PV Evaporative Chimney, EC with chimney-like channels, and EC with an atmospheric water harvester.

In this thesis, three distinct EC systems incorporating underground cooling were designed and constructed to prevent the reduction in electrical power output of PV panels operating in hot and arid climates due to overheating. The EC systems were open-water-based configurations: one utilizing a cellulose pad (CP), another employing cotton wicks

(CWs), and the third using hemp ropes (HRs) as porous EC materials. The impact of these systems on PV panel temperature, energy output, and efficiency was evaluated through a series of experiments conducted for each system and its configurations. The results were then compared with those obtained from a reference panel operating without EC. The novelty of this thesis lies in the design and implementation of the EC systems. The liquid distribution system developed in this study was innovative and provided uniform water distribution over the porous materials. Furthermore, thermal camera analyses confirmed that the systems achieved uniform cooling across the PV panel surface. Moreover, the designed underground cooling system, including a steel underground tank and heat exchanger, successfully maintained the water temperatures between 25.5 °C and 26 °C, offering stable and effective cooling performance.

First, the concepts of solar energy, PV systems, PV solar cells, factors impacting solar cells, cooling technologies for PV systems, and EC systems used for photovoltaics (PVs) were described in detail. Afterward, the design and setup process of the EC systems, the materials and methods used for the experiments, the results and discussion, and the conclusions are presented comprehensively in the separate sections.

1.2. Solar Energy

The presence of solar energy makes it possible for life to exist in the world and provides the essential energy needed for sustenance (Mahdavi et al., 2022). It serves as the primary source for all energy supplies apart from nuclear energy and is regarded as one of the most versatile sources for renewable energy technologies (Mahdavi et al., 2022; Siah Chehreh Ghadikolaei, 2021; Sripadmanabhan Indira et al., 2020). The potential of solar energy worldwide is illustrated in **Figure 1.1**.

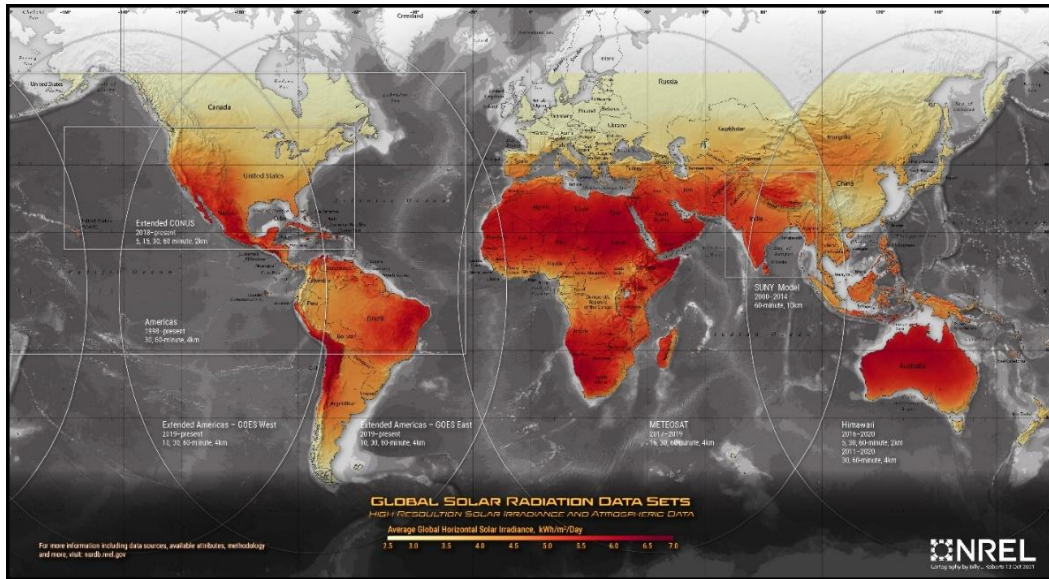


Figure 1.1. The map illustrating the potential of solar energy worldwide (National Solar Radiation Database: International Data Sets, 2024)

Solar energy is abundantly present, clean, reliable, and environmentally friendly source of energy. Therefore, it has numerous applications such as electricity production, heat generation, space heating, water heating, drying vegetables, water distillation, ventilation, air conditioning and refrigeration (Bilen & Erdoğan, 2023; Kazem et al., 2023; Şirin et al., 2023). Harvesting solar energy is recognized as a highly adapted, feasible and cost-effective method for energy generation when compared to other renewable energy sources (Herrando et al., 2023; Jiao et al., 2024; Şirin et al., 2023). Solar energy can be harnessed mainly through three methods: heat, electricity, and solar fuel (photosynthesis) (Hayat et al., 2019), as illustrated in **Figure 1.2**. The photosynthesis process uses approximately 11% of solar energy that is the largest utilization of solar energy.

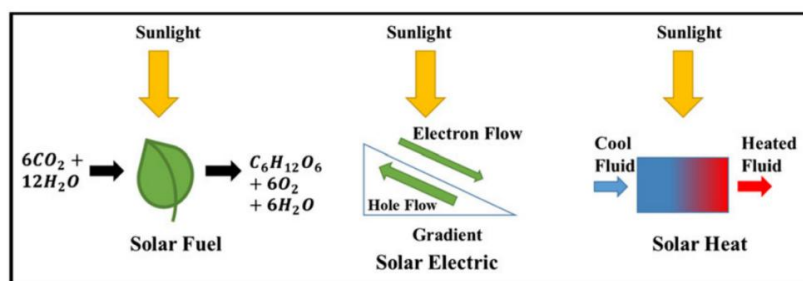


Figure 1.2. The Main three methods to harness solar energy: solar fuel, electricity, and heat (Hayat et al., 2019)

Solar energy has been utilized since ancient eras. Thermal energy harvested from solar energy has been used since the 7th century BC to create fire and incinerate ants with magnifying glasses (Sripadmanabhan Indira et al., 2020) . In 1839, Alexander Edmond Becquerel discovered that certain semiconductors could produce electricity when they were exposed to solar irradiance (Akrouch et al., 2023; Bilen & Erdoğan, 2023; Li et al., 2023; Siah Chehreh Ghadikolaei, 2021; Sripadmanabhan Indira et al., 2020; Tang et al., 2023). In 1883, Charles Fritts crafted the first PV cell, achieving 1% efficiency by applying a thin layer of gold onto selenium (Bilen & Erdoğan, 2023; Sargunanathan et al., 2016; Siah Chehreh Ghadikolaei, 2021). In 1885, Aleksandra Stoletov manufactured the first cell to function outdoor utilizing a photoelectric effect. In 1905, Albert Einstein revealed the fundamental principles of solar electricity with the photoelectric effect. The first P-N junction solar cell with an electrical efficiency of 6% was developed after Russell Ohl discovered Pb semiconductors in 1939 (Siah Chehreh Ghadikolaei, 2021). In 1954, Daryl Calvin, Calvin Souther Fuller and Gerald Pearson developed the first practical photovoltaic cell (Bilen & Erdoğan, 2023; Tang et al., 2023). Following this, the investigation into the efficiency and economic advantages of transforming absorbed sunlight into electricity was started (Tang et al., 2023). In 1955, Hoffman Electronics commercially manufactured solar panels, each cell offering 2% efficiency and 14 milliwatt (mW) of power. In 1958 and 1959, using solar panels in satellites led to the recognition and adaptation of solar electricity by the public (Bilen & Erdoğan, 2023).

The primary types of solar energy are solar thermal systems, concentrated solar power (CSP), PV systems, and combination of solar thermal systems and PV systems (Herrando et al., 2023; Mahdavi et al., 2022; Peinado Gonzalo et al., 2020; Tembhare et al., 2022). CSP operates by focusing solar energy to heat a transfer fluid, which is then utilized to produce energy. It has four major configurations: Parabolic trough collector (PTC), solar power tower (SPT), linear Fresnel reflector (LFR) and parabolic dish systems (PDS). PV systems transform solar energy into electricity (Peinado Gonzalo et al., 2020).

2. PV SYSTEMS

PV systems stand out as highly promising renewable energy technologies to meet future energy demand and address the associated shortage of conventional energy sources (Hasanuzzaman et al., 2016; Pathak et al., 2022). Moreover, it is a cornerstone of the worldwide effort to shift towards cleaner and more sustainable energy production (Lazaroiu et al., 2023). A PV system primarily consists of solar panels, a charge controller, batteries and other storage units, and inverters (Bilen & Erdoğan, 2023; Siah Chehreh Ghadikolaie, 2021), as demonstrated in **Figure 2.1**. An inverter converts the DC into alternating current (AC) that is stored in batteries or transported toward electrical grids (Li et al., 2023). Depending on several factors such as PV panel surface temperature, shading, wind speed, solar radiation, and dust accumulation, the efficiency of a PV system usually varies between 15% to 20% (Siow et al., 2024). Monocrystalline silicon, polycrystalline silicon, thin-film, flexible, and transparent solar panels are types of PV panels (Bilen & Erdoğan, 2023).

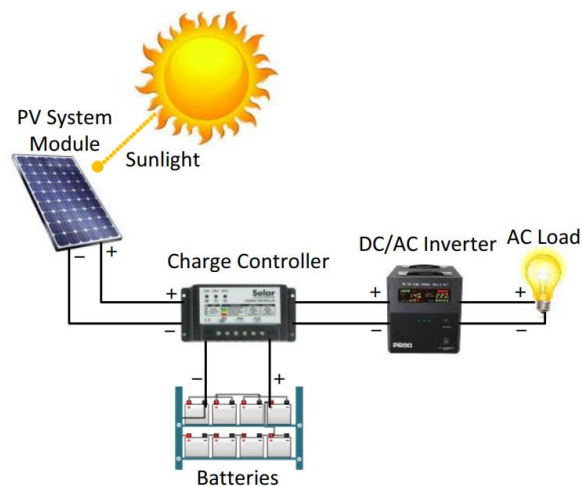


Figure 2.1. The schematic diagram of a usual PV system (Dewi et al., 2019)

PV panels comprise of photoelectric conversion semiconductors called solar cells or PV cells that are the fundamental component of the panels and use solar energy by converting absorbed sunlight into DC electricity without the involvement of any mechanical components or emissions into the environment (Peinado Gonzalo et al., 2020; Rustemli et al., 2013; Sato & Yamada, 2019; Shukla et al., 2017). PV cells produce

electric power via the PV effect, which occurs when electrons move within specific materials by electromagnetic radiation. This effect is generated in a p-n junction. Solar cells are electrically joined in series, and multiple series connections can be combined in parallel (Peinado Gonzalo et al., 2020).

The optimal material utilized for fabricating a solar cell has a bandgap ranging from 1.1 to 1.7 eV, and direct band structure. In addition, it should be easily accessible and nontoxic, appropriate for extensive reproduction, should possess high PV conversion efficiency, and enduring stability over time (Hayat et al., 2019).

Nearly all PV panels are constructed in the form of modularity for ease of manufacturing and installation. The transparent cover glass has stringent criteria for its mechanical features. It should be strong enough to protect the panels from deformation and maintain their relatively high transmittance index to minimize electricity production loss. The back sheet protects PV solar cells from damage, and seal PV panels to prevent moisture infiltration (Li et al., 2023). The standard structure of a PV panel is displayed in **Figure 2.2**.

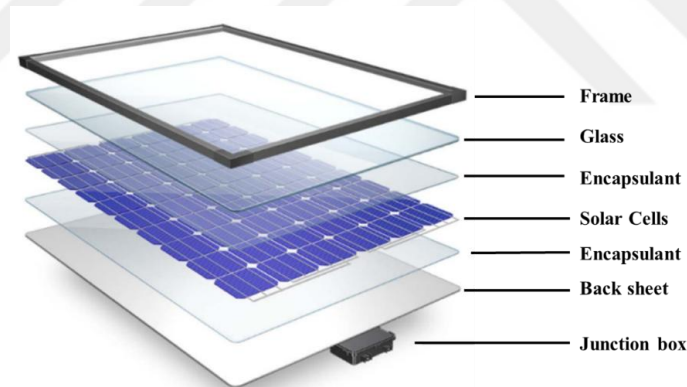


Figure 2.2. A usual structure of a PV panel (K et al., 2018)

A PV array comprises PV panels, and its power output capacity extends from hundreds of Watts (W) to megawatts (MW). Similar to PV cells, the panels are connected in series, parallel or combination of both configurations (Peinado Gonzalo et al., 2020).

Stand-alone PV systems and grid-connected PV systems are the main PV power system configurations (Meral & Dinçer, 2011; Peinado Gonzalo et al., 2020). Furthermore, PV/Thermal (PV/T) and concentrated/concentrating PV (CPV) solar power systems are hybrid PV power system configurations.

2.1. Stand-Along PV Systems

Stand-alone systems do not have any interaction with a utility grid and comprises of a PV array, energy storage devices like batteries, charge controller, AC consumers such as television, and lighting or DC consumers such as electric engines, and heaters, and power conditioners such as inverters (Khatib et al., 2016; Meral & Dinçer, 2011; Peinado Gonzalo et al., 2020). A basic stand-alone PV system with a battery storage system is illustrated in **Figure 2.3**. Stand-alone systems can be backed up with a wind turbine, a diesel generator or a cogeneration engine (Peinado Gonzalo et al., 2020).

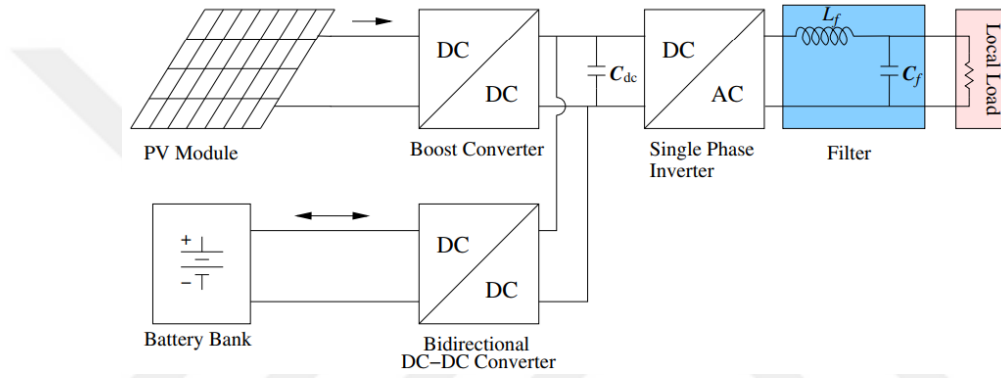


Figure 2.3. A basic stand-alone PV system with integrated battery storage (Sahu et al., 2022)

2.2. Grid-Connected PV Systems

Likewise stand-alone PV systems, grid-connected PV systems consists of a PV array, converters, and energy storage devices, but the electric power generated by the systems is directly sent into either a public grid or a house grid, as demonstrated in **Figure 2.4** (Meral & Dinçer, 2011; Peinado Gonzalo et al., 2020; Zhang et al., 2022). The produced electricity can either be utilized immediately in buildings or industrial applications or be sold to electricity suppliers during daylight hours. However, at night, electricity can be purchased from the grid since a gid-connected PV system without a storage device cannot produce enough power (Meral & Dinçer, 2011).

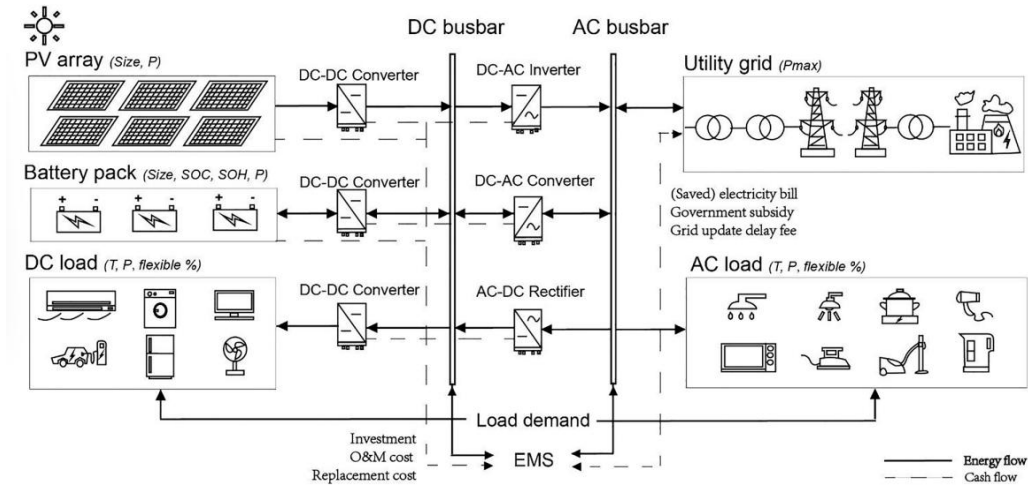


Figure 2.4. A schematic diagram of grid-connected PV system with battery storage unit (Zhang et al., 2022)

2.3. PV/T Systems

PV/T systems, also known as hybrid PV-thermal systems, comprises of PV arrays and solar collectors, generate energy by directly converting solar irradiance into electricity while also extracting thermal energy from PV panels, which is usually achieved by utilizing a working fluid, or coolant such as air, water, nanofluids, and phase change material. The heat extracted from the panels can subsequently be employed in heating applications. Hence, PV/T systems mitigate the adverse effects of thermal energy on the efficiency of PV panels and improve the overall efficiency of the power system (Allouhi et al., 2023; Al-Waeli et al., 2017; Reddy et al., 2015; Saloux et al., 2013).

Hybrid PV/T systems cogenerate electricity and thermal energy (Rounis et al., 2021); therefore, they outperform standard PV systems that generate only electricity and waste heat. Additionally, they have greater solar conversion efficiency and quicker return on investment, and require less material, so a smaller space for installation (C. Good, 2016; C. Good et al., 2015; X. Yang et al., 2018).

PV/T systems hold several applications in domestic and industrial field, particularly in preheating air and water. They can be integrated into buildings to generate both electrical, thermal energy like hot water or space heating, and to supply air ventilation or hot air (Saloux et al., 2013; Sultan & Ervina Efzan, 2018). A basic diagram of a PV/T system used in building applications, and an air-based clapboard-shaped wallboard PV/T system utilized for space heating in winter conditions are demonstrated in **Figure 2.5 (a)**, and **Figure 2.6**, respectively.

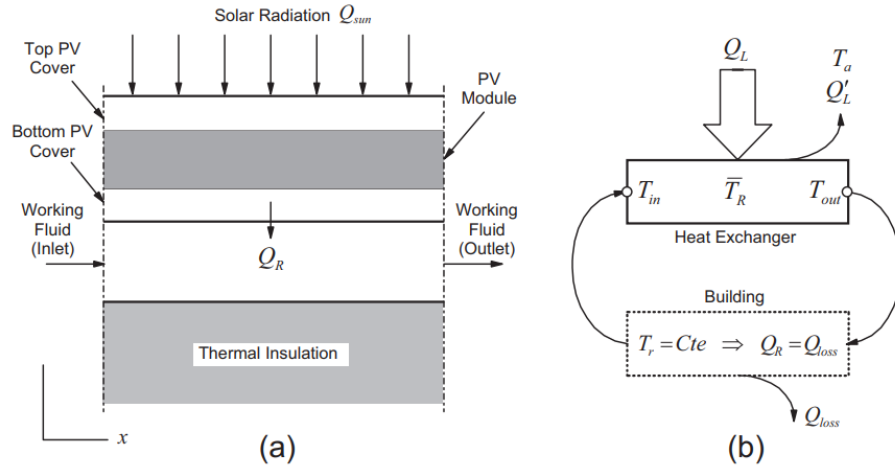


Figure 2.5. (a) A basic schematic diagram of a PV/T system; (b) Energy flow diagram of thermal aspect of the system (Saloux et al., 2013)

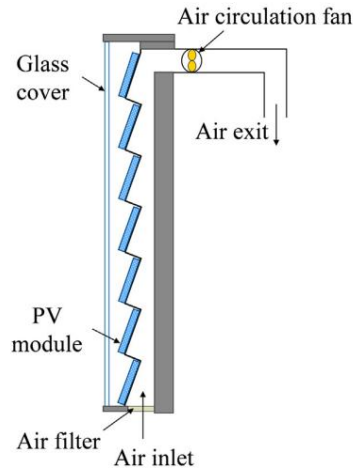


Figure 2.6. An air-based clapboard-shaped wallboard PV/T system utilized for space heating in winter conditions (Yazdanifard & Ameri, 2018)

PV/T collectors can produce greater energy per unit area relative to both PV panels and solar thermal collectors (Abdelrazik et al., 2018), which were the early PV/T prototypes that primary emphasis placed on their thermal performance (Rounis et al., 2021). There are three types of collectors for PV/T systems: flat-plate collectors, concentrating collectors, and heat pipe collector (Abdelrazik et al., 2018).

The efficiency of PV/T systems characterizes the performance of PV/T systems, which can be accurately presented as exergy (optimal useful energy) efficiency (Yazdanifard & Ameri, 2018).

2.4. CPV Systems

CPV systems use optical concentrating components such as Fresnel lens, quantum dot, parabolic troughs, dishes, v-groove mirrors, luminescent glass, refractive prism, and a compound parabolic concentrator, and tracking systems to concentrate solar irradiance on the solar cells, to improve the efficiency of PV systems (Baig et al., 2013; Ejaz et al., 2021). Concentrating solar radiation allows utilization of cheaper semiconductors in PV panels and reduces the required solar cell area for similar power generation, so reducing the expenses of PV systems (Du et al., 2012; A. Hasan et al., 2018). However, the increment in the concentration of solar irradiance results in an increase in the temperature of the solar cells, leading to a decrease in the conversion efficiency, and lifespan of the cells, and an increase in the probability of failures. Therefore, concentrated PV systems require a proper cooling system to recover the efficiency of the solar cells, and mitigate thermal-related damages (Du et al., 2012; Renno et al., 2017; Xiao et al., 2018) or they can be used as a hybrid CPV/T system to subtract the thermal energy for domestic and industrial application such as water heating, and space heating, thus enhance the overall performance (A. Hasan et al., 2018). CPV/T systems are high efficient, easy to manufacture, proper for large-scale solar power plants, relatively cheaper, and simultaneously produce electricity and thermal energy (Ju et al., 2017; O. Z. Sharaf & Orhan, 2015). A Low concentration PV/T (LCPV/T) system consisting of PV cell and a point-focus Fresnel lens concentrator with microchannel cooling, and CPV-PCM system are shown in **Figure 2.7** and, Figure 2.8, respectively.

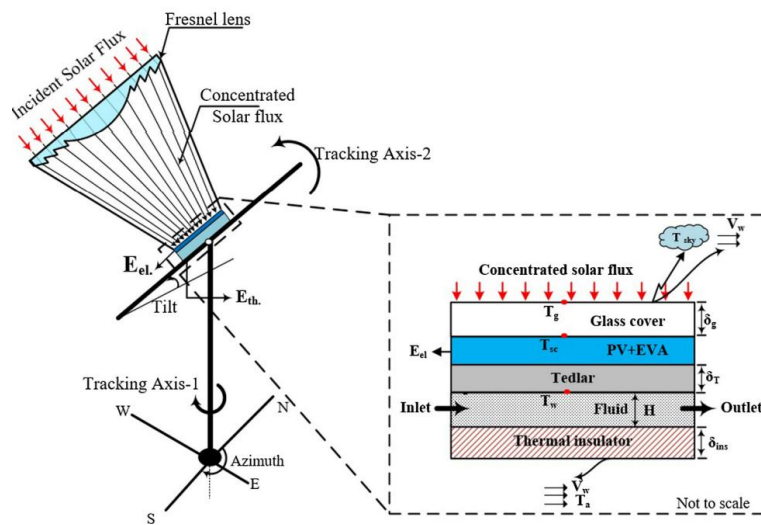


Figure 2.7. LCPV/T system integrated with a microchannel heat sink (Radwan et al., 2016)

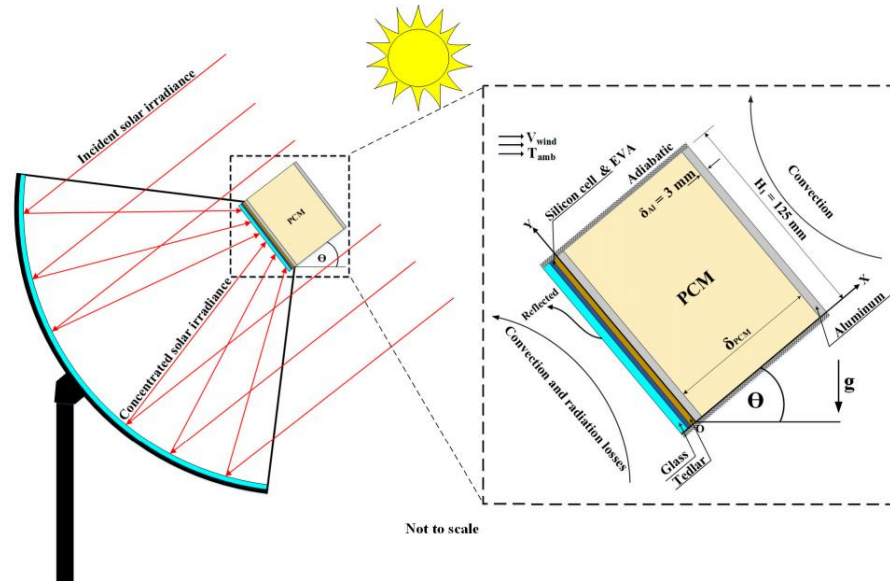


Figure 2.8. CPV-PCM system (Emam et al., 2017)

CPV systems were mainly designed for large-scale grid-connected power stations (Xiao et al., 2018). They are classified into low concentration, medium concentration, and high concentration groups based on concentration ratio (CR) that quantifies the degree of increase in radiation intensity received by the cell area (A. Hasan et al., 2018). High and medium concentration PV systems have larger sizes and require accurate tracking systems while low concentration PV systems usually do not require tracking systems and can be integrated building applications (Xiao et al., 2018).

There are several factors including direct normal irradiance (DNI), thermal regulation, system integration, cost management, reliability and tracking impact the utilization, and design of CPV systems. For instance, the most critical criteria for CPV systems using Fresnel lens optics are conversion efficiency, structure area cost, flux density uniformity, and allowable tracking error (Ejaz et al., 2021).

The primary challenges of CPV systems are standardizing solar cell size and concentrations levels. Additionally, the impact of soiling is site-specific, so cannot be generalized. However, it is crucial to consider soiling effect and apply a proper cleaning method to sustain a clean system. Moreover, a tracking system has a significant role in CPV systems because failing to track the sun can lead to degradation of concentrators edges, thus potentially compromising the long-term functionality of the reflective system (Ejaz et al., 2021).

3. TECHNOLOGIES OF PV SOLAR CELLS

Various structures have been studied in the advancement of PV solar cell technology. Key materials were utilized to fabricate solar cells are crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) (Tang et al., 2023). While silicon-based PV technology remains the most established, it is presently not the sole competitor in the market. PV technology can be categorized into four generations depending on material utilized, manufacturing process techniques, temperature tolerance, and the efficiency of the PV solar cells (Kant & Singh, 2022; Salameh et al., 2021; Singh et al., 2021). **Figure 3.1** outlines a timeline of four generations of solar cells with the materials used in each generation.

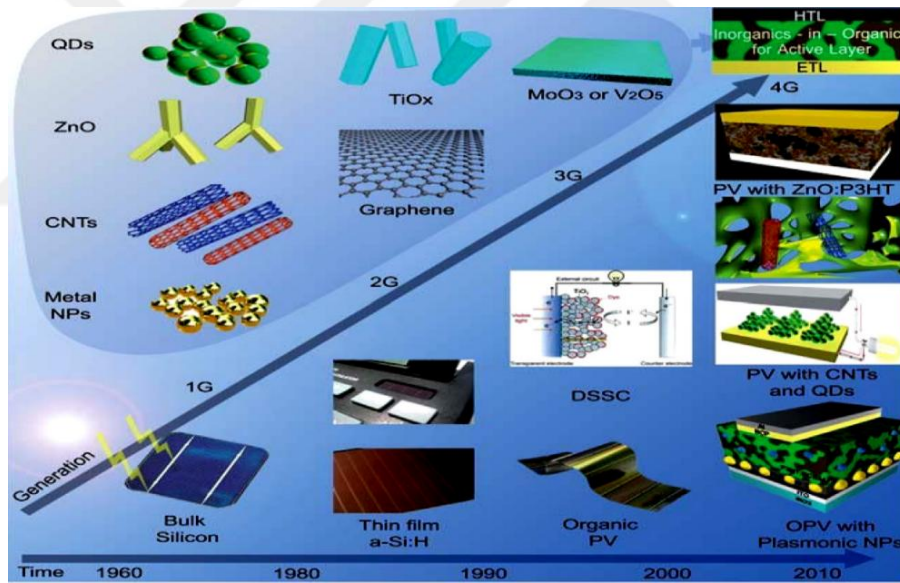


Figure 3.1. A timeline of the four generation of solar cells along with the materials utilized in each generation (Kant & Singh, 2022; Luceño-Sánchez et al., 2019)

The initial dominance in the market was held by first-generation silicon-based solar cells for an extended period until the development of second-generation thin-film cells. The third-generation solar cells including dye-sensitized cells, organic and perovskite cells continue to be the subject of intensive research and development (Kant & Singh, 2022; Salameh et al., 2021; Singh et al., 2021). The fourth-generation solar cells combine the affordability and adaptability of polymer thin-films with the durability of

organic nanostructures so they are also known as hybrid (inorganic-in-organics) solar cells (Kant & Singh, 2022; Luceño-Sánchez et al., 2019).

First-generation solar cells have a greater efficiency than second generation solar cells have, yet they possess greater cost per m^2 (Sinke, 2019), as seen in **Figure 3.2**. However, it is anticipated that manufacturing cost of first-generation solar cell will decrease because of advancements in ribbon silicon technology, which avoids ingot casting and slicing (Hayat et al., 2019). Third-generation solar cells technology aims to reduce the expenses of PV manufacturing to less than 1 dollar per W, with the ultimate goal of decreasing the price to \$0.50/W and the possibility of further reduction to \$0.20/W or less (Kant & Singh, 2022).

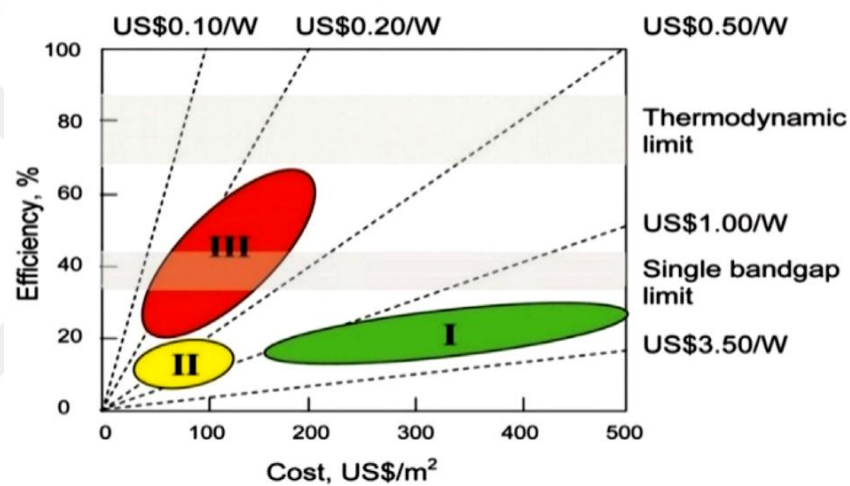
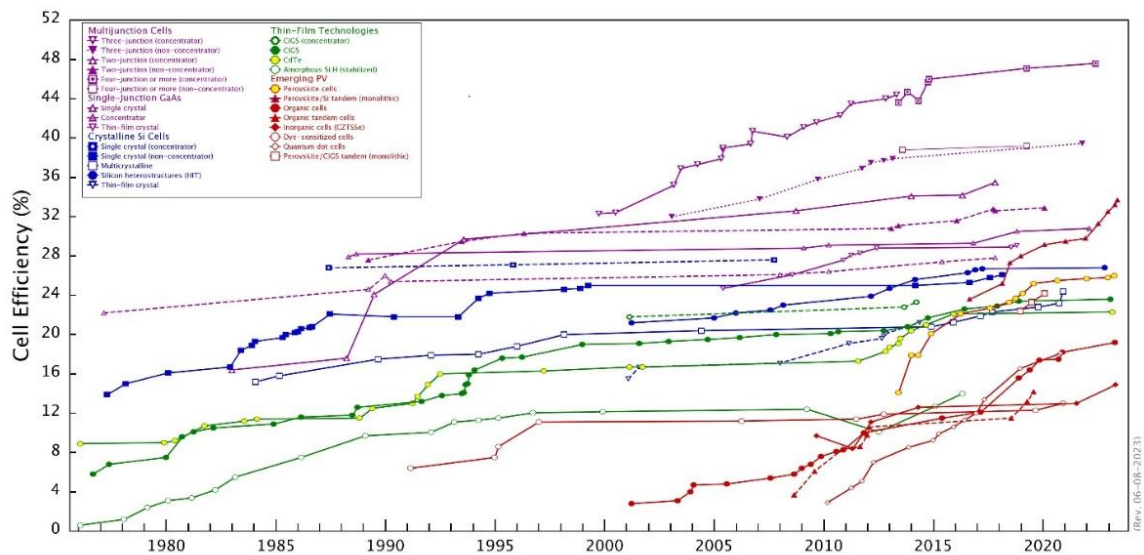


Figure 3.2. The anticipated efficiency and cost range for first, second and third generations of PV systems. Tinted areas: 67-87% is thermodynamic limit; 31-41% is single bandgap limit (Kant & Singh, 2022)

The selection of solar cells is conducted based on two key factors: efficiency and bandgap energy of the solar cells. The bandgap energy depends on the semiconductor materials (Alzahrani et al., 2021). **Figure 3.3** illustrates laboratory efficiency of different PV technologies along with their efficiency trends over time.



solar cells (Salameh et al., 2021; Tang et al., 2023). Manufacturing silicon-based solar cells consists of several steps including fabrication of silicon ingots, wafer slicing, surface texturing, the p-n junction formation through ion implantation or diffusion, anti-reflective coating, metallization with metal electrodes, as displayed in **Figure 3.4**. Subsequently, the solar cells are assembled into panels, and the panels are encapsulated and framed. Finally, a junction box is assembled, and the panels are tested (Lazaroiu et al., 2023).

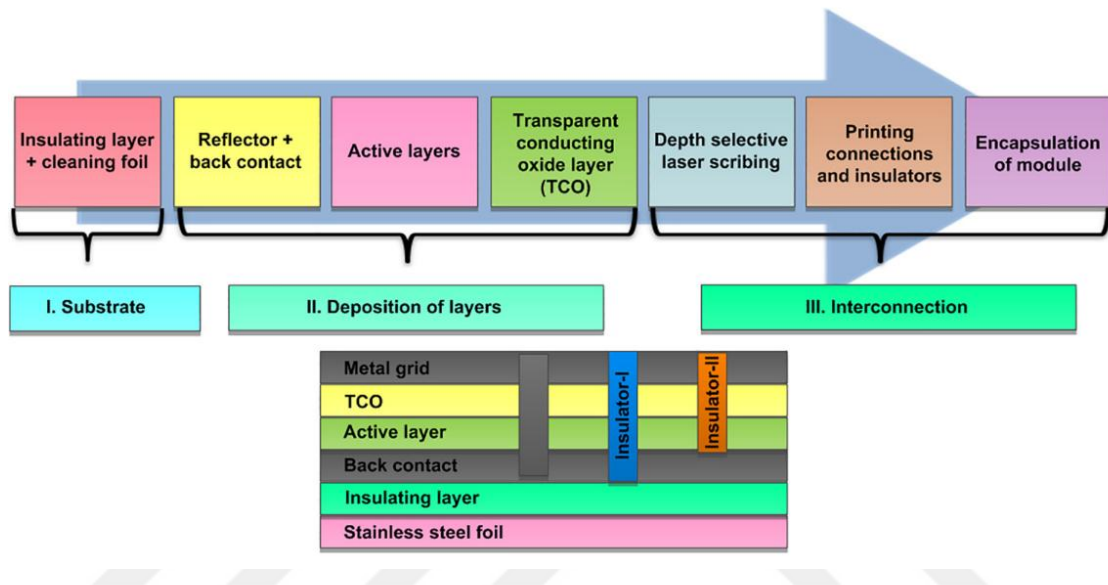


Figure 3.4. Production and formation of a crystalline silicon solar cell (Singh et al., 2021)

Mono-crystalline PV panels have a higher efficiency, and longer lifetime of electric production compare to multi-crystalline silicon PV panels, but they are more expensive (Bilen & Erdoğan, 2023; Şirin et al., 2023; Tang et al., 2023). Also, mono-crystalline solar cells demand less space due to their high efficiency, and exhibit enhanced performance during periods of low sunlight (Kant & Singh, 2022). On the other hand, multi-crystalline silicon PV panels are widely utilized in the market due to their lower cost resulting from a straightforward manufacturing process, as well as their efficiency of 13%-16% (Bilen & Erdoğan, 2023; Kant & Singh, 2022). Additionally, GaAs (gallium arsenide), which is a compound semiconductor formed from gallium (Ga) and arsenic (As) and possess structures similar to silicon, based PV cells are considered as the first-generation solar cells and are another alternative to mono-crystalline solar cells (Pandey et al., 2016; Singh et al., 2021). Even though GaAs is more expensive material than silicon is, it possesses high efficiency, low weight, and high heat resistance, which allow it to be used in CPV panels and space applications (Pandey et al., 2016). The power conversion

efficiency of commercial silicon-based PV panels generally stands at 15%-20%, and these panels reached a peak efficiency of 26.7 in 2020, with research efforts concentrated on lowering manufacturing cost and enduring durability (Lazaroïu et al., 2023; Pandey et al., 2016).

Mono-crystalline silicon consists of a homogeneous crystal structure present throughout the material manufactured in the shape of wafers obtained from silicon ingots. Surface texturing on the cells is either a pyramid or inverted pyramid shaped silicon surface at the micrometer scale to minimize optical losses caused by front reflection. In addition, to further diminish reflection losses, an anti-reflection coating crafted from materials like silicon nitride (Si_3N_4), titanium oxide (TiO_2), or silicon dioxide (SiO_2) can be applied. (Salameh et al., 2021). Efficiency of mono-crystalline silicon solar cells is around 24% (Bilen & Erdoğan, 2023).

Multi-crystalline silicon comprises of numerous small silicon grains with various crystal orientations. These are typically prepared by slicing multi-crystalline ingots formed from cooled molten silicon. (Salameh et al., 2021). Efficiency of multi-crystalline silicon solar cells is around 20.4% (Hayat et al., 2019).

3.2. Second Generation PV Solar Cells

Second-generation solar cells, also known as thin-film solar cells are thinner in size, cheaper and more flexible in comparison to the first-generation solar cells (Singh et al., 2021). Thin-film semiconductors are developed because reducing the thickness of wafer-based silicon decreases the weight and high material cost of silicon, so the cost of PV panel production since the cost of silicon takes up as much as 50% of the total manufacturing costs of PV solar panels (Pandey et al., 2016; Salameh et al., 2021). CdTe, a-Si, and CIGS are the main materials used in the production of thin-film solar cells. These materials have lower power temperature coefficient; therefore, thin-film solar cells have a better performance in comparison to crystalline silicon solar cells in hot environments (Salameh et al., 2021). However, they have shorter lifetimes (Kant & Singh, 2022). Thin-film solar cells attained an efficiency of up to 23.4% in 2020, with research concentrated on enhancing stability and developing novel material (Lazaroïu et al., 2023). The second generation of PV solar cells can be categorized into three groups: a-Si, CdTe and CIGS solar cells (Salameh et al., 2021).

The non-crystalline and disordered structure of a-Si leads to a 40 times greater absorptivity rate than that of mono-crystalline silicon. Therefore, a-Si material-based PV cells are favorable in comparison to CdTe, and CIGS (Pandey et al., 2016). Furthermore, a-Si solar cells are non-toxic, and do not contain heavy metals like cadmium or lead (Kant & Singh, 2022).

A CdTe material based single-junction cell with 11.45 eV bandgap is a promising option for transforming solar irradiance into electric energy. CdTe solar cells achieve an efficiency of 21% in laboratory conditions (Kant & Singh, 2022). The schematic demonstration of a CdTe solar cell is presented in **Figure 3.5**. The solar cell consists of glass, transparent conductive oxide (TCO), buffer layer, cadmium selenide telluride (CdSeTe) and CdTe materials, and back contact.

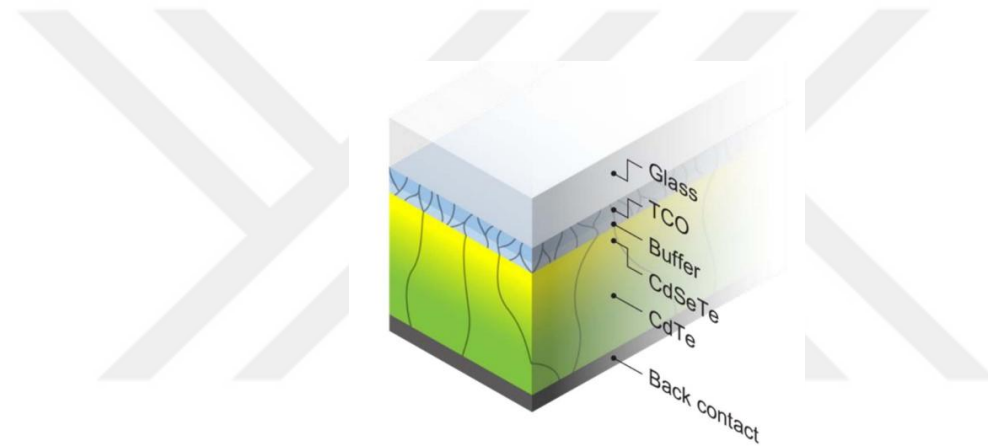


Figure 3.5. The schematic presentation of a typical CdTe solar cell (Wilson et al., 2020)

In addition, CIGS based multi-crystalline semiconductors have attained interest because of its impressive laboratory efficiency of 20.3%, high reliability, and ability to absorb UV (ultraviolet) and IR (infrared) radiation (Kant & Singh, 2022; Pandey et al., 2016). The illustration of a cross-sectional conventional and passivated back-contact structure of CIGS solar cells is shown in **Figure 3.6**. They comprise of TCO, buffer layer, CIFS material, molybdenum diselenide (MoSe_2), dielectric, molybdenum (Mo), and a substrate.

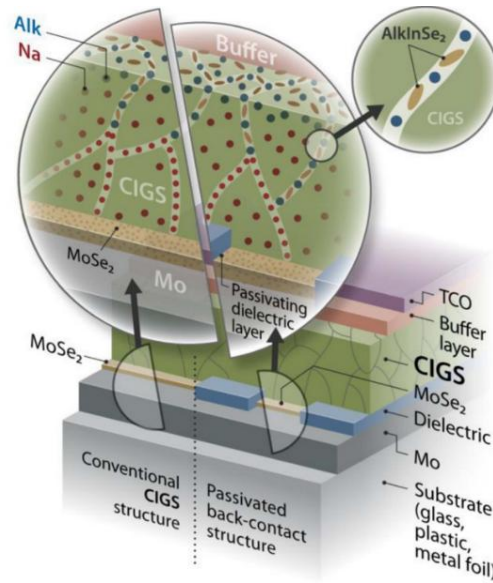


Figure 3.6. The illustration of a cross-sectional conventional and passivated back-contact structure of CIGS solar cells (Wilson et al., 2020)

3.3. Third Generation PV Solar Cells

The third-generation PV solar cells are emerging technologies representing the most recent advancements in research of solar cells, which involve the integration of easily processable organic materials and hybrid semiconductors. Even though the third-generation solar cells exhibit lower efficiencies and cell stability, significant research activity persists due to the potential for developing inexpensive and high-performance devices. Furthermore, the lightweight and flexible panels produced utilizing this technology are appealing for practical applications. Dye-sensitized, organic, Perovskites, quantum dot solar cells, and solar cells with multiple junctions are the types of the third-generation solar cells (Kant & Singh, 2022; Salameh et al., 2021).

Dye-sensitized solar cells (DSSCs) consist of a mechanical support layer coated with TCO, semiconductor film, generally TiO_2 , a sensitizer adhered to the surface of the semiconductor, and electrolyte containing a redox mediator, and a counter electrode that is capable of regenerating the redox mediator (Tyagi et al., 2013). **Figure 3.7** illustrates a schematic presentation of a dye-sensitized organic solar cell. The efficiency of current DSSCs can achieve up to 14.1% (Lazaroiu et al., 2023).

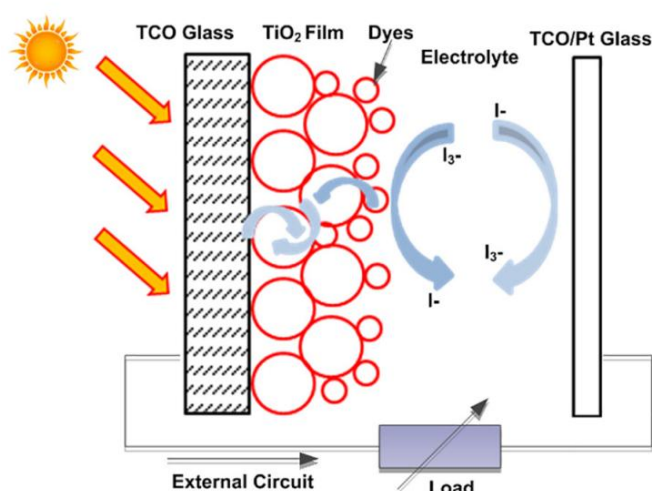


Figure 3.7. A schematic presentation of dye-sensitized organic solar cell (Singh et al., 2021)

Discovery of organic semiconductors unveiled the fundamental principle behind organic solar cells (polymeric solar cells) which utilize organic electrons to generate power. Light absorption and charge transport is provided by conductive organic polymers (Kant & Singh, 2022). A usual organic solar cell structure is shown in **Figure 3.8**. The efficiency of an organic solar cell is usually about 10% (Hayat et al., 2019), yet they achieved efficiencies as high as 18.% in 2020, with research concentrated on enhancing stability and developing novel materials (Lazaroiu et al., 2023).

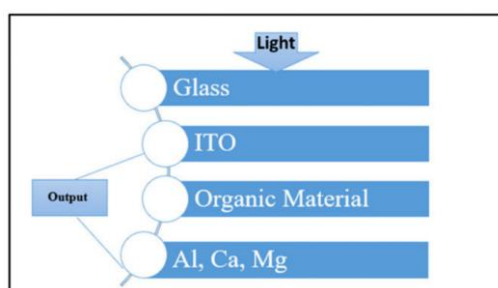


Figure 3.8. A schematic presentation of a typical organic solar cell with different components (Hayat et al., 2019)

The active layer of a Perovskites solar cell comprises of the crystal structure of mineral calcium titanate (CaTiO_3) that is an inorganic compound. Different absorber materials based on methyl ammonium lead (Perovskites) halide have been investigated for semiconductor applications. The power conversion efficiency of Perovskites solar cells can be over 25% (Kant & Singh, 2022). For example, hybrid perovskite solar cells

demonstrated efficiencies reaching as high as 29.1% in 2020, with research concentrated on enhancing stability and developing novel materials (Lazaroiu et al., 2023).

Quantum dots (QDs) are unique semiconductors with a capability of regulating bandgap energy by changing the size of QDs without altering the fundamental material or construction, which makes them favorable for solar cells (Kant & Singh, 2022; Tyagi et al., 2013). However, QDs can be degraded by oxygen, water, heat, and UV radiation exposure, and there are defects on the surface of the QDs, which temporarily capture electrons and holes. Therefore, other materials such as silicon, can be introduced as doping for increasing the efficiency of QD solar cells (Kant & Singh, 2022).

3.4. Fourth Generation PV Solar Cells

Fourth-generation solar cells, which is also referred to as inorganic-in-organic or hybrid solar cells, merge the cost-effectiveness and adaptability of polymer thin-films and the durability of organic nanostructures such as metal oxides, and metal nanoparticles, or graphene, carbon nanotube, and its derivatives (Kant & Singh, 2022; Luceño-Sánchez et al., 2019). Additionally, they exhibit great flexibility, low volatility (Kant & Singh, 2022).

3.5. Working Principles of PV Solar Cells

PV solar cells are the fundamental electrical components of PV panels and primarily comprise two semiconductor layers: a top negative (n)-type layer with excess electrons and a bottom positive (p)-type layer with electron deficiencies (holes). These layers establish a p-n junction, which forms an internal electric field. When solar radiation (photon energy) hits the top surface of a solar cell, it excites electrons in the semiconductor lattice, creating electron-hole pairs. The internal electric field drives the electrons toward the n-type layer and the holes toward the p-type layer, thereby generating a potential difference across the junction (Akrouh et al., 2023; Alzahrani et al., 2021; Li et al., 2023).

If an external circuit connects the n- and p-layers, electrons flow through the circuit, producing electric current. The energy of incoming photons must exceed the semiconductor's bandgap energy to generate electron-hole pairs and initiate current flow (Akrouh et al., 2023; Li et al., 2023). (Alzahrani et al., 2021). This continuous process

under sunlight constitutes the PV effect. **Figure 3.9** illustrates the fundamental concept of how a solar cell functions.

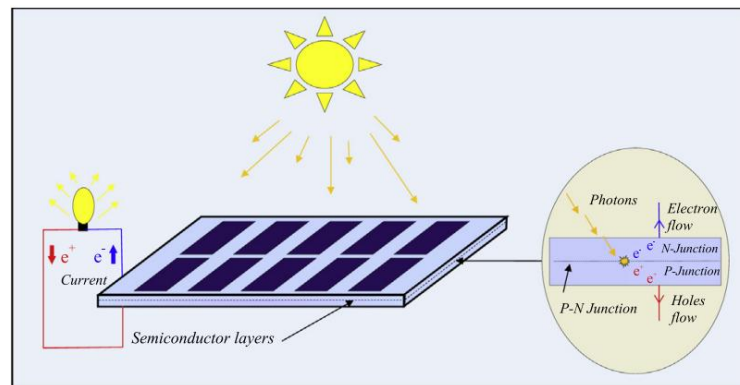


Figure 3.9. The fundamental operating concept of a solar cell (Akrouch et al., 2023)

4. FACTORS IMPACTING THE EFFICIENCY OF PV SYSTEMS

Even though PV systems are one of the most suitable technologies for sustainable electric energy production, they face challenges regarding their efficiencies. While commercial PV panels could theoretically achieve an efficiency up to 29%, in real world scenario, the efficiency of the panels is at around 26% (K. Hasan et al., 2022).

In practical usage, PV systems encounter various factors that impact their performance, productivity, and long-term reliability, thus impact the economy of power production (Aghaei et al., 2022; Fouad et al., 2017; K. Hasan et al., 2022). These factors can be categorized as: Environmental factors, PV system factors (PV constructional factors), installation-related factors, cost factors, and miscellaneous factors (operation and maintenance factors) (Fouad et al., 2017; K. Hasan et al., 2022). Despite continuing improvements in the construction and installation processes of PV systems, significant challenges persist in managing environmental factors (K. Hasan et al., 2022).

4.1. Environmental Factors

PV systems must be exposed to direct solar radiation (DSR) in the outdoor environment; therefore, the energy conversion efficiency of the systems is significantly affected by environmental factors. Temperature, solar radiation, soiling and dust accumulation, wind velocity, shading, and humidity are the main environmental factors affecting the efficiency of PV systems (Aghaei et al., 2022; Fouad et al., 2017; K. Hasan et al., 2022).

4.1.1. Solar radiation

Solar radiation is defined as the power from the sun received on a unit surface area (Fouad et al., 2017; Rajagukguk et al., 2020). The electricity produced from a PV system directly depends on the availability of solar irradiance which usually varies based on climate conditions, seasonal alterations, geographical location, time of the day, and position of the sun in the sky (Aghaei et al., 2022; D. L. King et al., 2002; Fouad et al.,

2017; K. Hasan et al., 2022; Mondol et al., 2007b). Moreover, cloudy conditions are mainly responsible for fluctuations in solar irradiance values (K. Hasan et al., 2022). The position of the sun changes due to changes in its altitude, which refers to the angle formed by the sun's rays, the horizontal plane, and azimuth angle. Azimuth angle is the angle between true north and projection of the sun's rays onto horizontal (Fouad et al., 2017; Stevanović, 2022). The latitude angle of the location determines the optimal tilt angle which deviates by approximately -15° and $+15^\circ$ from the latitude angle in summer and winter, respectively. For every degree offset from the south in azimuth angle, solar radiation decreases by 0.008% (K. Hasan et al., 2022).

Sunlight reaching to a PV panel surface includes direct, diffused, and reflected radiation. Although direct radiation is the largest ratio of sunlight, it is important to consider both diffused and reflected radiation when analyzing a PV system (Fouad et al., 2017). Diffused radiation includes sunlight from sky, ground, and nearby objects. Assessing solar irradiance is complicated in the presence of nearby objects that cast shadows or reflect solar radiation onto a PV system (K. Hasan et al., 2022). The electrical power output from a PV system increases with rising solar irradiance (Fouad et al., 2017; K. Hasan et al., 2022; Nasrin et al., 2018), as seen in **Figure 4.1**.

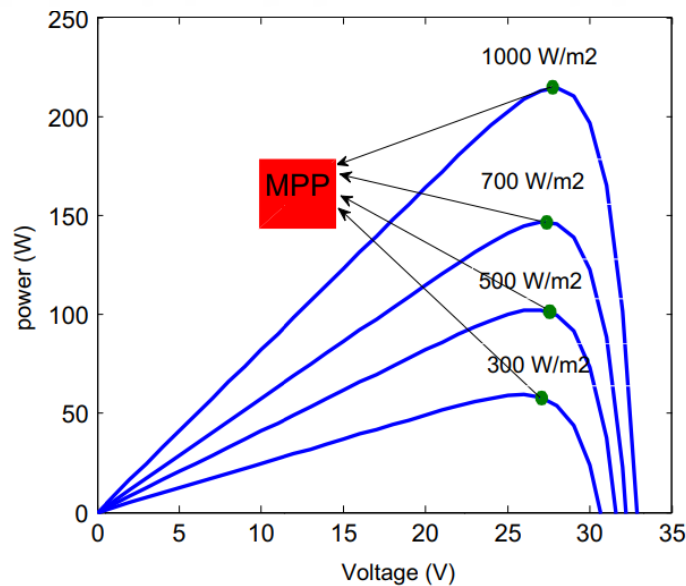


Figure 4.1. Power-voltage curves of a PV panel and the position of the Maximum Power Point (MPP) with different solar radiations at a constant temperature of 25 °C (Maghami et al., 2016)

4.1.2. Temperature

PV Panel temperature is a crucial factor that significantly affects the performance and energy output of a PV system (Aghaei et al., 2022; Fouad et al., 2017). Temperature has an accelerating impact on various degradation mechanisms of a PV panel, especially those associated with chemical reactions and diffusion (Aghaei et al., 2022). An increase in temperature of a solar cell primarily impacts the open circuit voltage (V_{oc}) that linearly declines as the cell temperature increases (Fouad et al., 2017; Kayri, 2024; Zaihidee et al., 2016) because bandgap energy usually decreases under high operating temperatures due to stronger electron–phonon interactions and thermal vibration, which increases the speed of the electrons, so the resistance in the circuit (Kayri, 2024). Thermal vibration increases the spacing between atoms and the increased electron activity reduces the energy difference between the conduction band and valence band, thereby the bandgap energy decreases. This allows electron–hole recombination, reducing the number of charge carriers that maintain the potential difference. Thus, higher solar cell temperature causes a reduction in fill factor (FF) of the cell, and a decrease in maximum power and overall efficiency of a PV system. FF determines the presence of both series resistance, which is surplus resistance in current flow, and shunt resistance, which is unwanted leakage pathways, in a PV cell and its circuit (K. Hasan et al., 2022).

Figure 4.2 presents a correlation between electrical efficiency and cell temperature for a typical summer day (Bahaidarah et al., 2016; Bhakre et al., 2021; Pathak et al., 2022). Additionally, the relationship between the surface temperature and power output for different types of PV panels is given in **Figure 4.3**.

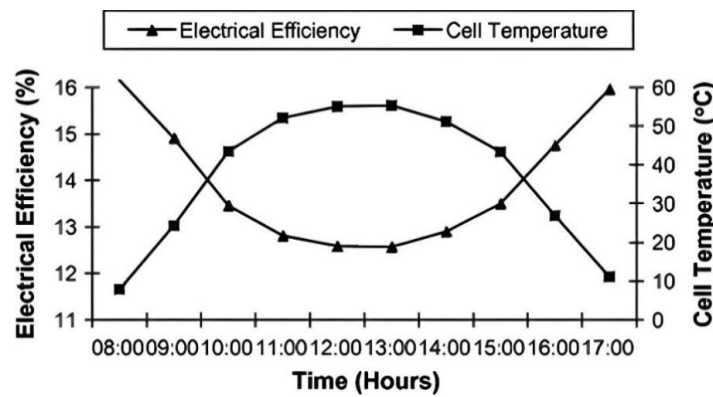


Figure 4.2. Correlation between electrical efficiency and cell temperature under typical summer conditions (Bahaidarah et al., 2016; Bhakre et al., 2021; Pathak et al., 2022)

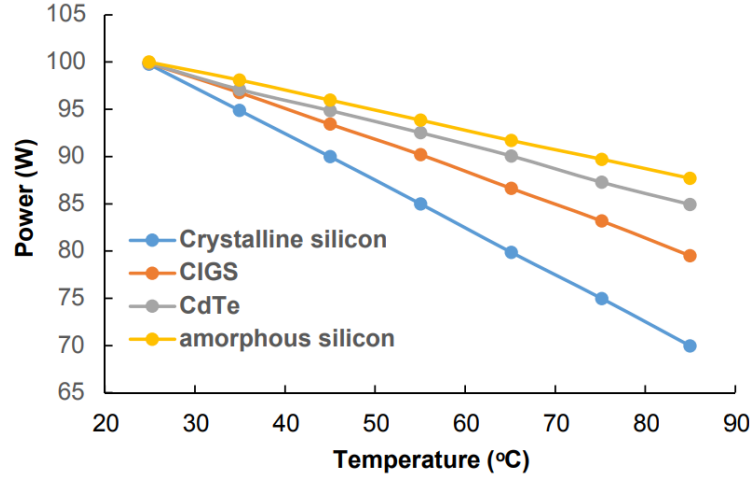


Figure 4.3. Temperature increase versus power output for different types of PV panels (Hamzat et al., 2021)

Every 1 °C rise in a crystalline silicon PV cell temperature leads to a 2.2 milli volt (mV) decrease in cell voltage, thus approximately 0.5% decline in the electrical power (Benghanem et al., 2016; Fouad et al., 2017; Johnston et al., 2021). **Figure 4.4** shows a relation between power output of a PV cell and voltage at different temperatures, and under a constant solar radiation of 1000 W/m².

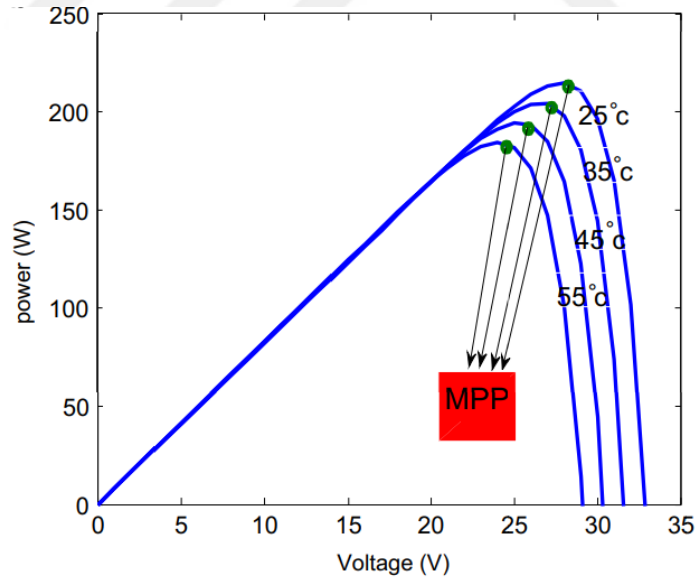


Figure 4.4. P-V curves of a PV panel and the position of the MPP at different temperatures (Maghami et al., 2016)

A PV panel temperature (T_{panel}) is a function of different variables such as ambient temperature (T_{amb}), wind speed (w_s) and solar radiation (Fouad et al., 2017; K. Hasan et al., 2022). Thus, the PV panel temperature can be calculated by the following equation.

$$T_{\text{panel}} = T_{\text{amb}} \times \exp(-a - b \times ws) + \Delta T \times \frac{\text{Solar Radiation}}{1000} \quad (4.1)$$

Where; a , b , and ΔT are constant, have specific values for a solar cell (a glass or polymer sheet), which are 3.59, 0.0750, and 3, respectively (K. Hasan et al., 2022).

Furthermore, the temperature is affected by material of a PV panel and properties of a PV system (Fouad et al., 2017). The flow of thermal energy out of a PV cell relies on factors such as shape of the cell, heat-conducting properties of the surrounding materials, and installation configuration of a PV panel (Aghaei et al., 2022).

The temperature coefficient, which is the ratio of alteration in power with respect to temperature, is a vital parameter that validates the loss in power because of temperature elevation (D. L. King et al., 1997; Zaihidee et al., 2016). For instance, standard power temperature coefficient for mono-crystalline PV panels range between 0.38% and 0.45% per °C. This implies that with each 1 °C increase in temperature, there is a corresponding power loss between 0.38% and 0.48% (Fouad et al., 2017).

4.1.3. Soiling and dust accumulation

Soiling can occur due to dust, dirt and pollen accumulation, air pollution, the growth of microbial algae or the presence of bird droppings on a PV panel surface (Aghaei et al., 2022; Peinado Gonzalo et al., 2020). Dust accumulation or biological soiling do not cause corrosion, delamination, and cell cracks on the panel, yet they can block the sunlight, leading to significant electrical production loss since solar radiation scatters across the surface of the panel due to presence of soiling (Aghaei et al., 2022; Fouad et al., 2017; Kayri & Bayar, 2024; Meral & Dinçer, 2011; Saidan et al., 2016). Therefore, soiling must be considered when assessing degradation outdoors (Aghaei et al., 2022). The annual dust reduction factor of a PV panel usually is 93%. For example, if we consider a 100 W panel, it will generally function at 93 W due to dust or dirt accumulation (Fouad et al., 2017; Meral & Dinçer, 2011). The degree of reduction in the power output of a PV panel primarily depends on density of dust accumulation. For instance, the deposition of 20 g/m² of dust on the panel causes a decrease in short circuit current (I_{sc}), V_{oc} , and efficiency by approximately 15%-21%, 2%-6%, and 15%-35%, respectively (Zaihidee et al., 2016).

The level of soiling can vary based on the surface characteristics of a PV panel, where the panel is installed and how it is positioned, including its tilt angle and its height from the ground (Aghaei et al., 2022). In addition, dust accumulation is climate-dependent and thus its amount relies on the location, type of dust particulars and sizes (Aghaei et al., 2022; Kayri & Bayar, 2024; Ridha et al., 2021). Particularly, in desert climates, dust accumulation can be significant. Also, in tropical regions with great humidity and common dew formation, biological soiling can limit the penetration of solar irradiance into solar cells. Dew formation can result in cementation of dust particles, making them difficult to remove through natural cleaning (Aghaei et al., 2022).

Although bird droppings can be regarded as a type of biological soiling, their impact differs from dust and other forms of biological soiling. They have the potential to locally obstruct solar radiation, thereby affecting the performance and reliability of a PV panel to a significant extent (Aghaei et al., 2022). If bird droppings are not cleaned from surface of the panel, they can function as partial shading, resulting in temperature variation through the cells, as known current matching problem. Subsequently, this leads to the formation of hotspots, which are specified areas of higher temperature, on the cells and thus lasting structure damage because large current flow through a limited, resistive area (Aghaei et al., 2022; Bahaidarah et al., 2016; Royne et al., 2005).

As a result, the reasons behind soiling can be categorized into three groups: environmental factors such as wind, temperature, humidity, and pollution; dust composition such as sand, clay, bacteria, and carbon; and installation attributes such as material, and location (Peinado Gonzalo et al., 2020).

4.1.4. Wind velocity

The electric energy generated by a PV panel is affected by wind speed and direction. Factors such as temperature, surface structure of the PV panel and dust accumulation characterize the effect of wind on the performance of the panel (K. Hasan et al., 2022; Jathar et al., 2023). The increase in temperature of solar cells is highly responsive to wind velocity rather than the direction of wind. The most economically efficient way for cooling a PV panel is the utilization of convective heat transfer through natural wind flow, which is influenced by surface structure of the panel. Convective cooling is more effective at low wind velocity and for flat surfaces. Also, wind removes dust particles from the surface of PV panels, thereby reducing dust accumulation.

However, wind flowing can have an opposite effect in desert areas, as wind itself carries a substantial quantity of dust and sand particles (K. Hasan et al., 2022).

4.1.5. Shading

Shading, the shadowing effect, is described as the blockage in the path of sunlight reaching the surface of a PV panel (K. Hasan et al., 2022; Jathar et al., 2023). It decreases the electrical production of a PV panel (Fouad et al., 2017; K. Hasan et al., 2022; Kawamura et al., 2003; Maghami et al., 2016). It can be caused by different reasons such as poles, trees, dust accumulation, snow, and buildings (Fouad et al., 2017; K. Hasan et al., 2022). Leaves, birds and bird droppings that fall directly on a PV panel can result in shadowing (Fouad et al., 2017). Additionally, atmospheric dust, fog, and smoke decrease solar radiation and result in a soft shading on PV panels (K. Hasan et al., 2022; Jathar et al., 2023). The shading impacts the current flow in the shaded solar cells, thus affecting the entire panel because the cells are usually connected and wired in series (Fouad et al., 2017). The current generated in unshaded solar cells flow through shaded solar cells, causing PV panel to operate in negative voltage ranges, which leads to power dissipation rather than generation (K. Hasan et al., 2022). The performance loss of a PV panel due to shading can be over 80%, depending on the ratio of shaded cells in the panel, and material of the cells (Fouad et al., 2017).

4.1.6. Humidity

Water droplets and vapor can accumulate on a PV panel surface due to the relative humidity, leading to diffraction of solar irradiance away from the PV cells and reducing power output of the panel (K. Hasan et al., 2022), as shown in **Figure 4.5**. Moreover, exposure to high humidity for a long time can cause corrosion in the PV panel as moisture penetrates the solar cells (K. Hasan et al., 2022; Jathar et al., 2023). The presence of moisture in the panel increases electrical conductivity of the material and leakage currents (K. Hasan et al., 2022). Furthermore, humidity may cause the formation of sticky and adhesive dust layers on the PV surface, consequently resulting in soiling (Fouad et al., 2017; K. Hasan et al., 2022).

For silicon-based solar cells, humidity functions as a layer that captures incoming solar radiation, thereby enhancing efficiency of the cells to a certain degree. However, prolonged exposure to humidity diminishes the efficiency of the cells (Jathar et al., 2023).

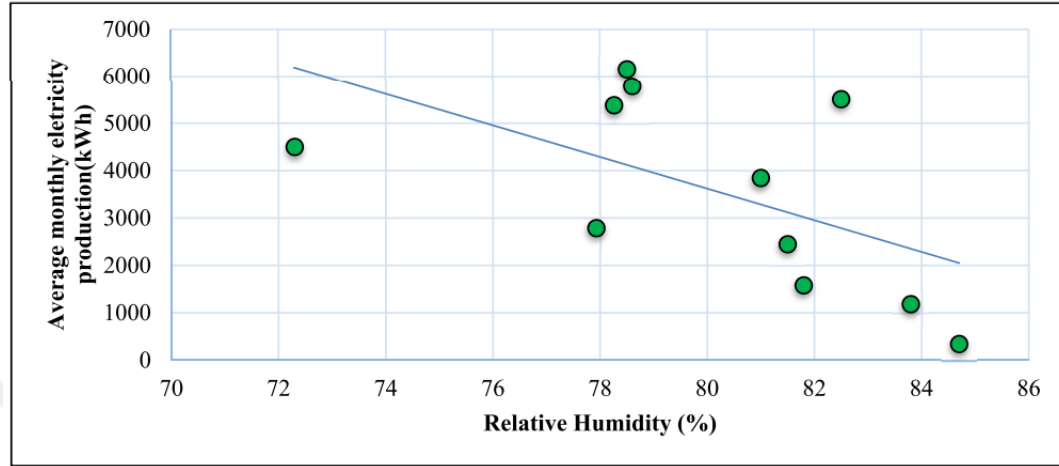


Figure 4.5. Impact of relative humidity on electricity generation of PV cells (Jathar et al., 2023)

4.2. PV System Parameters

Different factors associated with the components of a PV system can impact the power output of the whole system. These factors are:

4.2.1. I-V characteristics

The current at MPP (I_{mpp}), voltage at (V_{mpp}), I_{sc} , V_{oc} and power at MPP (P_{mpp}) are key characteristics of a PV panel that directly influence its power output (Fouad et al., 2017).

The I-V curve of a solar cell is impacted by solar radiation and temperature (Alzahrani et al., 2021). The correlation between I-V curve and solar radiation, and the relationship between I-V curve and temperature are presented in **Figure 4.6** and, **Figure 4.7** respectively.

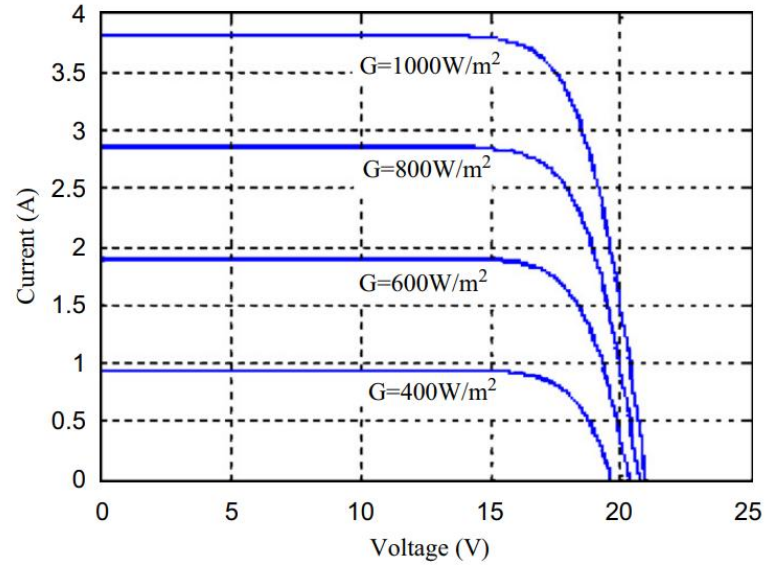


Figure 4.6. Influence of radiation on the I-V curve (Chenni et al., 2007).

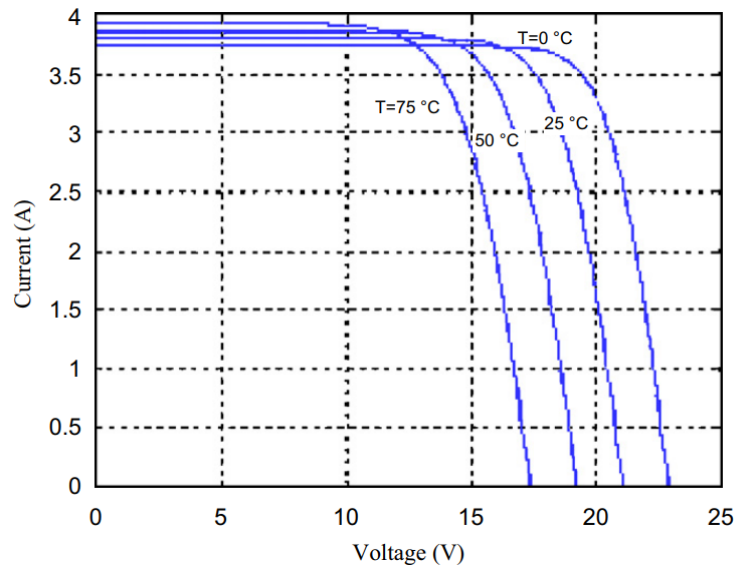


Figure 4.7. Influence of temperature on the I-V curve (Chenni et al., 2007)

I_{sc} varies linearly with solar radiation. V_{oc} relies on the temperature of a PV cell. Increase in the cell temperature leads to a minor rise in I_{sc} , yet a major decline in V_{oc} . Therefore, the overall power output from the cell decreases as the temperature increases (Alzahrani et al., 2021; Chenni et al., 2007; Zaihidee et al., 2016).

The ratio between the MPP and V_{oc} and I_{sc} (the optimal squareness of the I-V curve) produced by a solar cell states a high FF which can be detected at low temperatures, and relatively high temperatures when utilizing multi-junction PV cells and concentrated solar radiation (Alzahrani et al., 2021).

Electricity production in a PV panel relies on the I_{sc} , and V_{oc} , as P_{mpp} is determined by the Equation 4.2, as shown below (K. Hasan et al., 2022).

$$P_{mpp} = V_{mpp} \times I_{mpp} = (FF) \times V_{oc} \times I_{sc} \quad (4.2)$$

Where; V_{mpp} and I_{mpp} are voltage and current at the MPP, respectively.

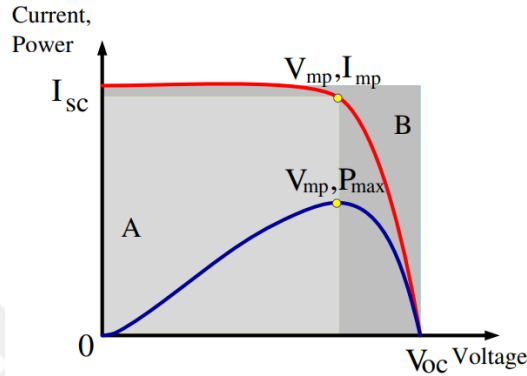


Figure 4.8. The presentation of I-V curve (Dewi et al., 2019)

In **Figure 4.8**, “A” region represents a solar cell with low FF while “B” region represents the cell with high FF (Dewi et al., 2019).

At elevated temperatures, the I-V curve is flat at which value of the FF is low, indicating a low power output for solar cells, particularly for single-junction PV cells (Alzahrani et al., 2021).

4.2.2. Inverter efficiency

Inverter efficiency primary determines the conversion of DC power sources to alternating current (AC) power load (Dewi et al., 2019; Ridha et al., 2021). It impacts the overall performance of a PV solar system (J. Good & Johnson, 2016). Losses from converting DC produced by the solar system into AC are due to several factors such as losses from transformer (magnetic and copper losses), inverter self-consumption, and losses in the electronic components (Fouad et al., 2017; Mondol et al., 2007a). The overall efficiency of transforming DC to AC generally ranges from approximately 88% to 92% under actual field circumstances, with an average reduction factor of 90%. The efficiency of an inverter tends to decrease gradually after reaching a solar irradiance of

approximately 400-700 W/m². This reduction is because of a rise in temperature in the inverter due to managing loads with more power (Fouad et al., 2017).

The output waveform of an inverter can be classified into three categories: square wave inverter, modified sine wave inverter, and pure sine wave inverter. Square wave inverter is not complicated and has the lowest efficiency because its high ratio of harmonics content can interface with the electromagnetic field within conductive components. Sine wave inverters possess greater efficiency and performance, but they are more expensive relative to other inverter waveforms. They are mainly utilized for grid-connected systems (Ridha et al., 2021).

4.2.3 Battery efficiency

Batteries in a PV system store surplus electricity produced by the system and are necessary due to the fluctuating nature of power output from the system (Bortolini et al., 2014; Datta et al., 2021; Fouad et al., 2017; Ridha et al., 2021). They supply the electricity to fulfill the load demand during nighttime and when solar radiation levels are low (Ridha et al., 2021). Storing electric energy with batteries is expensive and batteries need to operate in regions without extreme temperatures and with sufficient ventilation (Bortolini et al., 2014; Datta et al., 2021; Fouad et al., 2017).

A battery efficiency is measured by the proportion of the charge extracted (in Ampere hours, Ah) throughout discharge divided by the quantity of charge (Ah) required to return the battery to its initial state of charge (SOC). Hence, efficiency of the battery relies on state of charge, defined as the current capacity of the battery divided by its nominal capacity, as well as the rates of charging and discharging currents (Fouad et al., 2017; Meral & Dinçer, 2011). Different factors can affect the efficiency of batteries including their nominal capacity, charge or discharge control, SOC, regulation and their lifespans (Ridha et al., 2021). Batteries with lower SOC levels exhibit higher charging efficiencies. For instance, in the literature, it was stated that the charging efficiency of a battery remained at 91% within the SOC range of 0-84%. However, it significantly decreased to 55% when the SOC range was between 79% and 84%. Furthermore, the efficiency dropped below 50% for SOC levels by more than 90%. This indicates that a significant amount of electricity generated by a PV system can be lost when it is stored in batteries with high SOC, particularly in hot climates. Moreover, batteries operating on low SOC levels for an extended period of time can potentially have a permanent reduction

in their capacity. The lifetime span of a battery is mainly effected by the number of charging/discharging cycles and temperature (Fouad et al., 2017). Lead-acid batteries are preferred for PV systems because of their low cost (Ridha et al., 2021).

4.2.4. Charge controller

A charge controller in a PV system tracks the maximum MPP at a particular Maximum Power Point Tracking (MPPT) and diminishes the battery charging time to quickly repose the PV system. It maintains the battery at its maximum voltage level by improving the efficiency of the PV system (Dewi et al., 2019) . Moreover, it serves to protect the battery against over or undercharging with a process carried out in three stages: bulk, boost, and float. The process can prolong the lifetime of the battery (Ridha et al., 2021).

4.2.5. Structure of a PV panel

Materials that solar PV cells are fabricated, atomic structure of the solar cells, and band-gap energy highly impacts the design and performance of a PV panel system (Fouad et al., 2017). Materials such as silicon (Si), GaAs, copper indium diselenide (CuInSe₂), CdTe etc. affect the solar cells efficiencies and cost of the PV panel (Pandey et al., 2016).

An atomic structure of a solar cell can exist in different forms, including mono-crystalline, polycrystalline, amorphous or nano configurations. It impacts the efficiency of the cell and its cost. For example, mono-crystalline solar cells are more expensive, and demand more complex manufacturing procedures when compared to polycrystalline solar cells, but their efficiencies are higher (Fouad et al., 2017; Pandey et al., 2016).

When solar radiation hits the surface of a PV panel, photons with a specific threshold of energy are able to release electrons from their atomic connections, producing an electrical flow. The band-gap energy is the energy needed to shift an outer-shell electron from the valence band to the conduction band and varies based on the material and atomic structures (Fouad et al., 2017).

4.2.6. Efficiency of a PV panel

The energy conversion efficiency of a PV panel refers to the ability of a PV panel to transform solar irradiance into electricity and is stated as the percentage of absorbed solar irradiance that is transformed into electrical current (Fouad et al., 2017; Lazaroïu et al., 2023; Meral & Dinçer, 2011). It is contingent upon the rated power of the panel, the surface area of the panel and the solar radiation (Fouad et al., 2017; Meral & Dinçer, 2011). In addition, it relies on the material used to manufacture the panel, band-gap energy, and atomic structure of the panel (Fouad et al., 2017; Green, 2015).

PV efficiency is determined by evaluating the power output of the panel under a specific light intensity, temperature and standard test conditions (STC), where the temperature of solar cells (T_c) is 25°C, solar radiation (E) is 1000 W/m² with an air mass (AM) 1.5 spectrum (Chenni et al., 2007; Lazaroïu et al., 2023).

The efficiency of a silicon-based PV panel is commonly calculated by linear relationship presented as follows:

$$\eta_{\text{panel}} = \eta_{\text{panel}, T_{\text{ref}}} [1 - \beta_{\text{ref}} (T_{\text{cell}} - T_{\text{ref}})] \quad (4.3)$$

Where; $\eta_{\text{panel}, T_{\text{ref}}}$ (usually provided by the manufacturer) is the power conversion efficiency of the panel at reference temperature, for MPP, β_{ref} (1/°C; usually provided by the manufacturer; it is 1/0.005°C for silicon-based PV panels) is the temperature coefficient, T_{cell} (°C) is the operation temperature of the solar cells and T_{ref} is the reference temperature (generally 25°C) (Aly et al., 2019).

Furthermore, the power output of the panel can be calculated by using the definition of efficiency which is the ratio of electric power generated by the panel (P_{out} , power out) to solar irradiance on the front surface of the panel (P_{in} , power in).

$$P_{\text{out}} = \eta_{\text{panel}} \times P_{\text{in}} = \eta_{\text{panel}} \times (A_{\text{panel}} \times \text{DSR}) \quad (4.4)$$

Where; A_{panel} is the front area of the panel, and DSR is the direct solar radiation, on the front surface of the panel (Aly et al., 2019).

4.3. Installation Factors

It is essential to remove obstacles such as trees, grass, and root balls, before installing the equipment of a PV system. In order to effectively install the system while diminishing interference with other important activities like agriculture, close attention must be given to land pattern and distribution (Jathar et al., 2023).

Installation factors such as cables, PV panel orientation, mismatch, tracking mechanism, and the MPPT affect the performance of a PV system since the power output of the systems is dependent on the losses linked to these installed components (Fouad et al., 2017).

4.3.1. Features of cables

Cables play an important role in the electrical part of a PV system, but they are a significant source of energy losses, which are due to wires including DC losses along the array of solar panels and AC losses at the output of an inverter. In addition, there are losses due to increased resistance of the cables, which resulted from cable heating over time (Dewi et al., 2019). Therefore, the selection of cables for a PV system, particularly for grid-connected PV systems should be done with precision to ensure their ability to endure harsh environments and voltage (Maghami et al., 2016). Furthermore, it should minimize the power losses due to the wiring connections between the converter, batteries and other parts in the PV system (Fouad et al., 2017).

4.3.2. PV panel orientation

The PV panel orientation of a PV system is an important factor for energy output of the system because there are certain optical losses that differ with the angle-of-incidence (AOI) of solar radiation reaching the panel. The AOI influences the direct component of solar radiation, while diffuse component remains largely unaffected by the AOI (Fouad et al., 2017; Mondol et al., 2007b).

A PV panel most efficiently uses solar radiation when its surface is oriented perpendicular to the sun (Aslam et al., 2022; Fouad et al., 2017; Lave & Kleissl, 2011). The latitudinal angle of an area is typically used as the standard criterion for determining the optimal installation angle of a PV panel. Large deviations from the latitudinal angle

leads to decreased absorption of sunlight, so reducing the power generation of the panel. Angle of inclination varies depending on location, thus it is site-specific (Aslam et al., 2022).

4.3.3. Panel mismatch

Mismatch losses in a PV system occur when solar panels with different features or operating in different conditions are connected in series or parallel configurations (Wurster & Schubert, 2014). The panel with lowest power output dictates the overall performance of the entire PV system. Panel mismatch causes at least 2% loss in power output and can escalate to 10% in some cases (Fouad et al., 2017).

4.3.4. Tracking mechanism

Tracking mechanisms are used to synchronize PV panels according to the movement of the sun, ensuring that solar irradiance remains vertical to the surface of the panels, thereby improving the power output of the system. These mechanisms can be either single axis or dual axis configurations that can produce 25-45% more electrical energy relative to panels positioned on a fixed optimum tilt angle (Fouad et al., 2017). Utilizing a tracking mechanism in a PV system relies on the location, and climate conditions because it is an extra expense to the system, and it can lead to overheating of the panels where solar radiation is high (Abdallah & Nijmeh, 2004; Fouad et al., 2017).

4.3.5. Maximum power point tracker

The performance of a PV panel is altered by changes in the position of the sun, solar irradiance and temperature variations. The MPPT is employed to extract the most power from the PV panel and efficiently transfer it to the load (Abd-Elhady et al., 2016; Ridha et al., 2021). This is obtained by adjusting the panel output to align with peak power point, leading to a significant improvement in the energy output of the PV system (Abd-Elhady et al., 2016). Different factors impact the behavior of the MPPT, including voltage alterations due to temperature, fluctuations due to cloud cover, I-V curve of the panel, and the conditions of the battery. A 10% to 25% increase in the charge current can be achieved by using the MPTT. However, it is important to consider the advantages of

utilizing MPTT alongside its additional expense and risks related to reliability (Fouad et al., 2017). The efficiency of the MPTT usually ranges from 95% to 98% (Ridha et al., 2021).

4.4. Cost Factors

Main cost-related factors are expenses from connection cables, and initial capital investments such as cost of PV panels and other components of a PV system (Fouad et al., 2017).

4.4.1. Cables expenses

Cables provide connections between solar panels and other electronic devices in a PV system. They are usually UV resistant, and weather resistant including high temperature tolerant (K et al., 2018). Utilization of large cables between PV panels and a battery or inverter diminishes power losses from the panels, yet increases the expenses relying on feature, and sizes of the cables (Fouad et al., 2017).

4.4.2. PV system expenses

Costs of PV panels, batteries, inverters/charger regulators, mechanical and electrical installation, transportation, project management, and design are considered as initial capital investments for a PV system (Akinyele et al., 2015; Fouad et al., 2017; Sarasa-Maestro et al., 2016). Additionally, other expenses are the cost of support structure and cables (Sarasa-Maestro et al., 2016). Batteries account for approximately 35% to 50% of the capital cost of the PV system over its 25-year lifespan because of the short lifespan of batteries. Inverters typically represent around 8%-12% of the overall lifetime expenses of the system. Apart from maintenance costs, there are no operation costs for the system (Fouad et al., 2017).

4.5. Miscellaneous

Degradation due to glass breakage, and hotspot formation, characteristics resistance, shunt resistance, performance ratio, maintenance and cleaning, sizing of a PV

system, and surface area of PV panels can be regarded as miscellaneous factors of a PV system (Fouad et al., 2017).

4.5.1. Degradation

Degradation of a PV system is the gradual decline in the attributes of the system and impacts its capacity to produce electric power (K. Hasan et al., 2022). When the power output of a PV panel is below 80% of its initial level, it is considered that it is under degradation (Fouad et al., 2017; K. Hasan et al., 2022), which can be due to broken interconnections, corrosion, adhesion loss, broken cells, delamination or discoloration of the encapsulant, broken glass, moisture intrusion, and failure of the bypass diode and weld ribbons (Fouad et al., 2017). Furthermore, environmental factors including temperature, humidity, and solar radiation, and mechanical shock contribute to the degradation of a PV system (K. Hasan et al., 2022). For example, a polycrystalline panel consistently exposed to outdoor climate in an open circuit system for years exhibited an approximate performance decline of 0.5% per year (Fouad et al., 2017). Also, it was claimed that an approximately 0.7% of yearly decline in efficiency was observed in both monocrystalline and polycrystalline PV panels due to aging (Alves dos Santos et al., 2021). The performance of a PV panel due to degradation can typically range from 0.5% to 2% per year based on type of the panel, operation conditions of the panel (Fouad et al., 2017).

4.5.2. Glass breakage

Glass breakage failures occur in a PV panel because of the clamps, tightening of screws during mounting or a mechanical impact (Fouad et al., 2017). Glass breakage could potentially decrease the direct solar irradiance on the PV cells, causing a slight reduction in the efficiency of the panel (Tas & van Sark, 2023). Moreover, oxygen and water vapor can enter the panel and subsequently lead to electrical circuit corrosion, resulting in loss of efficiency in the long term. Furthermore, glass breakage can lead to hotspots, causing overheating of the panel (Fouad et al., 2017). Glass breakage was responsible for 10% of the failure cases on PV panels after two years of operation (Tas & van Sark, 2023).

4.5.3. Cracking

Cracks in a solar panel can occur during manufacturing, transportation, and following the installation of the panel (Alves dos Santos et al., 2021; Dhimish et al., 2017). Certain weather conditions like hailstorms, strong winds and heavy snow loads have the potential to cause cracks on the surface of PV panels (Dhimish et al., 2017). Moreover, PV panels have become more fragile and vulnerable to both thermal and mechanical stress because semiconductor materials have been thinner to decrease the manufacturing expenses, resulting in cracking in solar cells. Cracking can cause hotspots, moisture infiltration into the solar cells and thus corrosion, delamination, and discoloration (Alves dos Santos et al., 2021), thus a loss in overall power output of the PV panel (Dhimish et al., 2017).

4.5.4. Hotspots

Hotspots are specific regions of elevated temperature and hotspots heating happens when a solar cell is shaded, damaged or basically produces lower current than other cells connected in series in a PV panel (Aghaei et al., 2022; Fouad et al., 2017; K. Hasan et al., 2022). The cells causing hotspots waste the solar radiation as heat rather than generating electricity and deform the p-n junction (Alves dos Santos et al., 2021; Fouad et al., 2017). The power due to the shaded or damaged cells varies based on how the cells are arranged in the panel, whether in series or in parallel. Usually, increasing the amount of cells connected in series elevates power loss, whereas increasing the number of cells linked in parallel reduces the power loss due to the shaded or damaged cell (Fouad et al., 2017).

4.5.5. Characteristic resistance

The output resistance at the MPP of a PV panel represents the characteristic resistance of a PV solar cell. When the load resistance matches the characteristic resistance of the solar cell, the maximum power is transferred to the load, and the panel achieves peak performance (Fouad et al., 2017).

4.5.6. Shunt resistance

Shunt resistance is defined as any parallel high conductive routes (shunts) along the p-n junction of a solar cell or on the cell edges (E. Cuce et al., 2017). Defects in manufacturing PV panels, such as impurities, can lead to notable power reductions due to the existence of shunt resistance. A low shunt resistance allows the light-generated current to flow through an easier path, decreasing the quantity of current flowing through the solar cell and voltage output of the solar cell. Therefore, shunt current can cause cell heating and hotspot formation in the material of a PV panel (Fouad et al., 2017). Shunt resistance is really sensitive to alterations in the temperature of the solar cell (E. Cuce et al., 2017).

4.5.7. Performance ratio

Performance ratio (PR) stands out as one of the most effective performance metrics and displays the correlation between the real (measured) and theoretical (expected) energy outputs of a PV system (Fouad et al., 2017; Gopi et al., 2021). It represents the proportion of energy available for transmission to the grid after determining the energy consumed and system losses such as cable, inverter, location, shading losses (Fouad et al., 2017; Khalid et al., 2016; Lagarde et al., 2023). PR is influenced by different factors such as radiation, tilt angle, ambient temperature, module quality, design parameters, and efficiency of electrical components. The PR of a PV system consisting of hundred PV panels approximately ranges from 70% to 90%, with a median PR of around 84% (Fouad et al., 2017).

4.5.8. Maintenance and cleaning

Cleaning PV panels on a regular basis is important to maintain optimum performance since even a slight layer of dust can considerably reduce the efficiency of the panels (Fouad et al., 2017). The optimal cleaning technique should be developed according to the design and capacity of a PV system. Cleaning of a PV system can be achieved by natural, water, manual, and mechanical cleaning, and electro-dynamic screens (EDS). Rain and wind commonly clean PV panels in the natural cleaning method; therefore, the panels are generally inclined to a tilt angle to carry away the dust particles

by natural cleaning. Water cleaning technique requires a substantial amount of water at constant high pressure to effectively remove any soiling or dust accumulation on the surface of PV panels and extract unwanted heat from the panels in arid and hot environments. Manual cleaning is carried out by using special brushes with bristles designed to prevent scratches on the surface of PV panels, which is more effective than natural cleaning technique. Mechanical cleaning with an automatic water system or a robotic water spray is more effective than natural cleaning with rain or wind. EDS set on a PV panel can guarantee an automatic and continuous cleaning on the surface of the panel (K. Hasan et al., 2022).

Additionally, scheduled and proper maintenance of all parts of a PV system is required to uphold the performance of the system to an acceptable level and eliminate the unwanted power losses (Fouad et al., 2017; K. Hasan et al., 2022). For instance, the water levels in each cell of a lead-acid battery utilized in a PV system is vital for good charging and discharging cycle. Hence, water levels of the cells must be regularly checked and kept in certain levels (K. Hasan et al., 2022).

4.5.9. Sizing of a PV system

Sizing of a PV system determines energy requirements to operate the system (Fouad et al., 2017; Usman et al., 2020). The quantity of PV panels, the electricity production of each panel, the arrangements of panel connections, and the size of other components in the system are associated with the sizing of the system. A PV system must produce sufficient energy to meet the energy consumption by the loads and the system itself (Fouad et al., 2017). Its size strongly depends on the environmental factors (Khatib et al., 2013).

4.5.10. Surface area of PV panels

Energy conversion efficiency of a solar cell is determined by dividing the MPP by input solar radiation and surface area of the PV panel (Meral & Dinçer, 2011). Thus, the quantity of electrical current produced by a solar cell varies with surface area of the PV panel (Fouad et al., 2017).

5. COOLING METHODS FOR PV SYSTEMS

The conversion efficiency of PV panels mainly relies on the bandgap of semiconductors and wavelength of the solar irradiance (Verma et al., 2021). PV panels usually transform up to 20% of the solar irradiance into electric current (Allouhi et al., 2022; K. Hasan et al., 2022; Hernandez-Perez et al., 2020; Jathar et al., 2023; Ma et al., 2020). The rest of the irradiance is converted into heat energy, leading to elevated temperatures in solar cells because PV cells cannot convert all irradiance spectral wavelength (Aly et al., 2019; Hernandez-Perez et al., 2020; Jathar et al., 2023; Stropnik & Stritih, 2016; Verma et al., 2021). For instance, crystalline silicon solar cells transform solar irradiance with wavelengths ranging from 300 nanometers (nm) to 1100 nm into electricity, while the rest of the irradiance is absorbed and converted into heat energy (Jiao et al., 2024; Verma et al., 2021). Therefore, the solar cells operate at temperatures higher than ambient temperature (25°C) (Elminshawy et al., 2019; Sahay et al., 2015). Elevated temperatures in the solar cells reduce the conversion efficiency of solar cells (Dwivedi et al., 2020; K. Hasan et al., 2022; Hernandez-Perez et al., 2020; Jathar et al., 2023; Stropnik & Stritih, 2016) because it significantly decreases both V_{oc} and FF, thus output power of the PV panel even though there is a negligible increase in I_{sc} (Dwivedi et al., 2020; Hernandez-Perez et al., 2020; Sahay et al., 2015; Verma et al., 2021). Moreover, prolonged exposure to heat can cause ageing of the solar cells, potentially leading to major failures to PV panel itself (Hernandez-Perez et al., 2020; Jathar et al., 2023). Hence, different cooling methods have been innovated to diminish the elevated temperatures of PV panels, thus recovering the output power, and prolonging their lifespans.

How the cooling is conducted is critical because non-uniform cooling of a PV panel can cause serious issues such as the current matching problem. This can lead to the formation of hotspots, thus causing lasting structural damage. Therefore, a cooling method should keep the temperature of solar cells at desired levels with constant distribution over the surface of the PV panel (Bahaidarah et al., 2016; Royne et al., 2005).

Categorization of cooling methods can be made based on cooling fluid, their phase systems, including cogeneration or not, having moving components or no moving parts,

and having an external device or not (Royne et al., 2005; Sahay et al., 2015). PV cooling technologies can be classified into three groups: passive cooling (no need for energy input or an external device such as a pump, fan, and condenser), active cooling (requires energy input or an external device) and combination of passive and active cooling (Hamzat et al., 2021; Hasanuzzaman et al., 2016; Mahdavi et al., 2022). In the following sections passive and active cooling techniques for PV panels will be presented in detail. Subsequently, EC methods for PV panels, conducted experimentally, theoretically, and numerally, will be discussed separately.

5.1. Passive Cooling Methods

Passive cooling approaches are effective techniques to extract surplus heat from the surface of PV panels and do not require any energy input for an external device such as a fan, pump, and condenser. The extra heat in the panels is removed via natural convection, conduction, radiation, and evaporation (Mahdavi et al., 2022; Mariam et al., 2024). Passive cooling methods for PV panels may vary, yet they usually fall into two primary conceptual categories: heat sink like aluminum fins, or with a reservoir filled with phase change material attached to the rear surface of the PV panels and submersion of the panels in a coolant such as water (Nižetić et al., 2021). These cooling methods sustain reduced operating temperatures for the panels, and the size of the panels and design of the cooling approach greatly influences the performance of the cooling method (Koohestani et al., 2023; Mariam et al., 2024).

Passive cooling methods have received attention due to their low cost and simplicity since they do not rely on mechanical components or external energy sources (Mariam et al., 2024), thus not requiring maintenance (Mahdavi et al., 2022). However, they might not be adequate for extreme climates like hot and arid environments or periods of intense solar radiation (Koohestani et al., 2023; Mariam et al., 2024). Therefore, different coolants such as nanofluids, nanoparticles and phase change materials have been researched to enhance the performance of passive cooling techniques (Mariam et al., 2024).

5.1.1. Natural air cooling

Natural ventilation happens when air naturally circulates and dissipates heat from hot areas because of the buoyancy effect (Ibrahim et al., 2024). Therefore, it facilitates natural airflow over the front or rear surface of PV panels without an extra material or complex mechanism (Koohestani et al., 2023). As a PV panel heats up, it increases the temperature of the air layer surrounding it, causing heated air to ascend (Ibrahim et al., 2024), as demonstrated in **Figure 5.1**. Air ducts and solar chimney design configurations can be integrated into PV panels to enhance the natural air-based convection.

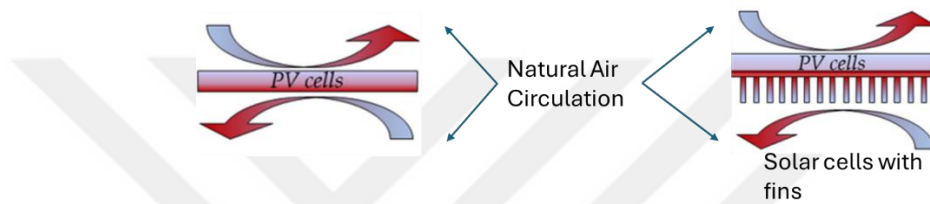


Figure 5.1. Natural air circulation with/without fins (Ibrahim et al., 2024)

Utilization of natural circulation of air is the simplest and cheapest technique for PV panel cooling (Mahdavi et al., 2022). Also, it is environmentally friendly, and highly effective in cold climates (Koohestani et al., 2023). It is especially employed to façade and rooftop building-integrated photovoltaic/ thermal (BIPV/T) systems to remove the unwanted heat from the solar cells, so increasing their efficiencies and prolonging their lifetime. A rooftop BIPV/T system with natural ventilation is shown in **Figure 5.2**.

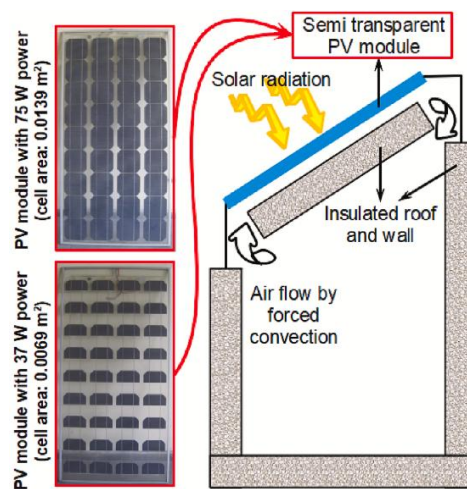


Figure 5.2. A rooftop BIPV/T system with natural ventilation (Şirin et al., 2023)

Additionally, aluminum finned plates attached to the back surface of PV panels, designed in different patterns, can be used to diminish the excess heat generated by the solar cells through natural ventilation (Mahdavi et al., 2022). The operating temperature of PV panels are maintained at desired levels by increasing the surface area of the panel with fins, which carry away the unwanted heat from the solar cells (Mariam et al., 2024).

5.1.2. Passive liquid cooling

Water has a higher specific heat capacity and thermal conductivity compared to air, making it a more efficient coolant. PV panels can directly submerge in water or evaporative effect of water can be used to dissipate heat (Koohestani et al., 2023). In addition to water, de-ionized water, isopropyl alcohol, ethyl acetate, and dimethyl silicone oil have been studied as alternative liquid for liquid immersion cooling method (Hamzat et al., 2021; Koohestani et al., 2023). When selecting the optimal liquid for liquid immersion, factors such as optical transmittance, refractive index, and optical stability of the liquid must be considered (Koohestani et al., 2023).

The evaporative effect of water can be used by wick structures mounted on the rear side of PV panels. The wicks dipped in a water reservoir absorb water and passively carry it to the backside of the panels, where it removes excess heat and evaporates (Hasanuzzaman et al., 2016; Maleki et al., 2020).

Immersing PV panels in water or other alternative liquids serves as a highly effective passive cooling technique because it maximizes the contact area between water/liquid and the panels and removes thermal resistance, and unwanted heat can be extracted from both side of the panels (Koohestani et al., 2023; Mahdavi et al., 2022). It is particularly advantage method in areas where both the ambient temperature and solar irradiance are large during the year (Mahdavi et al., 2022). It proves highly efficient and widely researched for concentrated PV systems (Koohestani et al., 2023). However, PV panels must be submerged in clean water rather than a lake or polluted river because the glass surface of the panels can be block or contaminated by undesired layer formations or coating, reducing the solar irradiance penetration into the panel surface. Cleaning these formations is challenging, and insufficient (Velmurugan et al., 2022). Moreover, there is a long-term degradation due to liquid environment and optical losses due to the thickness of the coolant, which affect the overall power output and lifetime of PV systems (Koohestani et al., 2023).

Furthermore, solar panels can be floated on a water reservoir to benefit from the cooling effect of the water. It is an effective and clean cooling technique, especially for large solar farms, to extract the excess heat and maintain optimal efficiency for the PV panels. The installation expenses for floating PV panels are 15% higher relative to those for solar panels installed on land, but the operation and maintenance expenses are lower. Moreover, positioning PV panels on a lake, canal, dam, or pond can limit algae growth due to the shading effect, leading to a decrease in water contamination (Mahdavi et al., 2022).

5.1.3. Heat pipe cooling

A heat pipe is a device that facilitates significant heat transfer between its evaporation and condensation sections. It operates in a small passive refrigeration cycle (Koohestani et al., 2023; Mahdavi et al., 2022; M. Sharaf et al., 2022). The working liquid circulates through capillary tubes (Koohestani et al., 2023; Mariam et al., 2024). When it is connected to a PV system, the evaporation section absorbs the extra heat generated by the PV panels and subsequently releases the heat through the condensation section (Koohestani et al., 2023; Mahdavi et al., 2022). There is a sustain equilibrium temperature between evaporator and condenser. A cross-section of a heat pipe is displayed in **Figure 5.3** (Mariam et al., 2024).

This passive method is particularly suitable for PV systems operating in areas with high-latitude or cold environments (Mahdavi et al., 2022). Even though heat pipes are expensive equipment, they possess great heating capacity and efficiency. The heat capacity of the pipe material determines the system efficiency of heat pipes. Also, the type of working liquid, filling ratio, and inclination angle are parameters that impact the efficiency of heat pipe cooling method (Koohestani et al., 2023).

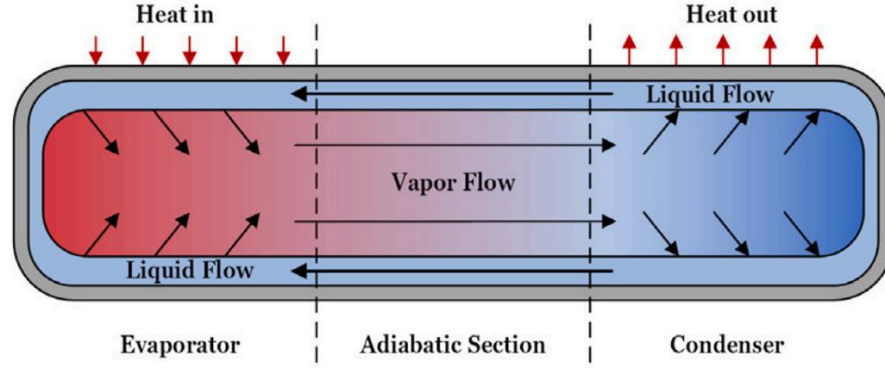


Figure 5.3. The cross-section of a heat pipe (Mariam et al., 2024)

5.1.4. Phase change materials cooling

PCM possess a high latent heat of fusion, enabling them to change from solid to liquid and vice versa within a narrow temperature interval, thereby storing and releasing substantial amounts of heat (Hasanuzzaman et al., 2016; Ibrahim et al., 2024; M. Sharaf et al., 2022). Therefore, they are suitable for passive cooling technologies for PV panels and can be incorporated at backside of the panels to remove the unwanted heat until the temperature of PCM increases to their melting point, and liquid state, sustaining the panels at desired temperature range for a certain period (Ali, 2020; Ibrahim et al., 2024; M. Sharaf et al., 2022). Subsequently, when the sun is not present, PCM releases the heat absorbed during the day to the surroundings or the heat stored can be utilized in thermal applications, resulting in decrease its temperature (Ibrahim et al., 2024; M. Sharaf et al., 2022), as demonstrated in **Figure 5.4**. As a result, this passive cooling cycle enhances the overall efficiency, and lifespan of the solar panels (Ibrahim et al., 2024; Kandeal et al., 2020; Maleki et al., 2020; M. Sharaf et al., 2022). PCM cooling improves the efficiency of the panels by around 2% to 6%. The efficiency enhancement significantly relies on PV panel size, design of the PV and cooling system and the location of the system (Nižetić et al., 2021).

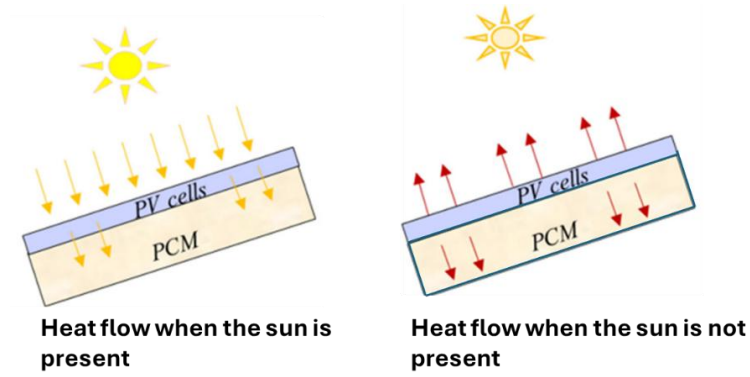


Figure 5.4. Working principle of PCM cooling system for PV solar cells (Ibrahim et al., 2024)

5.1.5. Radiative cooling

Radiative cooling is a passive cooling method that enhances the cooling effect by altering the spectrum of emissivity of PV panel surfaces with a spectral selective surface located on top of the PV cells. It basically increases the thermal emissivity of the cells while sustaining effective solar absorption (Kandeal et al., 2020; Nižetić et al., 2017). As seen in **Figure 5.5**, radiative cooling is employed a PV panel by integrating a thin layer with high emissivity, within the wavelength range from 8 to 13 micrometer (μm), onto the top surface of the panel.

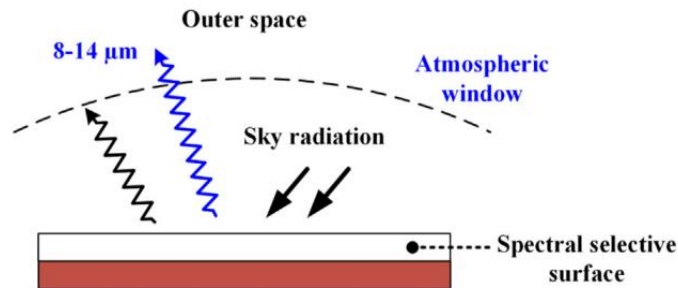


Figure 5.5. Radiative cooling method for a PV panel (Kandeal et al., 2020; Koohestani et al., 2023)

5.2. Active Cooling Methods

Active cooling methods are promising approaches to subtract excess heat from PV panels in a certain point by utilizing an external source of energy or electric energy produced by the panels, and an additional device such as a fan, and pump that circulate the coolant like water or air (Hasanuzzaman et al., 2016; Maleki et al., 2020). These

methods are used in situations where the extra efficiency provided by the cooling system is greater than the energy consumed by a fan, pump, or condenser (H. Sainthiya & N. S. Beniwal, 2017). Forced convection is the primary factor of active cooling methods (Bilen & Erdoğan, 2023). Air-based active cooling methods are generally used in hot areas with water scarcity, although they possess limited-performance, as air has a low density and heat capacity (Elminshawy et al., 2019). In comparison to the passive cooling methods, active cooling methods usually have a larger ability to subtract heat from PV panels, particularly in hot and arid climates, leading to higher electrical efficiency of the PV cells (Gharzi et al., 2020; Kane et al., 2017; Koohestani et al., 2023; Siah Chehreh Ghadikolaie, 2021). However, an active cooling system must carefully be designed based on the application of a PV system and climate conditions to obtain maximum efficiency (Nižetić et al., 2021).

5.2.1. Cooling with forced air

Air based active cooling methods use forced air convection provided by a fan or blower to remove the unwanted heat from PV panels (Gharzi et al., 2020; Siah Chehreh Ghadikolaie, 2021). The forced airflow is generally employed through channels, or a duct attached to the backside of the panels or directly on the front side of the panels to cool down the solar cells with enhanced heat transfer (Koohestani et al., 2023; Nižetić et al., 2021) as shown in **Figure 5.6**.

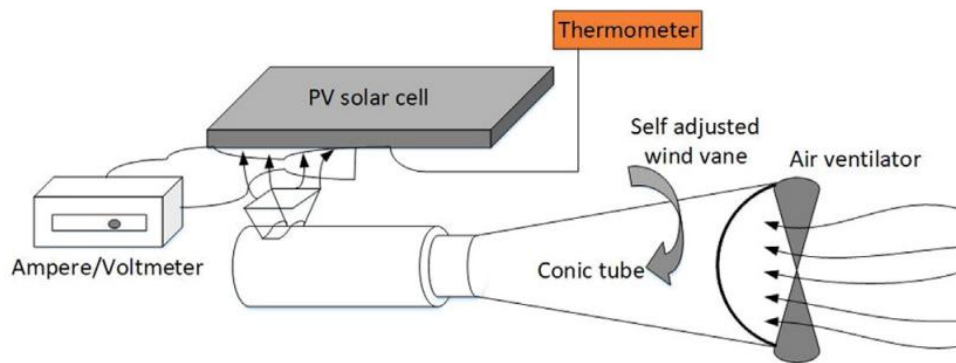


Figure 5.6. An active air-cooling system with wind tunnel for PV panels (Abdelrazik et al., 2018)

Low operation expenses and not requiring complicated components are two key advantages of active cooling methods (Siah Chehreh Ghadikolaie, 2021). However, they

demand larger power input to reach the same cooling efficiency of cooling with forced liquid due to poor thermal properties of air. Active forced air flow cooling is still widely utilized in rural areas with limited water sources (Royne et al., 2005).

5.2.2. Cooling with forced liquid flow

Liquid based active cooling methods utilize liquid flow through a tube mounted on the backside of PV panels or directly on the rear or front side of PV panels to extract excess heat, thus recovering the efficiency of the panels (Dwivedi et al., 2020). The liquid flow is typically provided by a pump. The PV panels must be air- and waterproof, and corrosion resistant (Hamzat et al., 2021). Water is a preferable coolant due to its good thermal properties. Extracted heat can be used for heating applications (Sahay et al., 2015).

Water or other liquids, such as nanofluids, and chemical fluids, can continuously be run over either front side or rear side of a PV panel as forming a thin water film, which is called liquid film cooling method, to uniformly cool the panels (Dwivedi et al., 2020). This cooling method is one of the best cooling alternatives among active cooling methods due to delivering uniform temperature distribution profile on the front surface of a PV panel (Mah et al., 2019). Also, water film prevents dust accumulation, and cleans the surface of solar panels (Siah Chehreh Ghadikolaei, 2021). Water/liquid flow rate defines the effectiveness of the cooling. Heat extraction for the same amount of cooling fluid is larger at higher solar radiation conditions (Mah et al., 2019).

Another active cooling method using forced water/liquid flow is jet impingement (also known as liquid spray) that dissipates excess heat from the back side of PV panels by cooling fluid pumped through nozzles (Pathak et al., 2022; Sato & Yamada, 2019). It has the ability to extract a large quantity of heat (Bahaidarah et al., 2016). The number of nozzles, nozzle pitch, nozzle geometry and distance between nozzles and PV panels are the key factors influencing the effectiveness of the cooling system. This cooling method is proper to control the temperature of solar cells (Siah Chehreh Ghadikolaei, 2021).

5.2.3. Microchannel cooling

Microchannels, small thermal sinks, using nanofluids, water or air can extract high amount of heat from a small area and be integrated to PV solar cells to keep the

temperature of the cells in desired levels (Bahaidarah et al., 2016; Dwivedi et al., 2020; Royne et al., 2005). They have varying channel designs such as rectangular, and circular, having dimensions differ from 10 μm to 200 μm (Dwivedi et al., 2020; Koohestani et al., 2023; Pathak et al., 2022). Microchannels are commonly classified as either single phase or two phase based on whether utilizing uniform or non-uniform fluids (Koohestani et al., 2023). They can be combined with jet impingement (Bahaidarah et al., 2016). PV cooling systems with microchannels are active cooling methods because they involve forced air or a heat transfer fluid; therefore, they also known as active heatsinks (Gharzi et al., 2020), as illustrated in **Figure 5.7**. The flow of the coolant in the microchannels is usually laminar and can drop the temperature of a solar cell up to 15 $^{\circ}\text{C}$, leading to a 14% increase in the power output of the cell (Dwivedi et al., 2020).

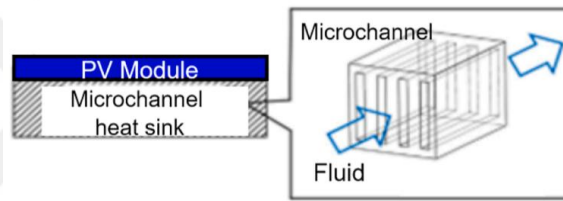


Figure 5.7. An active microchannel cooling for PV panels (Pathak et al., 2022)

5.2.4. Thermoelectric cooling

Thermoelectric cooling method uses silent, reliable, durable, and compact, solid-state components that comprise of negative and positive semiconductors, can sensitivity and accurately control the temperature by converting electric energy into a temperature difference and a temperature difference into electric energy (Gharzi et al., 2020; Pathak et al., 2022; Shukla et al., 2017). This method cools down solar cells by consuming electric energy and generates electric energy from the temperature differentials of the cells (Pathak et al., 2022). The solar cells are cooled by small electrical current that passes through the junction of two different wires, so the junction experiences a reduction in temperature, which phenomenon is known as Peltier effect (Bilen & Erdoğan, 2023). Thermoelectric colling systems are commonly attached to the rear side of PV panels and can be combined with water cooling systems, and PCM colling methods.

6. EC SYSTEMS USING POROUS MATERIALS

Evaporation occurs at temperatures lower than the boiling point, involving the transfer of mass from the liquid phase to the vapor phase. The driving force for evaporation is the concentration difference, likewise any other mass transfer process. In the evaporation process, substances generally move from regions with high concentration to those with low concentration (Haidar et al., 2018). Overall evaporation rate and the cooling effect due to evaporation are mainly affected by air temperature, air movement, relative humidity, and surface area exposed to the evaporation (V. Suresh et al., 2013).

EC occurs as a small fraction of coolant changes phase and dissipates the excess heat away from a surface (Alami, 2014). It describes a latent heat cooling process in which a coolant evaporates, establishing equilibrium with its vapor in the surrounding air and producing a cooling effect (Haidar et al., 2018). Commonly implemented in residential and industrial contexts, this concept is also employed to decrease PV panel temperatures (Haidar et al., 2018; Y. Yang et al., 2019).

EC systems are simple, sustainable, efficient, cost-effective, eco-friendly, and energy saving cooling methods, and highly effective in hot and arid climates (P. M. Cuce & Riffat, 2016; Poddar et al., 2022; Walsh et al., 2013; Y. Yang et al., 2019; Zheng et al., 2020). Therefore, they possess a great capability for managing PV panels operating temperature in hot and dry environments (Haidar et al., 2018). However, they have a limited capacity for humid climates since the air is close to the saturation, and a coolant/water increases the humidity inside a space while lowering the temperature (P. M. Cuce & Riffat, 2016; Lucas et al., 2017). EC systems can function as passive or active, depending on whether they require energy input or an external device (Alami, 2014; Kapilan et al., 2023).

EC systems are categorized into three types: direct, indirect and multistage EC systems (Kapilan et al., 2023). In direct EC systems, there is a contact between coolant and air and they decrease air temperature by utilizing the latent heat evaporation (P. M. Cuce & Riffat, 2016; Kapilan et al., 2023; Zhao et al., 2008). They increase the humidity up to 70 to 90%, so the humidified moist air must be continuously extracted to maintain the evaporation process (Sajjad et al., 2021). These systems are suitable for hot and arid

climates, and more effective when compared to indirect EC systems (P. M. Cuce & Riffat, 2016; Kapilan et al., 2023). On the other hand, in indirect EC systems, air temperature is reduced without changing its humidity level, making them more appealing choice relative to direct EC systems (Duan et al., 2012; Zhao et al., 2008). The characteristics of the heat/mass exchanging medium (also called wall) such as fibers, and ceramics, are important for indirect EC systems, as they impact the performance and efficiency of the systems (Zhao et al., 2008). Multistage cooling systems combine both direct and indirect EC processes (Kapilan et al., 2023).

EC systems for PV panels have been designed and experimentally examined in the literature. These studies aimed to enhance the overall performance and efficiency of PV panels by sustaining the solar cell operation temperature within desired levels, thereby reducing the negative effects of excessive temperatures on the panels' power output. In this section, experimental studies of EC systems using porous materials for PV panels are presented in detail and organized according to the materials and techniques employed in their evaluation.

6.1. EC System Using CWs

Chandrasekar et al. (Chandrasekar et al., 2013) developed a simple passive cooling system with CW structures mounted on the back surface of a PV panel in circular ring configuration. The free end of CWs was immersed in a reservoir filled with coolants. Water, Copper oxide (CuO)/water and aluminum oxide (Al₂O₃)/water nanofluids were used as coolant, which are absorbed and carried to the back side of the panel by CWs. The experimental results were compared with those of a reference PV panel without any cooling. There was a 30% decrease in the PV panel surface temperature, and a peak panel efficiency of 10.4% was achieved with utilization of wick structures in combination with water. The nanofluids were not as effective as water in terms of lowering the temperature.

Additionally, a passive EC system consisting of CWs structures in combination with heat spreaders were utilized by Chandrasekar and Senthilkumar (Chandrasekar & Senthilkumar, 2015) to control the temperature of PV panels. Similar to (Chandrasekar et al., 2013), the cooling components were positioned at the back side of a PV panel, with the free ends of the wicks submerged in water stored in the headers, and a reference PV panel is used for comparison. The temperature of the panels was measured with thermocouples placed on the back surface at five different points. Aluminum spikes were

also used as stiffeners to maintain proper contact between the wicks and spreaders and to prevent sagging of the wicks. The experimental setup, along with the steps involved in its fabrication was demonstrated in **Figure 6.1**.

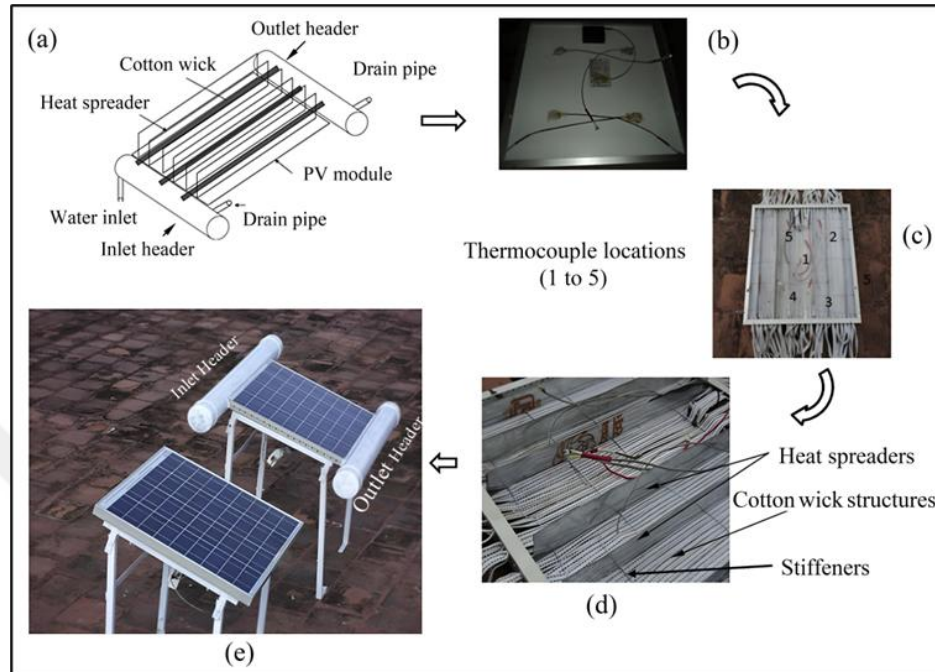


Figure 6.1. Demonstration of the experimental setup with the steps involved in its fabrication. (a) The rear side of the panel; (b) Thermocouple locations; (c) The CWs structures in combination with the spreaders; (d) The components of the EC system in detail; (e) The finalized experimental setup (Chandrasekar & Senthilkumar, 2015)

As a result, there was a 12% reduction in the temperature of the PV panel, resulting in a 14% enhancement in electrical power output of the panel, due to the cooling effect provided by the evaporation of water and the fin effects of the spreaders.

Furthermore, Alktrane and Bencs (Alktrane & Bencs, 2022) used the EC effect of CWs immersed in water at the rear side of PV panels. The temperature of a PV panel reduced by 22%, creating a 53% increment in the efficiency of the panel. Moreover, Alktrane and Bencs (Alktrane & Péter, 2023) repeated this passive EC method with pure water rather, and compared the outcomes with those of a PV panel cooled by rectangular aluminum fins (RAFs) and an uncooled reference panel. The passive EC system, utilizing CWs submersed in pure water, exhibited a similar temperature reduction of 22.3%, as (Alktrane & Bencs, 2022) asserted, leading a 73% increase in the power output of the panel. Although utilization of pure water caused an additional expense in the system, and slightly increased the temperature reduction, it was significant, as salts in

regular water impair the wicks' absorption capacity by adhering to their surfaces. A PV panel with the EC, a PV panel with RAFs, and the panels with both the EC, and RAFs are shown in **Figure 6.2** (a), (b), and (c), respectively.

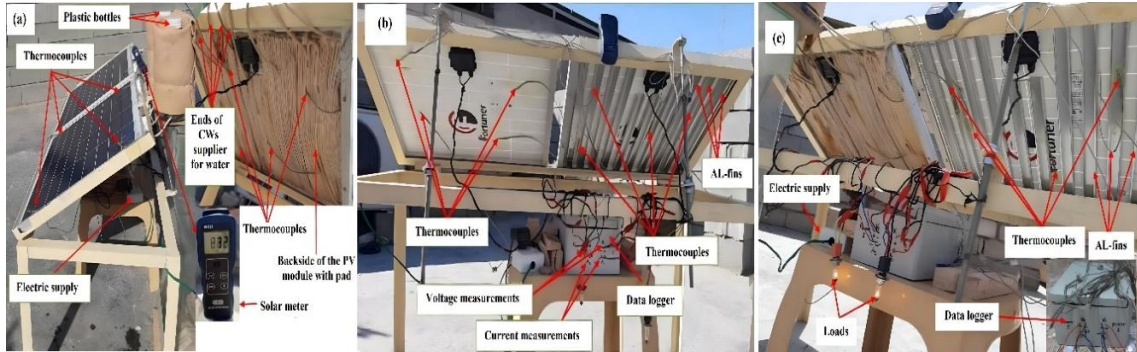


Figure 6.2. (a) Experimental setup of the passive EC system with CWs structures; (b) Experimental setup of the cooling system with RAFs; (c) Experimental setups of both cooling systems (Alktranee & Péter, 2023)

The EC displayed better performance in comparison to RAFs cooling. The experimental results from both cooling methods are presented in **Table 6.1**.

Table 6.1. The experimental results from both cooling methods

Cooling Methods	Temperature Reduction (%)	Increment in Power Output (%)	Increase in the Efficiency of the Panels
EC with CWs	22.3	73	97.6
RAFs Cooling	6.7	13.8	34.2

Likewise, Chandan et al (Chandan et al., 2022) experimentally evaluated the influence of an EC using CWs located at the rear surface of a PV-thermoelectric generator hybrid system, and compared it to an active air-cooling system (low and high flow rates) and an active water-cooling system in outdoor and indoor settings. The CWs cooling, air cooling and water cooling decreased the temperature of the PV panel 22% (14°C), 7% (approximately 4 °C), and 47% (around 30 °C), respectively. Consequently, the active water-cooling method was more effective in terms of reducing the temperature of the panel, yet the EC with CWs was a viable option regarding the expenses and complexities related to the active cooling systems.

CWs structures were suitable for PV cooling systems because they absorb water fast and can evenly distribute it over the rear side of a PV panel due to having a great

absorbent capacity, they are easy to obtain, maintenance-free, and chemically inert with respect to the panel's back layer (Alktranee & Bencs, 2022; Alktranee & Péter, 2023).

6.2. EC Cooling Using Cloths and Fabrics

An EC system utilizing cloth and rubber pipes was introduced by Haidar et al (Haidar et al., 2018) to regulate the temperature of PV panels. The cloth and rubber pipes were attached to the rear side of a PV panel, which remained open and in direct contact with the ambient air. The cloth was placed in direct contact with the back surface of the panel and aluminum bars were used to keep the cloth taut and in contact with the rear surface, preventing any gaps between the panel and the cloth. A valve was positioned between a water reservoir and pipes to manually regulate the water flow that was provided via gravity. The cooling system did not include a fan or a complex system. Wet cloth creates a gradient between the water vapor concentration at the water–air interface (saturation layer) and the surrounding dry air. This gradient instigates water evaporation, which absorbs heat from the PV panel and lowers its temperature. The EC system on the back surface of the panel and experimental setup are shown in **Figure 6.3** (a), and (b), respectively.

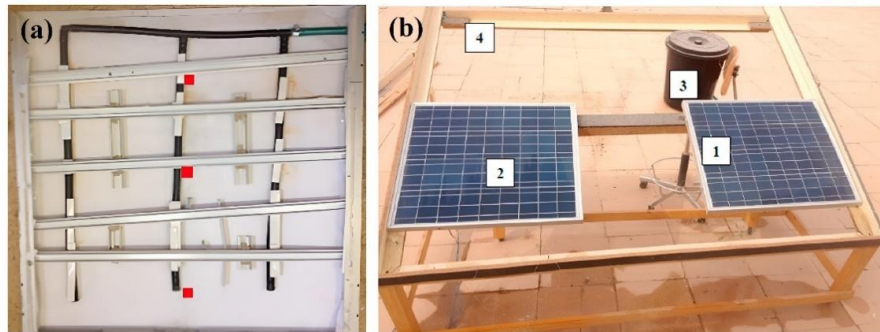


Figure 6.3. (a) The back surface of a PV panel with the EC system; (b) Experimental setup (no.1: a PV panel with the cooling system, no.2: a reference PV panel without a cooling system; no.3: water reservoir; no.4: the wooden frame) (Haidar et al., 2018)

Consequently, compared to a reference panel without cooling, the cooled panel's temperature experienced a significant decrease of more than 20 °C, accompanied by an approximately 14% rise in electrical power generation.

In addition, Dida et al (Dida et al., 2021) developed a passive, environmentally friendly, cheap, and noiseless evaporative system based on the capillary action of burlap

cloth to reduce the temperature of PV panels at desired levels. The aim was to maintain the efficiency of the panels at optimum range by extracting the excessive heat. Therefore, the cloth was directly attached to the back surface of a PV panel, with its upper part submerged into water supplied from a 50-liter (L) tank positioned above the panel. The capillary action of cloth, and gravity transferred water to the back surface of the panel. Unabsorbed water was recovered from a bottom hole in the panel via an elastic hose connected to a small water tank. The temperature of the panel was reduced by 20 °C, which was corresponding to 26% reduction, leading to a significant increment of 14.75 in electrical efficiency in comparison to a reference PV panel without cooling. Moreover, this EC system delivered a homogenous temperature distribution over the panel with a relatively small amount of working fluid.

Furthermore, a gravity-assisted passive EC system utilizing single- and double layers of burlap fabric attached to the rear surface of a PV panel by Malvika et al (Malvika et al., 2022). Additionally, in a scenario referred to as the anti-gravity mode, the bottom of burlap cloth was dipped into a reservoir located below the panel; therefore, water had to move upward against gravity towards the rear surface of the panel. The flow mechanism of the gravity-assisted EC is exhibited in **Figure 6.4**.

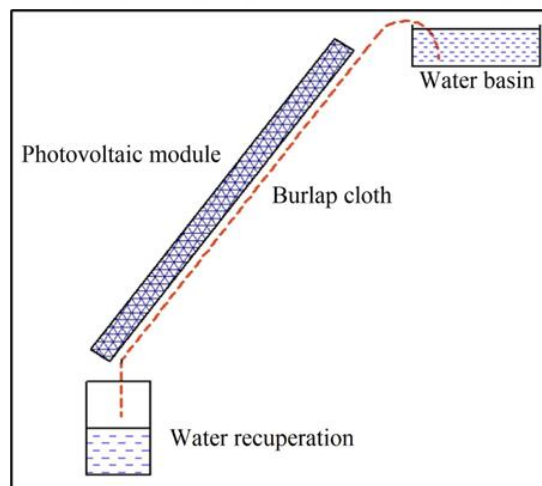


Figure 6.4. The flow mechanism of the gravity-assisted EC system (Malvika et al., 2022)

Malvika et al (Malvika et al., 2022) compared the experimental results from the EC systems to experimental results from a PCM cooling carried out in the same conditions. It was determined that both EC system configurations outperformed the PCM cooling. The temperature drops and efficiency improvements from these cooling methods are presented in **Table 6.2**.

Table 6.2. Experimental results of the EC systems utilizing burlap cloth and the cooling system using phase change material

Technique	Increase in Electrical Efficiency (%)	Temperature Drop (°C)
EC with single layer burlap cloth (Gravity-assisted)	3-18	15.6
EC with double layer burlap cloth (Gravity-assisted)	18-21	21.1
EC with single layer burlap cloth in anti-gravity mode	13	8.7
The cooling method with PCM	2	8.1

What's more, Almuwailhi and Zeitoun (Almuwailhi & Zeitoun, 2023) investigated the impacts of natural convection, evaporative natural convection, forced convection and evaporative forced convection on energy output and efficiency of PV panels. An insulated channel was installed on the back of a polycrystalline PV panel for natural convection. Wet fabric was to promote evaporative natural convection through the cooling channel, while air flow over the fabric enabled evaporative convective cooling. The air flow was provided by fans.

Natural convection increased the efficiency of the PV panel and electric energy generation by 1.7%, and 1.2%, respectively, with employinh air gap of 120 mm. Natural convection cooling was more effective with wider cooling channel. On the other hand, forced convection was more efficient with higher air velocities. Improvements in efficiency and daily electrical energy output of the panel with 3 m/s of air velocity were around 4%, and 4.4%, respectively.

Energy output rose by 3.6%, and panel efficiency improved by 2.7% when the panel was cooled down with evaporative natural cooling while evaporative forced cooling improved the efficiency of PV panel by 3.8% and its daily energy production by 3.8% at speed of 2 m/s.

Moreover, an active phase change cooling system applied in PV panels for thermal regulation and efficiency improvement was designed, facilitated, and experimentally investigated by Wang et al (Y. Wang et al., 2019) based on porous media(non-woven fabric). Ethanol was utilized as coolant. To achieve uniform coolant distribution in the porous layer on the back surface of a PV panel, a liquid distributor was designed. Ethanol was delivered by gravity from a storage tank above the panel to the distributor, sustaining a constant inlet temperature. Ethanol absorbed the excess heat from the panel by

evaporating and then the remaining liquid ethanol flowed into the storage tank. Vaporized ethanol was directed toward a condenser by a fan, where it was condensed. The condensed ethanol was directed back into the storage tank, so it was recovered and can be resented into the cooling system. The experiments were carried out in laboratory conditions, where an artificial solar simulator generated the solar radiation. The experimental setup is presented in **Figure 6.5**.

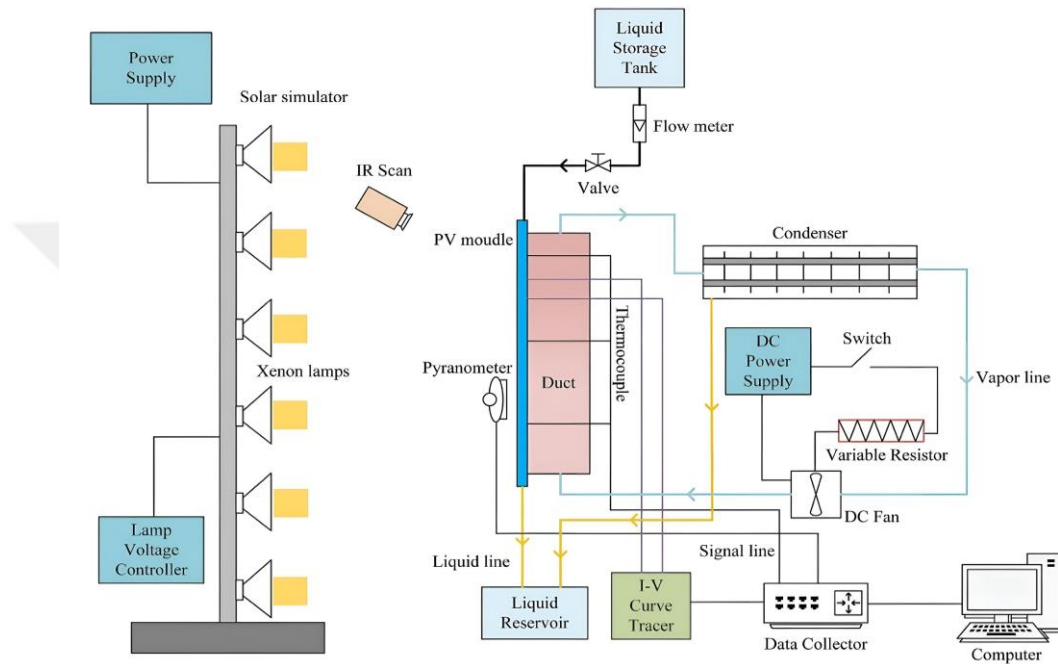


Figure 6.5. The schematic illustration of the experimental setup (Y. Wang et al., 2019)

Under a solar radiation of 900 W/m^2 , the electrical energy output increased by 19.32%, and the efficiency improved by 18.40%. The maximum specific power improvement was 21.37 W/m^2 . Ultimately, it was indicated that the active phase cooling system significantly enhanced the PV panel's electrical energy output and efficiency, so it offers a promising solution for advancing PV technology.

6.3. EC System Using Wood Wool

An passive EC using wood wool material as the cooling medium in combination with aluminum alloy heat sink structures was designed by Hasan et al (Ahmed Hasan et al., 2019) for PV panels. The heat sink structures, pin fins, enlarged the surface area of heat transfer, hence enhancing the cooling due to evaporative effect. Therefore, the moist

wood wool pad was arranged to maintain complete contact with the surface of the heat sink. The heat sink structures covered with wood wool material on the rear surface of the PV panel and a reference PV panel without the cooling system are displayed in **Figure 6.6** (a), and (b), respectively.

The wood wool pad was sustained at desired moisture levels by a continuous water flow supplied from a water tank through gravity force. The water mass flow rate was regulated by a fixed valve installed in the supply hose, allowing a steady distribution of water onto the wood pad through a perforated pipe.

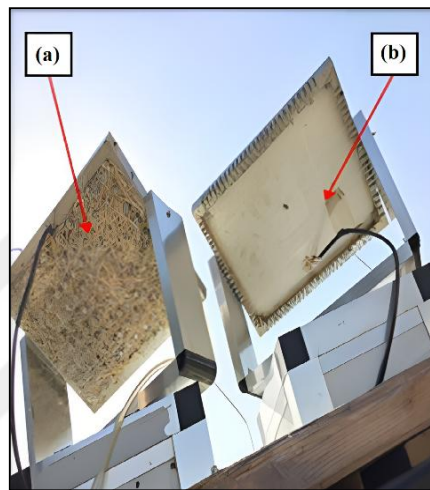


Figure 6.6. (a) The panel with the EC system; (b) The reference panel without cooling (Ahmed Hasan et al., 2019)

The experimental results highlighted that the PV panel achieved nearly a 27% reduction in temperature, which corresponded to a 32.7% enhancement in output power and a 31.5% improvement in efficiency relative to the reference panel.

6.4. EC System Using CP

Water from a small buried underground tank was utilized as a working fluid for an active EC system developed by Kadhim and Aljubury (Kadhim & Aljubury, 2020) to control the temperature of PV panels. The water tank was buried to maintain the temperature of water, at around 18.5 °C, lower than the daily ambient temperature. The cooling system consisted of a CP mounted at the rear surface of a PV panel and nozzles placed on the front side for spray cooling and surface cleaning. The CP was saturated by water from the underground tank through a perforated pipe positioned at the top of back

surface of the panel. Water was sent to the pad by a small water pump via the perforated pipe. The sketch of the front and back views of the active EC system are shown in **Figure 6.7**, and **Figure 6.8**, respectively.

The experiments were conducted in different cases. There was an average temperature drop of 4 °C on the temperature of the PV panel, and 1.74% enhancement in electrical efficiency for the first case that only considered back surface cooling. In the second case, both back surface cooling and frontside spray cooling were applied, which reduced the panel temperature by nearly twice as much and yielded a 1.06% higher electrical efficiency compared to the first case. Additionally, varying water flow rates were tested to achieve optimal cooling performance.

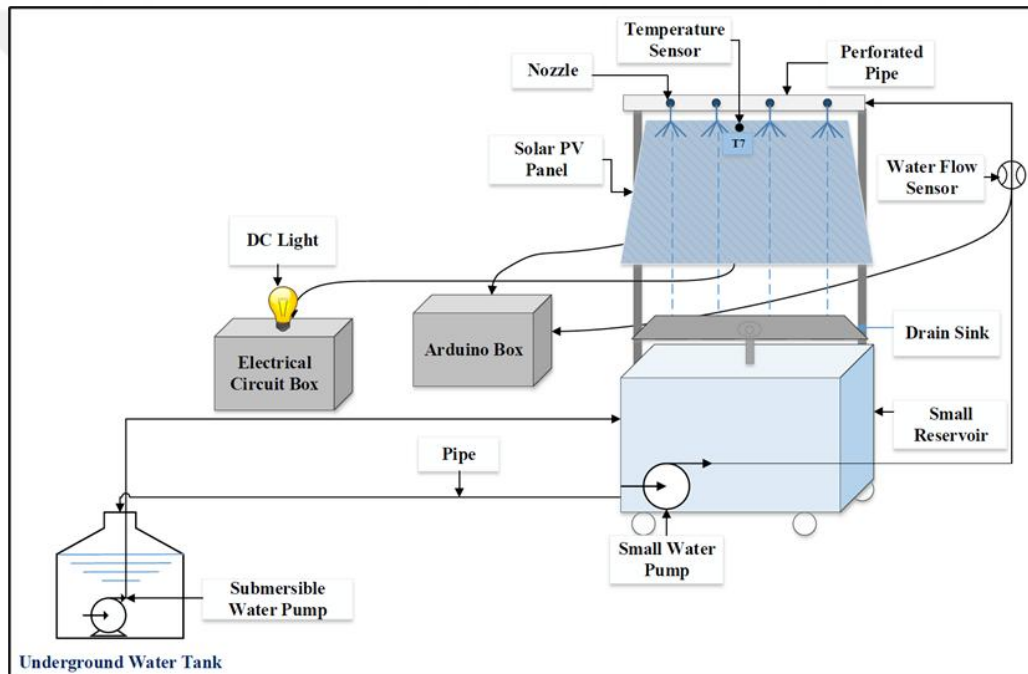


Figure 6.7. The front view of the active EC system (Kadhim & Aljubury, 2020)

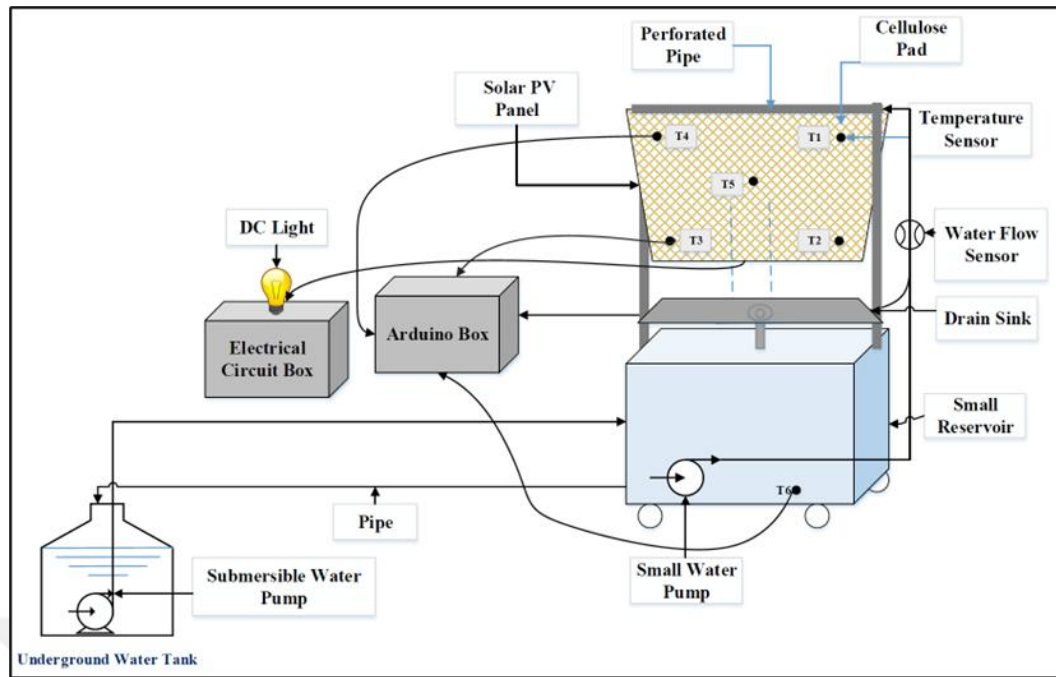


Figure 6.8. The back view of the active EC system (Kadhim & Aljubury, 2020)

Finally, it was stated that the usage of underground water is associated with sustainable practices, and the experimental findings provide a basis for further investigation and optimization of such integrated cooling strategies in PV technologies.

6.5. EC System Using Hydrophilic Pad

A water EC system using a hydrophilic pad manufactured from a blend of polypropylene and synthetic fiber was introduced by Jirapongphatai et al (Jirapongphatai et al., 2023) to reduce the temperature of PV panels, thus improving their electrical energy production. The hydrophilic pad was attached to the back surface of a PV panel, and the performance of the panel was experimentally investigated. Water was transferred to the pad through a small pump from a water storage tank, with varying flow rates and inlet temperatures. The test results from the cooled panel were compared to the results from an uncooled reference panel. A schematic presentation of the experimental setup, and back surface of the PV panel equipped with the hydrophilic pad are exhibited in **Figure 6.9** (a), and (b), respectively.

In summary, an approximately 46% temperature reduction could be achieved when the temperature of the PV panel was higher than 70 °C, resulting in a 10% increase in the total electrical generation. The panel produced greater electric energy in higher

water flow rates and lower inlet water temperatures. There was a 6.5% to 11.1% increment in net power output when the temperature of inlet water ranged from 20 °C to 30 °C.

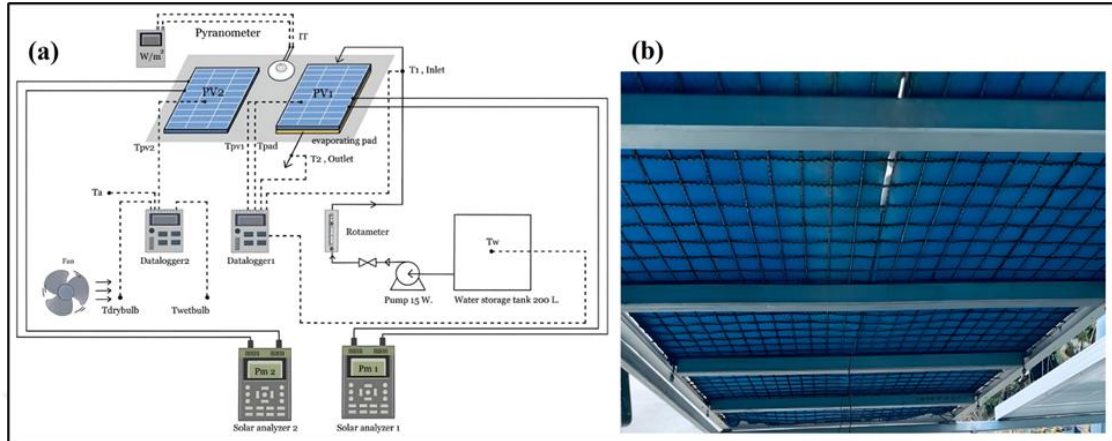


Figure 6.9. (a) Experimental setup; (b) Back surface of the PV panel with the hydrophilic pad (Jirapongphatai et al., 2023)

7. MATERIAL AND METHOD

In this thesis, EC systems with underground cooling were designed and then manufactured to prevent the decline in electrical power output of PV panels caused by overheating. The systems include three open-water-based systems: one equipped with a CP, one using WCs, and another using HRs. The influence of the EC systems on the temperature and efficiency of PV panels was evaluated by conducting a series of experiments for each system and its configurations.

The experimental setup and its modified versions used for these systems were stationed in Batman University Central Campus at 37°54'18" North and 41°07'47" East coordinates in Batman province where the climate is extremely hot and arid in summer season. The experiment site was not impacted by any shading factors. The electrical and mechanical equipment used in the experimental setup were compact and operated in a harmony. In order to adjust the orientation of the solar panels in the optimal south-facing direction, the time with the highest solar elevation angle on the adjustment day was determined using NOAA Solar Calculation Software, and the panels were positioned due south at that time and maintained in that position during the entire experimental period.

The experiments for all systems were carried out in July 2025 under outdoor conditions. Data was collected between 10:00 and 16:00 local time, both automatically every 15 min using a data logger and manually at the same intervals to ensure the accuracy of the measurements. Although three thermocouples were attached to the back of the cooled panel and one was placed at the center of the reference panel, with temperature data collected using a data logger, the average panel temperatures obtained from thermal camera readings were considered in all measurements, as the thermal camera is capable of providing more accurate results and can deliver the average temperature of the entire panel rather than being limited to only three discrete points.

The same panels were used for all EC systems. A characterization process was conducted to eliminate manufacturing mismatches among the panels. A weather station was installed at the experimental site to record meteorological data. The same measurement tools were employed for all EC systems. The specific methods and materials for each EC system are detailed in separate sections. Prior to data collection,

the pump was activated for a duration equivalent to the intended measurement period. The pump operated consistently at 10 V, 1.73 A, 17.3 W when the liquid distribution system was used. Additionally, manual spraying was conducted on the back side of the cooled panel for the cooling systems. It was performed at 30-min intervals for all systems, with the initial spray applied 30 min prior to the start of data collection. During the manual spraying on the rear side of the panel, the pump remained off. The underground water temperature ranged between 25.5 °C and 26 °C throughout all water-based experiments.

7.1. Characterization Process

Although both PV panels were almost identical, a characterization process was carried out to eliminate manufacturing mismatches that could be significant for sensitive comparative studies. In the characterization process, the energy values generated by both panels were assessed during the day by an Amprobe Solar-600 Solar Analyzer under solar radiation levels of 700 W/m², 800 W/m², and 900 W/m², and subsequently cooled PV panel was calibrated with respect to the reference panel. As a result, the calibration coefficient, *k*, (also called the power validation coefficient) was calculated by equation 7.1 and then employed to all test results. The average calibration coefficient was 1.04, indicating good agreement between the panels.

$$k = \frac{P_{mpp,reference\ PV\ Panel}}{P_{mpp,cooled\ PV\ Panel}} \quad (7.1)$$

The results of the calibration test of PV panels are presented in **Table 7.1**, and the correlations between the I-V and solar radiation, and between P-V curves and solar radiation, are illustrated in **Figure 7.1** and, **Figure 7.2**, respectively.

Table 7.1. The findings from the calibration test of PV panels

Parameters	700 W/m ²		800 W/m ²		900 W/m ²	
	Reference Panel	Cooled Panel	Reference Panel	Cooled Panel	Reference Panel	Cooled Panel
V _{oc}	21.03	21.34	21.03	21.40	21.06	21.40
I _{sc}	0.945	0.96	1.13	1.13	1.33	1.34
V _{mpp}	16.37	16.52	16.26	16.82	16.56	16.72

I_{mpp}	0.85	0.86	1.02	1.02	16.16	1.18
P_{mpp}	13.91	14.20	16.58	17.56	19.20	19.80
Panel Efficiency	12.57	13.53	13.82	14.64	14.23	14.67
FF	0.70	0.69	0.70	0.71	0.69	0.69

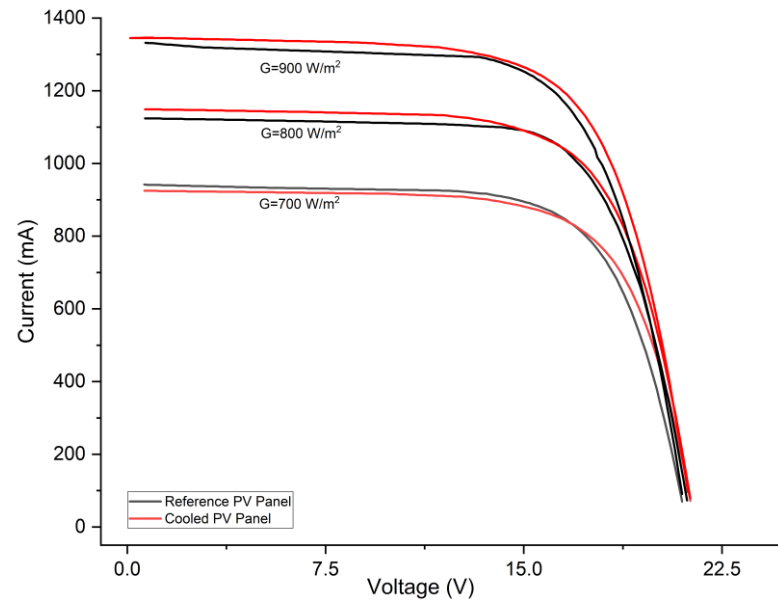


Figure 7.1. The relation between I-V curve and solar radiation

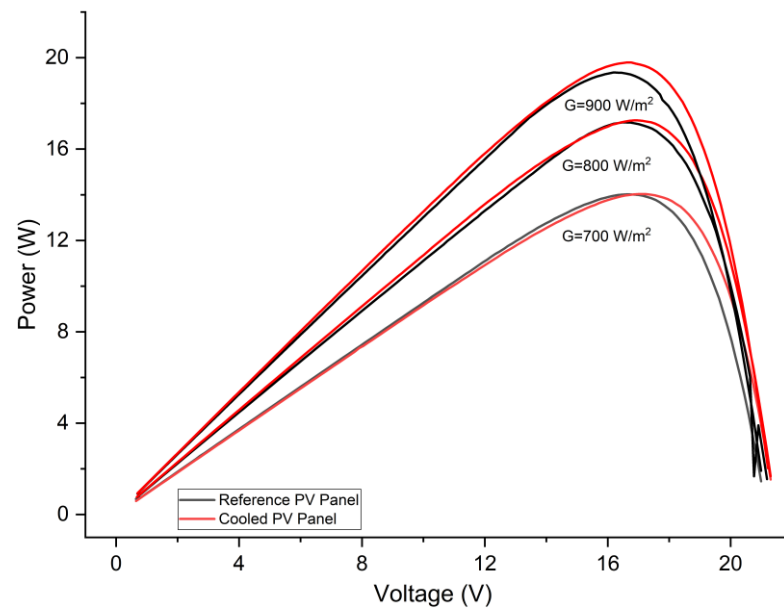


Figure 7.2. The correlation between P-V curve and solar radiation

7.2. Weather Station

Within the scope of the study, a weather station was designed and assembled to measure meteorological factors such as wind speed, wind direction, air temperature, and relative humidity, as these factors influence the power output of the PV panels along with solar radiation. A data logger and the sensors were appropriately positioned on the constructed metal structure to measure the variables in the experiment site. The weather station at the experiment site is shown in **Figure 7.3**.



Figure 7.3. The meteorological station (back and front views)

7.2.1. Anemometer

An NRG 40C model anemometer, as shown in **Figure 7.4**, was used to measure wind speed at the experiment site. The anemometer features a 3-cup design and has the capacity to measure wind speeds up to 96 m/s. The technical specifications of NRG 40C model anemometer are provided in Appx. 1.



Figure 7.4. The anemometer

7.2.2. Wind direction sensor

An NRG 200P mechanical type wind direction sensor, manufactured by NRG Systems, was used to determine wind direction. The sensor was equipped with a potentiometer which is capable of rotating 360°. The sensor operates within a temperature range of -55 to 60 °C and provides an accuracy of 1%. The wind sensor is demonstrated in **Figure 7.5**. The technical specifications of the wind wane are given in Appx. 2.



Figure 7.5. The wind direction sensor

7.2.3. Pyranometer

A CMP6 model pyranometer, produced by Kipp and Zonen Company, was utilized to assess solar irradiance at the experiment site, as displayed in **Figure 7.6**. The sensitivity of the CMP6 pyranometer ranges between 5-20 $\mu\text{V}/\text{W}/\text{m}^2$, which is regarded to be within an acceptable and precise range for scientific measurements. The technical specifications of the pyranometer are presented in Appx. 3.



Figure 7.6. The pyranometer

7.2.4. Air temperature and humidity sensor

An HC2S3 probe air temperature and humidity sensor, manufactured by Campbell Scientific Company, was employed to calculate ambient temperature and relative humidity at the experiment site. The air temperature and humidity sensor are illustrated in **Figure 7.7**. The temperature sensor of the probe operates within a range of -40 to +60 °C and the humidity sensor functions between 0 and 100% RH. The PT100 RTD temperature sensor inside the probe has an accuracy of ± 0.1 °C. A Rotronic sensor with an accuracy of $\pm 0.8\%$ is used in the probe to measure relative humidity. The technical specifications of HC2S3 air temperature and humidity sensor are introduced in Appx. 4.



Figure 7.7. The air temperature and humidity sensor

7.2.5. Data logger

A CR100 model data logger, manufactured by Campbell Scientific Company, was used to record the data obtained from anemometer, wind direction sensor, pyranometer, air temperature and humidity sensor, thermocouples (three on the back surface of the cooled PV panel, one on the middle back surface of the reference panel, and one underground). It has 16 analog and 8 digital inputs. The data logger is shown in **Figure 7.8**. The technical specifications of the data logger are given in Appx. 5. The data logger was programmed utilizing LoggerNet 4.2.1 software, developed by the manufacturer, to

record data acquired from the voltage divider circuit. To ensure the desired operation conditions for this study, the data logger program commands were written, as stated in Appx. 6. In addition, the connection diagram of data logger (NR200P: Wind wane sensor; NGR 40: Anemometer; HC2S3: Temperature and humidity sensor; CMP3/CMP6/CMP11: Pyranometer; TC (1), (2), (3), (4), and (5): Thermocouples) is demonstrated in Appx. 7.



Figure 7.8. Data logger

Wind speed and direction data were defined as vectors, while other data were specified as scalars. The data logger has an internal memory of 4 MB, but the data recorded by the data logger was periodically backed up to a computer through the RS232 port to prevent data loss.

The power needed by the data logger and all sensors was supplied by a 12V Orbus brand lead acid battery powered by a 16W external PV panel positioned at the top of the constructed metal structure.

7.3. Other Measurement Tools

A rheostat box containing various rheostat resistance was designed and manufactured to apply various electrical loads to the PV panels. It was proven that the rheostat box was suitable to obtain desired values and assess the performance of the PV panels and plot the I-V and P-V curves; however, obtained data required manual careful adjustment and long time. Therefore, the Amprobe Solar-600 Solar Analyzer, as shown in **Figure 7.9**, was used to measure the P_{mpp} , V_{mpp} , I_{mpp} , V_{oc} and I_{sc} of the PV panels. Its

specific characteristics were presented in Appx. 8. The rheostat box, including a picture taken from outside and a picture taken from inside the box, is illustrated in **Figure 7.10**.



Figure 7.9. Solar power analyzer

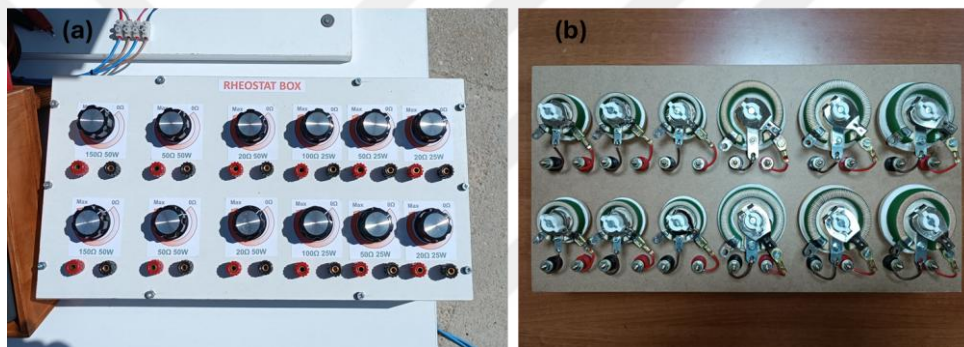


Figure 7.10. (a) An external view of the rheostat box; (b) an internal view of the rheostat box

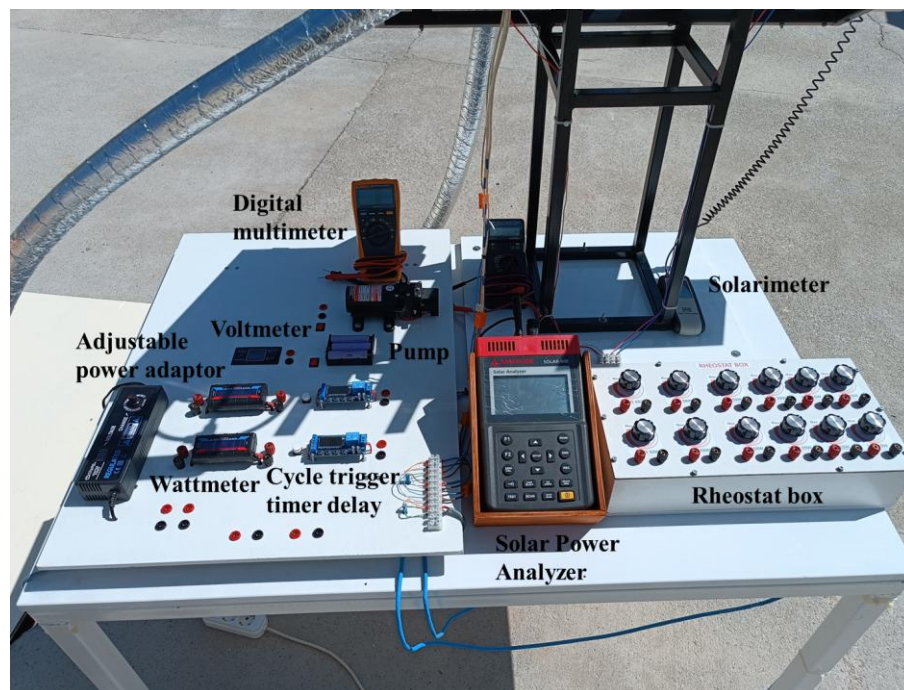


Figure 7.11. A view of measuring equipment, pump, and adjustable power adaptor.

The measuring equipment, pump, and adjustable power adaptor were all arranged on the board. **Figure 7.11** shows a view of the components on the board.

Three lithium-ion batteries, each rated at 4.2 V, were used to supply power to the measuring equipment, including the wattmeter, voltmeter, and cycle trigger timing delay.

The amount of water to be pumped to the liquid distribution system and the intervals during which the pump remained inactive were controlled by the cycle trigger timer delay.

A UTI721M thermal camera, as seen in **Figure 7.12**, was used to monitor the cooling process of the PV panel. In addition to the thermocouples placed on the back surface of the PV panels, the thermal camera was also used to measure the temperature of the panels. The thermal camera measurements were preferred over thermocouples because, while the thermocouples measured temperature at three specific points, the thermal camera was able to provide the average temperature over the entire panel surface. Moreover, the thermal camera can detect variations in surface temperature while not disturbing the cooling systems. The characteristics of the thermal camera are presented in Appx. 9.



Figure 7.12. Thermal camera

An RC high precision 200A wattmeter was used to measure the current, voltage, and power consumption of the pump. The measurements were also validated using a Fluke 179 true RMS digital multimeter.

DSR was measured using Cem DT-1307 solarimeter, as shown in **Figure 7.13**. Its technical specifications are provided in Appx. 10.



Figure 7.13. Solarimeter

A Radwag PS 1000.R2 precision balance, as shown in **Figure 7.14**, was used for weight measurements. Its technical specifications are given in Appx. 11.



Figure 7.14. PS 1000.RS precision balance

7.4. Porous EC Materials

A CP, CWs, and HRs with densities of 0.043 g/cm^3 , 0.291 g/cm^3 and 0.397 g/cm^3 , respectively, were used as porous materials in the cooling systems. Cellulose pads are commonly used in EC applications for various industries, including poultry, agriculture, horticulture, and food processing plants, due to their structures, which promote efficient water absorption and airflow. Therefore, they are used to control the temperature and humidity. CWs and HRs exhibit strong capillary action and absorbent capacity, and good mechanical strength. Moreover, these cooling materials are commercially available,

affordable and suitable for sustainable cooling applications for PV panels, as they do not react with panels' rear layer, and require minimum maintenance. The cooling materials and their microscopic images are shown in **Figure 7.15**.



Figure 7.15. Cooling materials and their microscopic structures

7.5. EC System with CP and Underground Cooling

The system is an active open-loop system that uses water as a coolant. Water was stored in a sealed steel underground tank located 3 meters below ground level, and a DC pump delivered it to a CP mounted on the rear surface of the PV panel through an inlet port located at the bottom, where it was uniformly distributed across the pad using a novel liquid distribution system. The pad was exposed to the outdoor conditions. Therefore, any

water not absorbed by the pad was collected in a tray located beneath the panel, gathered every 15 min, stored, weighed and returned to the underground storage tank by gravity. Thus, the amount of water that evaporated was determined for each experimental day. The CP is designed to absorb the coolant, which then evaporates as the PV panel heats up due to solar radiation, and ambient temperature. This evaporation process removes the excess heat from the rear surface of the panel. **Figure 7.16** illustrates a schematic diagram of the open water-based EC system with the PV panel setup.

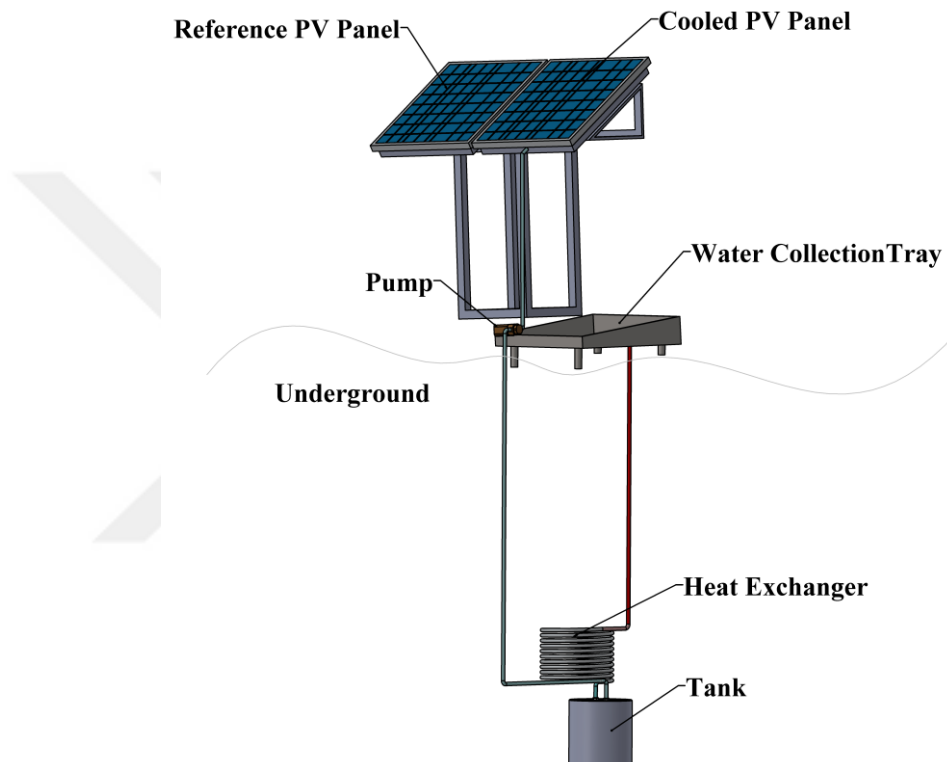


Figure 7.16. Schematic diagram of the PV panel combined with the open water-based EC system

The EC with the CP and underground cooling system was tested over 5 days. A different pumping pattern was applied each day. The patterns for the first, second, third, fourth, and fifth days were 1-s on/45-s off; 1-s on/90-s off; 1-s on/135-s off; 1-s on/180-s off; and 1-s on/300-s off, respectively. “1-s on / n-s off” indicates that the pump operates for 1 second to deliver water to the CP located on the rear side of the panel and then remains off for “n” seconds. The pump was operated at 10 V, 1.73 A, 17.3 W and delivered water at a mass flow rate of 15.7 g/s. The experiments were carried out between 10:00 and 16:00 local time.

Furthermore, without using the pump and liquid distribution system, water was manually sprayed onto the back side of the CP. The purpose was to achieve a more uniform water distribution and thereby ensure more homogeneous cooling of the panel. The manual spraying was carried out every 30 min between 09:30 and 16:00 local time. The results were recorded at 15 min intervals from 10:00 to 16:00 local time and compared with those obtained when the pump and liquid distribution system were used.

7.5.1. Experiment setup

The experimental site included the weather station, PV panels, and an underground cooling system, as shown in **Figure 7.17**. The schematic diagram of the key components of the experimental setup is illustrated in Appx. 12.



Figure 7.17. A view of the experimental site for EC system

7.5.2. PV panels

In the experimental setup, 2 identical Lexron mono-crystalline PV panels with maximum power of 25W were utilized: one with the EC system and a reference panel without the cooling system. PV panel characteristics are presented in **Table 7.2**. The characteristics of the panels were acquired in STC and were given by the manufacturers.

Table 7.2. The characteristics of PV panels in STC ($AM=1.5$, $E=1000 \text{ W/m}^2$, and $T_c=25 \text{ }^\circ\text{C}$)

Parameters	Value
P_{mpp}	25 W
I_{mpp}	1.21 A
V_{mpp}	20.70 V
I_{sc}	1.27 A
V_{oc}	24.84 V
Weight	1.68 kg
Dimensions (mm)	362 x 433 x 20

A carrying mechanism was fabricated for PV panels and its tilt angle was adjusted at 32° , which is the annual ideal solar angle for Batman province. The PV panels were positioned next to each other on the carrying mechanism, facing south. Pictures of the front and back surfaces of both PV panels on the carrying mechanism are shown in **Figure 7.18** (a), and (b), respectively.

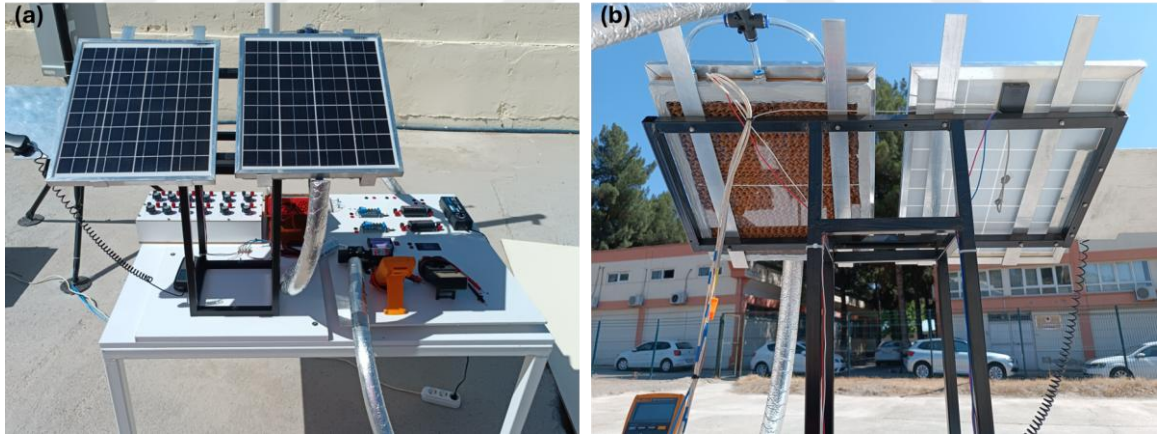


Figure 7.18. (a) The front surface of PV panel with cooling system (on the right) and reference PV panel (on the left); (b) the back surface of PV panel with cooling system (on the left) and reference PV panel (on the right) on the carrying mechanism

To fix the CP properly at rear surface of the cooled PV panel, the corners of the panel were raised with acrylic glasses with 40 mm high and 6 mm thickness. Mastic polyethylene sealant was used to attach the acrylic glasses to the corners of the PV panel. To improve the ventilation on the CP, four holes with a diameter of 9 mm were drilled into each corner of the acrylic glass sheets. The temperature of each PV panel was

measured using by K-type thermocouples attached to the rear side of the panels. A thermocouple was attached to the reference panel at the middle location (T1). On the cooled panel, thermocouples were attached at three locations: top (T2), middle (T3) and bottom (T4), as displayed in **Figure 7.19**. The thermocouples can measure temperatures ranging from 0 to 400 °C. The thermocouple cables were routed through plastic tubes to prevent interference with the data caused by exposure to the coolant.

To send the coolant to the CP, an inlet port (IP) with a reduction in diameter from 10 mm to 6 mm was mounted at the bottom. To enhance the ventilation on the CP, three outlet ports with diameters of 10 mm were attached at the top of the cooled PV Panel in three locations: left (OP1), middle (OP2), and right (OP3), as demonstrated in **Figure 7.19**.

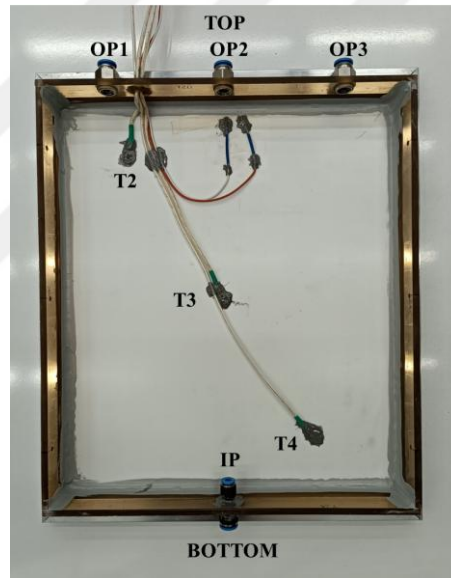


Figure 7.19. The rear surface of the cooled PV panel with three mounted thermocouples (T2, T3, and T4), three outlet ports (OP1, OP2, and OP3), and one inlet port (IP)

7.5.3 Cooling system

A honeycomb CP, with a thickness of 30 mm and gaps having a cross-section area of 0.338 cm^2 , was directly attached to the rear side of the cooled PV panel to absorb the coolant and remove the excess heat through evaporation. Before the pad was attached, it was precisely cut. To further enhance airflow through the CP, channels with a diameter of 4 mm were continuously and vertically drilled through the CP, at uniform intervals.

A liquid distribution system was designed to uniformly spread the coolant over the CP. The liquid distribution system was attached to the back of the panel using epoxy adhesive to ensure better attachment and water distribution, as shown in **Figure 7.20**. The thermocouples and the liquid distribution system were under the CP. Accordingly, essential modifications were made by slightly trimming the bottom edge of the CP to create a path for the thermocouple cables, pipe connectors, and pipes, ensuring that the cables did not obstruct the pad's contact with the rear surface of the panel and providing sufficient space for mounting the liquid distribution system on the evaporative surface. Holes with a diameter of 0.3 mm were drilled into the pipes located in the branched sections of the liquid distribution system.



Figure 7.20. The liquid distribution system on the rear side of the panel

Aluminum rods with a diameter of 4 mm, as seen in **Figure 7.21**, were placed on the top, middle, and bottom parts of the CP to secure it in place, ensuring continuous contact with the rear surface of the cooled PV panel for efficient cooling.

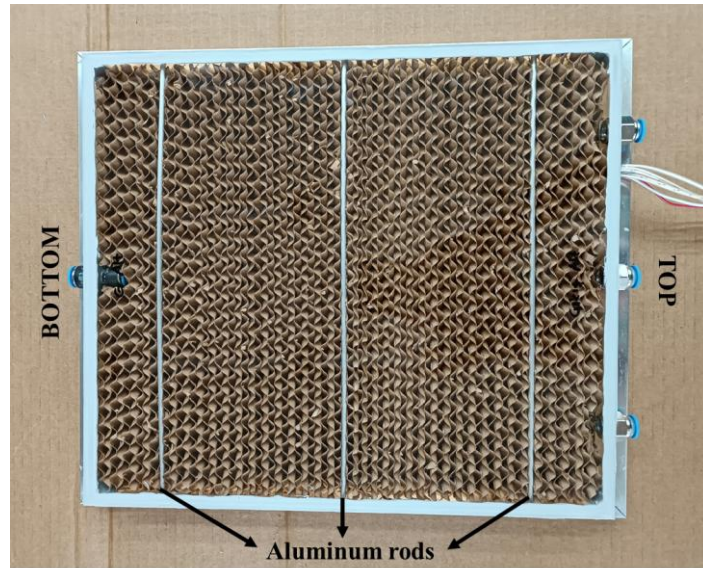


Figure 7.21. Aluminum rods on the top, middle and bottom of the cooled PV panel

The PV panel with the cooling system is illustrated in **Figure 7.22** (a). A schematic diagram of cooled PV panel with CP and liquid distribution system is demonstrated in **Figure 7.22** (b).

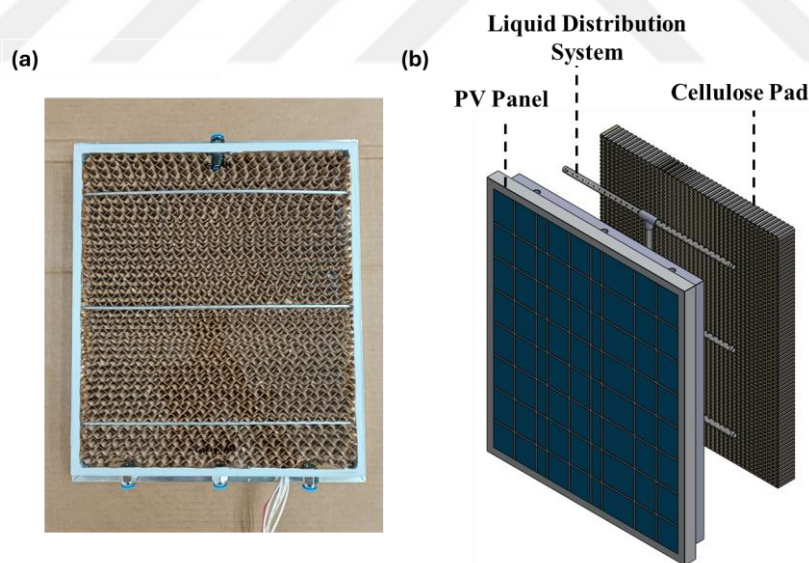


Figure 7.22. (a) PV panel with the cooling system; (b) The schematic diagram of cooled PV panel with the liquid distribution system, and CP

An aluminum heat exchanger was connected to the inlet port of a 13-liter steel underground storage tank to increase the surface area for heat transfer between water and the surrounding soil, which allows water to cool more efficiently. **Figure 7.23** displays the storage tank and aluminum heat exchanger installed underground. The tank was

equipped with a lid containing one inlet port and one outlet port for the coolant. The heat exchanger was positioned at the top of the storage tank, and its position and angle were carefully adjusted.

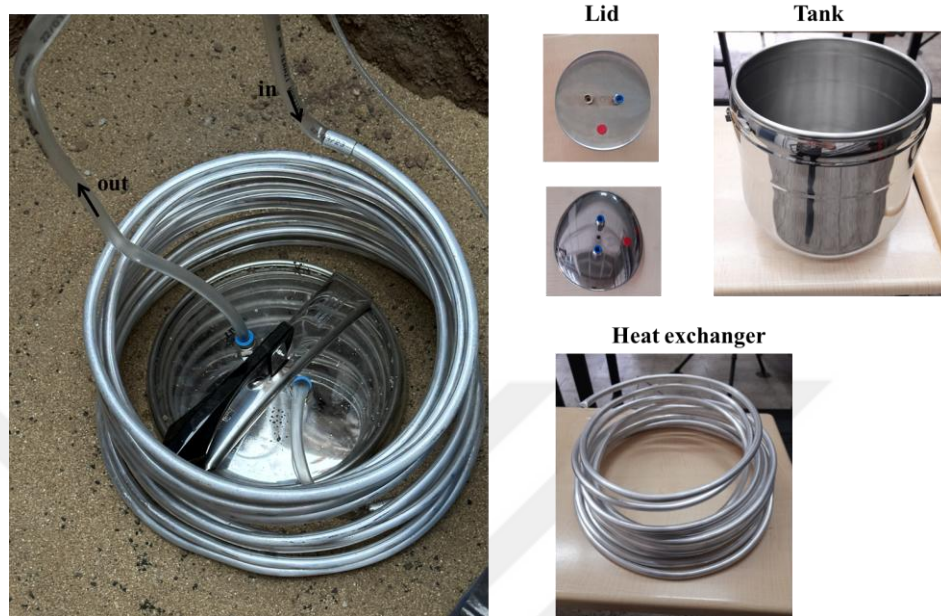


Figure 7.23. Underground metal tank and aluminum heat exchanger

The components of the cooling system were connected using plastic pipes with a diameter of 10 mm. A Handwerker brand DC pump with 24 W was used to circulate water in the EC system, powered by an adjustable power adaptor. Technical characteristics and a picture of the pump are shown in Appx. 13, and **Figure 7.24**, respectively.



Figure 7.24. DC pump

7.6. EC System with CWs and Underground Cooling

This system used the same liquid distribution mechanism and underground cooling technique as the EC with CP and underground cooling system. As a modification, the CP was removed and CWs were uniformly and properly attached to the rear surface of the cooled panel, as displayed in **Figure 7.25**. Mastic polyethylene sealant was applied in small dots to secure the CWs to the rear surface of the panel.

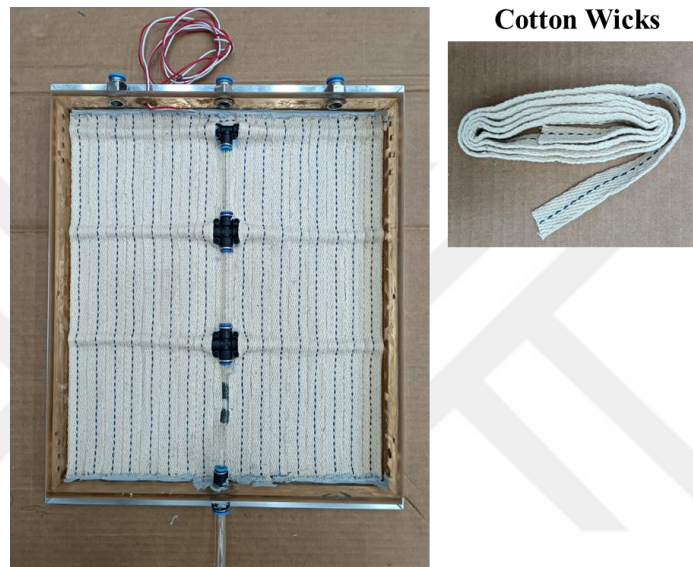


Figure 7.25. Cooled PV Panel with attached CWs

The EC with CWs and underground cooling system was tested over a period of 2 days. Based on the findings from the EC with CP and underground cooling, two different pumping patterns were determined and applied each day. The patterns for the first, and second day were 1-s on/180-s off; 1-s on/300-s off, respectively. The “1-s on / n-s off” cycle denotes that the pump operates for 1 second to supply water to the CWs positioned on the rear side of the panel, followed by an off period of “n” seconds. The pump was operated at 10 V, 1.73 A, 17.3 W and supplied water at a mass flow rate of 15.7 g/s. The experiments were conducted between 10:00 and 16:00 local time. An illustration of the cooled panel during an experimental day is shown in **Figure 7.26**.



Figure 7.26. Experimental setup of the cooled panel

Additionally, water was manually sprayed onto the back of the CWs without using the pump and liquid distribution system. The manual spraying was carried out every 30 min between 09:30 and 16:00 local time. The measurements were recorded at 15-min intervals from 10:00 to 16:00 local time each day and compared with the results obtained when the pump and liquid distribution system were in use.

7.7. EC System with HRs and Underground Cooling

This system employed the same liquid distribution method and underground cooling technique as the EC with CWs and underground cooling system. As a modification, the CWs were replaced with HRs, which were evenly and securely attached to the rear surface of the cooled panel, as shown in **Figure 7.27**. The HRs were secured to the rear surface of the panel using small dots of mastic polyethylene sealant.



Figure 7.27. Cooled PV Panel with attached hemp rope.

The EC system with HRs and underground cooling was evaluated over a 2-day period. Each day featured a distinct pumping cycle; on the first day, the pump operated 1-s /180-s off; on the second day, it was 1-s on/300-s off. “1-s on / n-s off” means the pump operates for 1 second, delivering water to the HRs on the rear side of the panel, and then remains off for “n” seconds. The pump ran at 10 V, 1.73 A, 17.3 W and delivered water at a mass flow rate of 15.7 g/s. The test was carried out from 10:00 to 16:00 local time each day. An illustration of the panel under cooling conditions during one of the experimental days is presented in **Figure 7.28**.



Figure 7.28. Test setup of the cooled panel

Furthermore, water was manually sprayed onto the back side of the HRs without using the pump and liquid distribution system. The manual spraying was conducted at 30-min intervals from 09:30 to 16:00 local time. Measurements were collected at 15-min intervals from 10:00 to 16:00 local time daily and compared to the results obtained when the pump and liquid distribution system were operational.



8. RESULTS AND DISCUSSION

Initially, the meteorological parameters, including wind direction ($^{\circ}$), average wind speed (m/s), ambient temperature ($^{\circ}\text{C}$), relative humidity (%), and average global solar radiation (W/m^2), were collectively presented for each experimental day in the figures. Subsequently, the temperatures of the reference and cooled panels, the corresponding temperature difference, and DSR were depicted together to facilitate comparative analyses. Furthermore, electrical performance indicators were presented along with DSR. Specifically, the MPP parameter (P_{mpp} , V_{mpp} , and I_{mpp}) were plotted together with DSR for each experimental result, while the V_{oc} and I_{sc} were presented together in separate graphs alongside DSR and P_{mpp} . This organization of figures was intended to enable systematic comparison and to reveal the influence of meteorological factors on the thermal, electrical performance, and I-V characteristics of the PV panels. After each experiment, panel efficiency (calculated using the total panel area) and total cell efficiency (calculated using only the cell area) were determined and presented graphically alongside the FF. Additionally, the energy output at each measurement point and cumulative energy produced by the panels on each experimental day were calculated and presented graphically along DSR. The effectiveness of the EC systems was evaluated based on the enhancement in their P_{mpp} , and percentage increase in their cumulative energy output relative to the reference panel.

The equations used to assess the panel and cell efficiencies, FF, energy output, cumulative energy and specific energy gain are listed as follows:

The panel and cell efficiency values for the panels were expressed by the following equations, respectively:

$$\eta_{\text{panel}} = \frac{P_{\text{mpp}}}{(A_{\text{panel}}) \times \text{DSR}} \quad (8.1)$$

$$\eta_{\text{cell}} = \frac{P_{\text{mpp}}}{(A_{\text{cell}}) \times \text{DSR}} \quad (8.2)$$

Where; η_{panel} is the panel efficiency, η_{cell} is the total cell efficiency, P_{mpp} is the MPP power, A_{panel} is the front area of the panel, A_{cell} is the total cell area of the panel, and DSR is the direct solar radiation recorded at the measurement points.

The FF values for the panels were calculated by the following equations:

$$FF = \frac{V_{\text{mpp}} \times I_{\text{mpp}}}{V_{\text{oc}} \times I_{\text{sc}}} \quad (8.3)$$

Where; FF is the fill factor, V_{mpp} is the voltage at MPP, I_{mpp} is the current at MPP, V_{oc} is the open-circuit voltage, and I_{sc} is the short-circuit current.

The energy output at each measurement point was assessed by the following equation:

$$E_E = \int_{t_1}^{t_2} P_{\text{mpp}} dt \quad (8.4)$$

Where; E_E is the energy output at the measurement intervals, P_{mpp} is the MPP power, and t_1 and t_2 are the initial and final times of the measurement point, respectively.

The cumulative electrical energy production (CEP) of the panels is determined by the equation below:

$$CEP = \int_{t_1}^{t_2} E_E dt \quad (8.5)$$

The specific energy gain (SEG), defined as the energy gain per gram of water evaporated, is formulated as follows:

$$SEG = \frac{CEP_{\text{cooled panel}} - CEP_{\text{reference panel}}}{m_{\text{evp}}} \quad (8.6)$$

Where; m_{evp} is the total water mass evaporated.

Besides, the wind direction is expressed in degrees. A direction of 0 or 360° corresponds to wind blowing from the north, 90° from the east, 180° from the south, and 270° from the west, as illustrated in **Figure 8.1**.

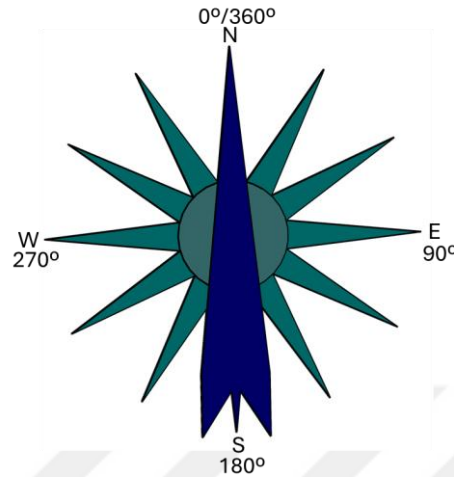


Figure 8.1. Wind direction diagram

8.1. Outcomes of the EC System with CP and Underground Cooling

The outcomes of the configuration of the EC system with CP and underground cooling are presented in the following sections:

8.1.1. Outcomes of the 1-s on/45-s off pump cycle

During the 1-s on/45-s off operating cycle, from 10:00 to 16:00 local time, the pump completed 480 cycles, delivering 7536g of water to the CP integrated to the rear surface of the PV panel. The liquid distribution system facilitated constant water dispersion. Altogether, 6664g of water was retained in the tray positioned under the panel, and 872g of water was evaporated.

On the day of the experiment (July 5, 2025), the weather station measured wind direction, average wind speed, mean air temperature, humidity and average global solar radiation at 15-min intervals, as shown in **Figure 8.2**. The wind direction was nearly constant, blowing from the northwest. The wind speed rose sharply after 15:00 local time and was also greater between 12:00 and 14:15 local time, the period of highest solar radiation. The mean air temperature readings rose continuously until 15:00 local time. It

varied between 26 °C and 35 °C throughout the test day. Conversely, the relative humidity decreased until 15:00, with minor fluctuations. The trajectory of solar radiation was in line with a regular daily pattern.

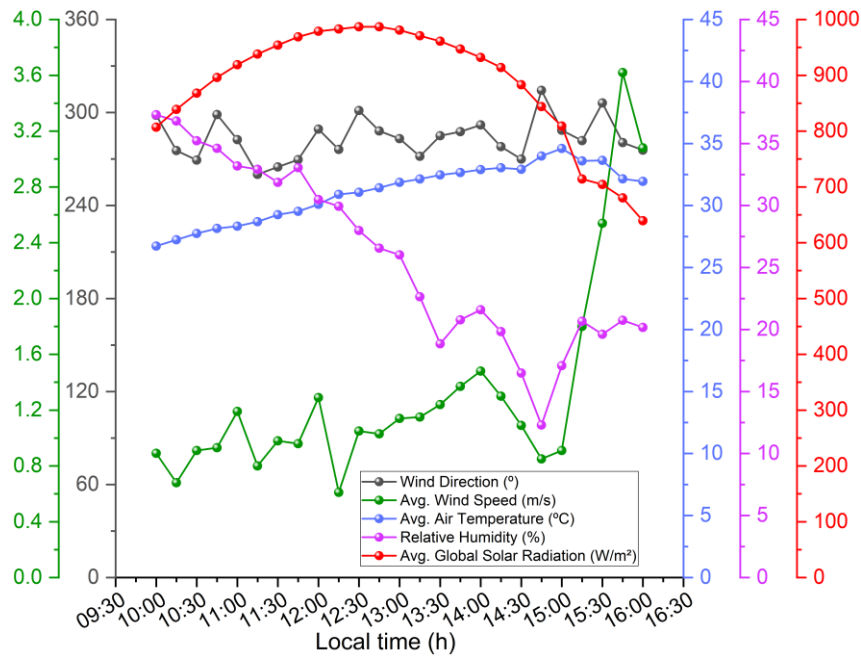


Figure 8.2. Meteorological parameters present during the test

The temperature deviations in the reference and cooled PV panels, the temperature decline in the panel's surface contributed by the EC, and their connection with DSR are presented in **Figure 8.3**. The highest temperature difference, ranging from 9.3 °C to 10.3 °C, was assessed between 12:00 and 13:45 local time, when solar radiation levels were relatively larger. Also, the temperature drop was comparably higher at 14:30, 14:45, and 15:00 local time, which were 8.7 °C, 10.1 °C, and 9.5 °C, respectively. Furthermore, despite lower solar radiation, slightly reduced air temperatures, and increased relative humidity, the cooling was still effective and maintained the temperature difference higher than 6 °C after 15:15 local time.

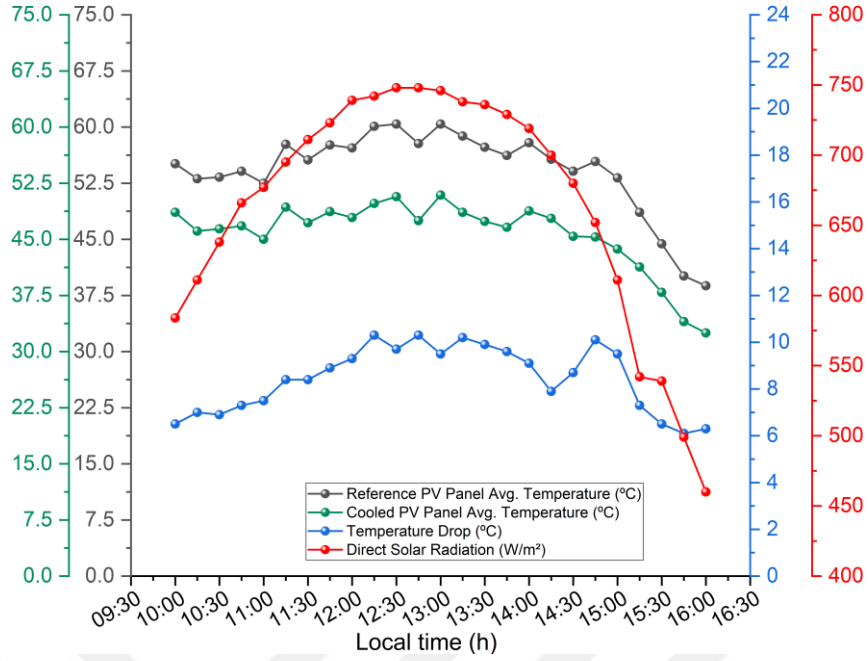


Figure 8.3. Temperature deviations, decline in temperature, and DSR.

Figure 8.4 evaluates the MPP characteristics, including P_{mpp} , V_{mpp} , and I_{mpp} , of the reference and cooled PV panels, and their correspondence with DSR. During the experiment, the P_{mpp} values for the cooled panel were higher than those of the reference panel, with a pronounced difference recorded between 12:00 and 13:45, possibly due to intensified solar radiation. Both panels' I_{mpp} values have presented very similar forms, and their curves corresponded closely with the P_{mpp} and solar radiation trends. Additionally, the panels' V_{mpp} values were almost constant, and had nearly linear curves, with the cooled panel showing marginally higher values than the reference panel. Consequently, the favorable thermal state of the panel contributed to increased voltage output, thereby improving power output.

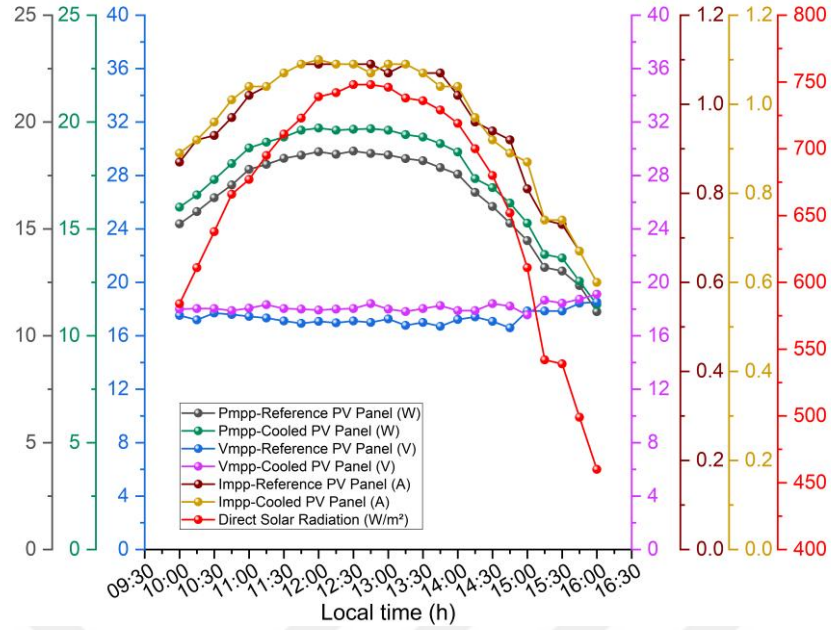


Figure 8.4. MPP characteristics, and DSR

The V_{oc} and I_{sc} attributes of the reference and cooled PV panels and how they are related to P_{mpp} and DSR are indicated in **Figure 8.5**. The I_{sc} outputs of the panels were nearly the same and mainly affected by solar radiation, while their V_{oc} outputs were steady, with the cooled panel exhibiting larger values, thus mostly impacted by the thermal phase of the panels. The increase in P_{mpp} values has mainly been resulted from the voltage improvement caused by the EC process.

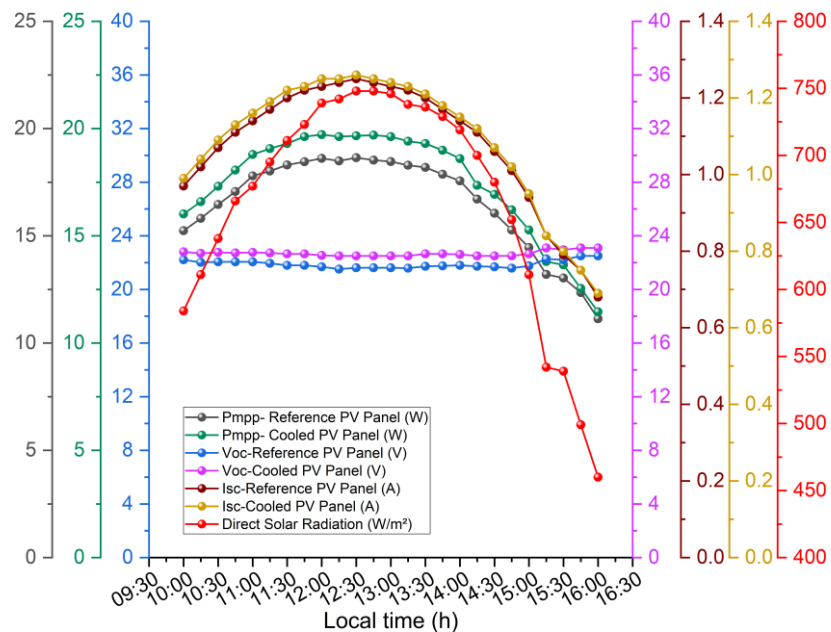


Figure 8.5. V_{oc} and I_{sc} attributes in correlation with P_{mpp} and DSR.

Figure 8.6 displays the panel efficiencies and total cell efficiencies of the reference and cooled PV panels, as well as the computed FF rates. For all measured points, the cooled panel outperformed the reference panel considering panel and cell efficiencies, highlighting the cooling system's effectiveness and its beneficial impact. The average panel efficiencies of the reference and cooled panels were 16.59% and 17.48%, respectively; the corresponding average total cell efficiencies were 22.43% and 23.63%. Consequently, average panel efficiency was enhanced by 5.38%, and total average cell efficiency rose by 5.33%. Both panels experienced a decline in efficiency over time, which can be attributable to reduced power output at the measurements points, caused by the increase in cell temperature resulting from higher operating temperature. The FF values for both panels were nearly equivalent. Therefore, the higher power output of the cooled panel resulted from the improved V_{mpp} and V_{oc} outputs brought about by the EC, as the I_{mpp} and I_{sc} outputs, and FF values were almost identical for both panels. As a result, using the liquid distribution system with CP, with the 1-s on/45-s off pump cycle enhanced the panel's efficiency.

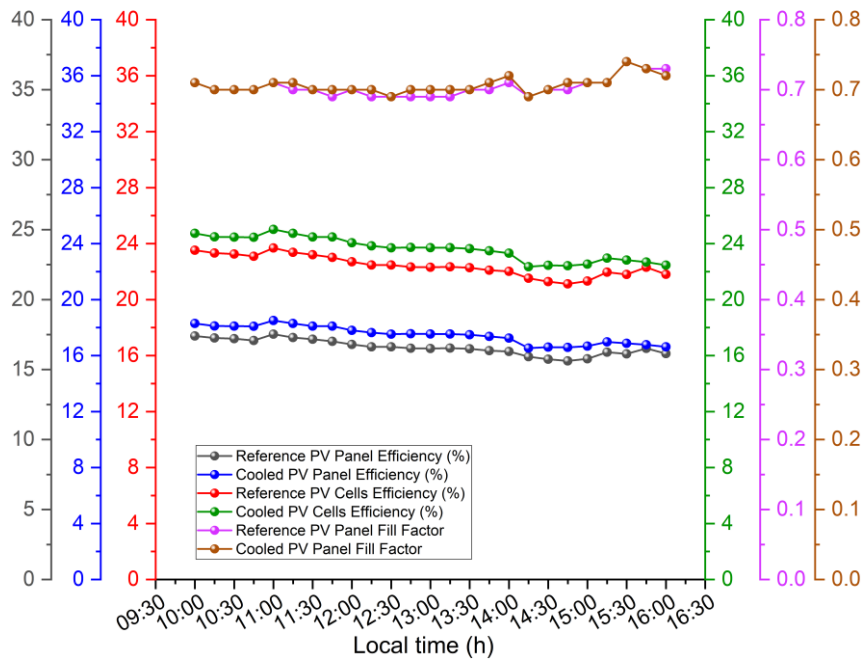


Figure 8.6. Cell and panel efficiencies and FF assessments

The energy outputs at recorded points, cumulative energy outputs of the reference and cooled PV panels are demonstrated in **Figure 8.7**. Additionally, the DSR levels recorded during the testing period are presented to illustrate their relationships with the

panel performance parameters. The cooled panel continuously delivered greater energy output values, specifically between 12:00 and 13:45 when solar radiation levels were the strongest, compared to the reference panel during the entire testing period. Ultimately, a 5.46% enhancement was assessed in cumulative energy of the panel, when it was subjected to the EC technique using the liquid distribution system with the CP, operating the 1-s on/45-s off pump cycle, considering the reference panel's cumulative energy output as the base point.

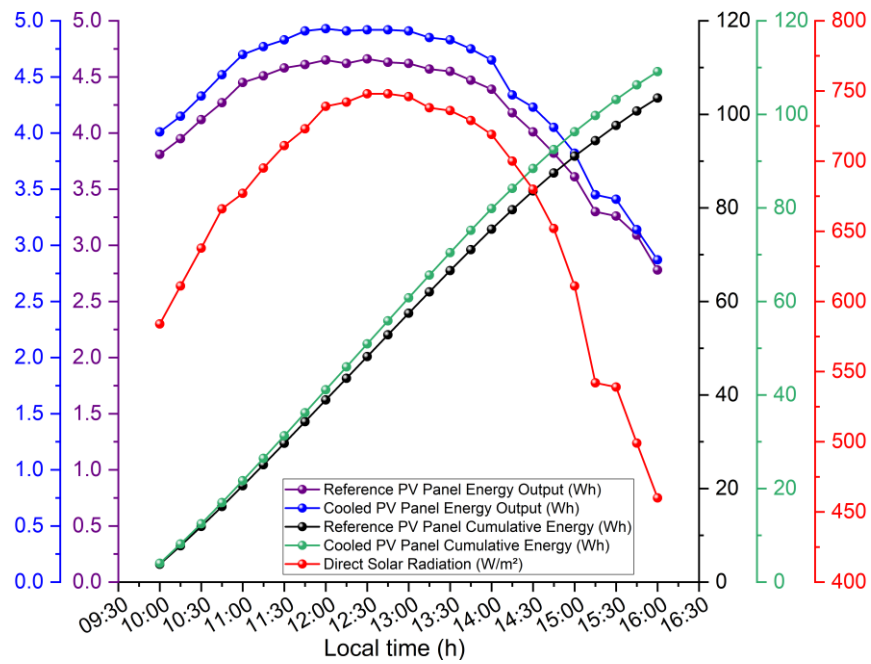


Figure 8.7. Energy and cumulative energy generation and DSR

Thermal camera images of the reference and cooled PV panels are positioned from earliest to latest at 30-min intervals between 10:30 and 16:00 local time in **Figure 8.8**. It can clearly be observed from the thermal images that the reference panel operated at significantly higher temperatures. Furthermore, the images show a uniform perceptible cooling effect across the panel surface.

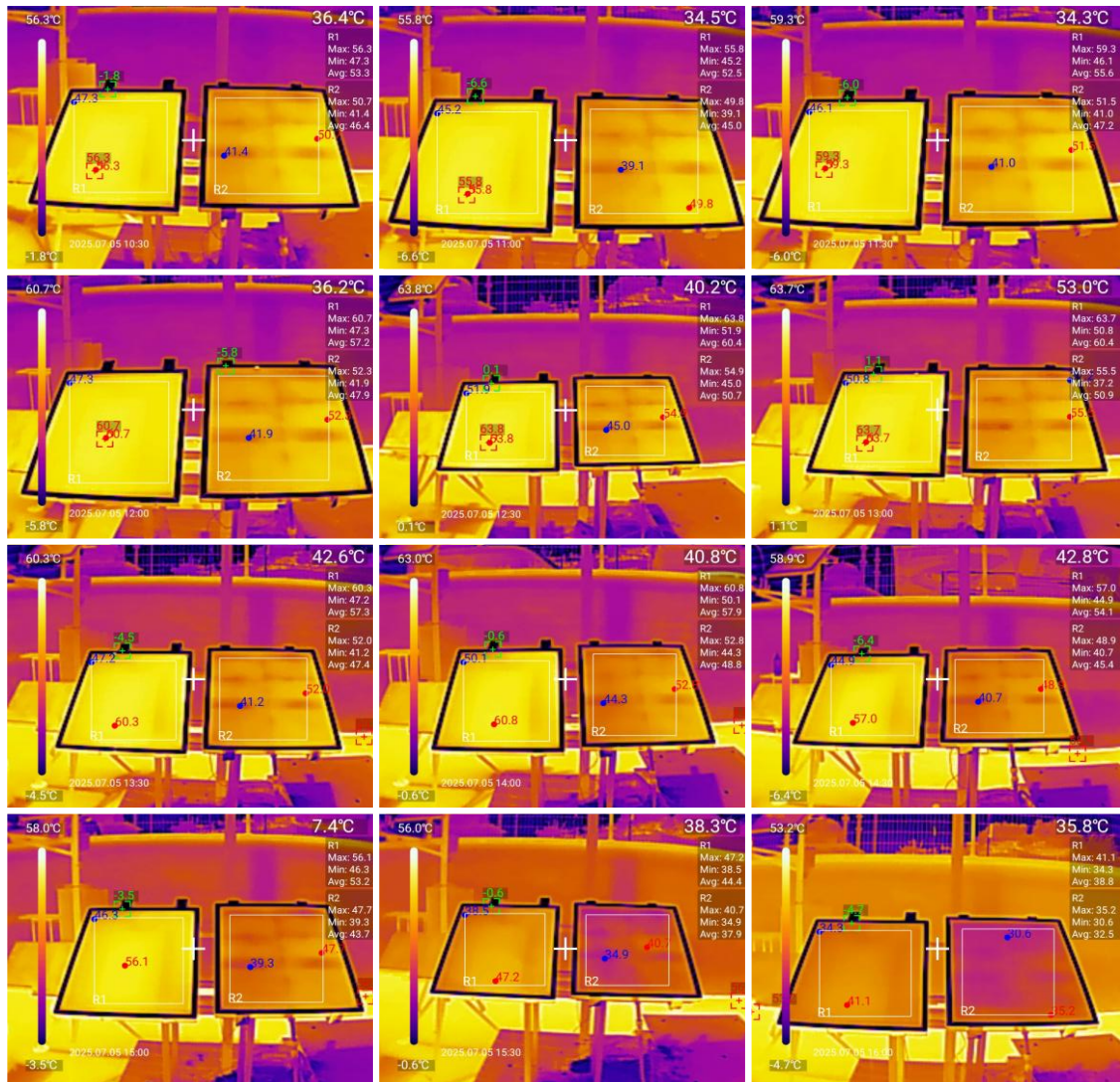


Figure 8.8. Thermal camera views of the reference (R1) and cooled (R2) panels at 30-min time points from 10:30 to 16:00 local time

8.1.2. Outcomes of the 1-s on/90-s off pump cycle

During the 240 cycles conducted by the pump from 10:00 to 16:00 local time, overall, 3768g of water was supplied to the CP attached to the rear side of the panel. Distribution of water was controlled via the liquid distribution system located between the rear side of the panel and the CP. Collectively, 2953g of water was dripped into the tray under the panel, and 815g of water evaporated.

The environmental conditions, involving wind direction, mean wind speed, average air temperature, humidity and average global solar radiation, accessed through the weather station on the assessment day (July 6, 2025) are demonstrated in **Figure 8.9**. The wind direction was steady and originated from the northwest, apart from 10:45 local

time, when it came from the northeast. The mean wind speed increased during the day, with fluctuations, reaching its peak value of 2.2 m/s at 14:45 local time. Likewise, the average air temperature continuously rose throughout the day, ranging from 31.3 °C to 38.6 °C. On the contrary, the relative humidity constantly decreases over the day, with minor variations. The average global radiation was greater between 11:45 and 13:15 local time, aligning well with the standard daily course.

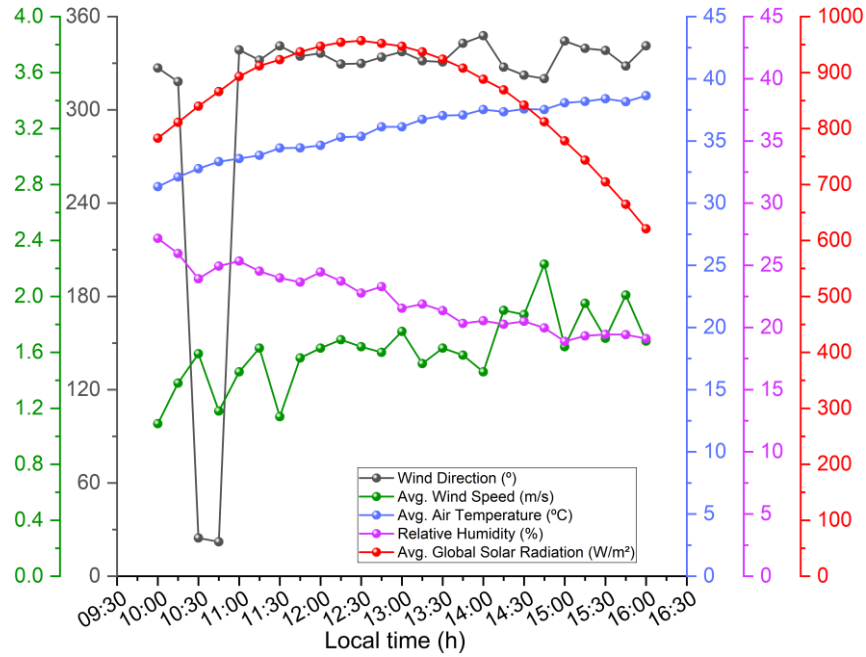


Figure 8.9. Meteorological variables present during the experiment

Figure 8.10 shows the temperature change in the reference and cooled PV panels, descent in temperature as a result of the EC, and their dependency on the DSR. Rather than first two measurements, the panel's surface temperature was constantly reduced by more than 7 °C by the EC technique during the whole day. The largest temperature difference was registered from 12:00 to 13:45 local time, as solar radiation intensity was relatively high. Due to the elevated air temperature, reduced relative humidity, and increased wind speed, similar temperature drop readings were recorded in the late afternoon compared to those measured during the peak solar radiation period. Thus, the CP was effective provided that it was sufficiently wet and there were adequate wind speed values.

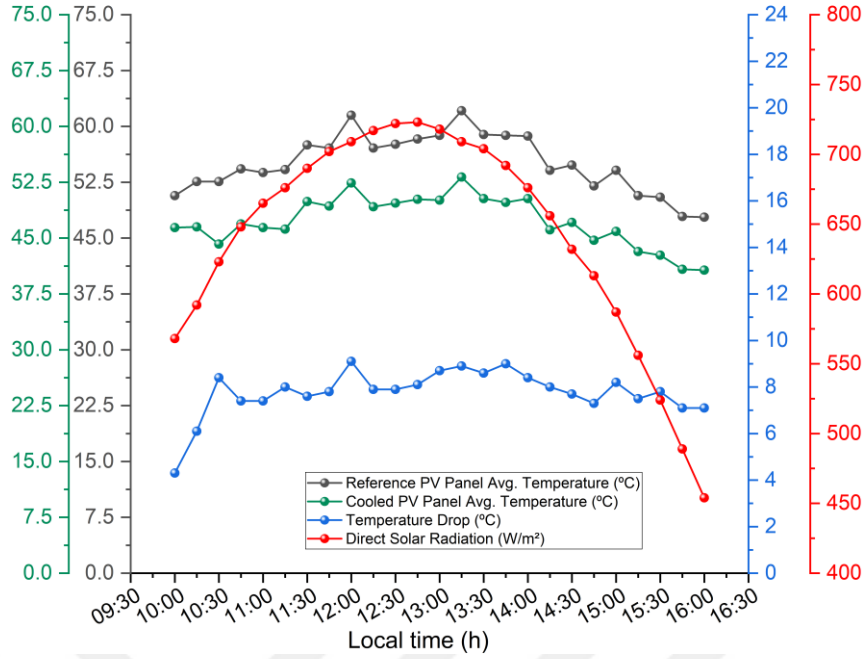


Figure 8.10. Temperature change, reduction in temperature, and DSR

The MPP characteristics, which are P_{mpp} , V_{mpp} , and I_{mpp} , of the reference and cooled PV panels, together with their linkage to the DSR, are expressed in **Figure 8.11**. Compared to the reference panel, the cooled panel produced higher P_{mpp} points over the experimental timeframe. The P_{mpp} difference between the panels was less in the early morning and late afternoon hours, which was probably due to the lower solar radiation levels during those periods. The I_{mpp} points remained nearly the same for the panels and closely followed the progression of solar radiation and P_{mpp} points, whereas the V_{mpp} points were consistently higher for the cooled panel throughout the testing period, showing roughly linear behavior. Consequently, the voltage increase was reflected in an improved P_{mpp} , confirming that the panel's power output depended heavily on solar radiation and temperature.

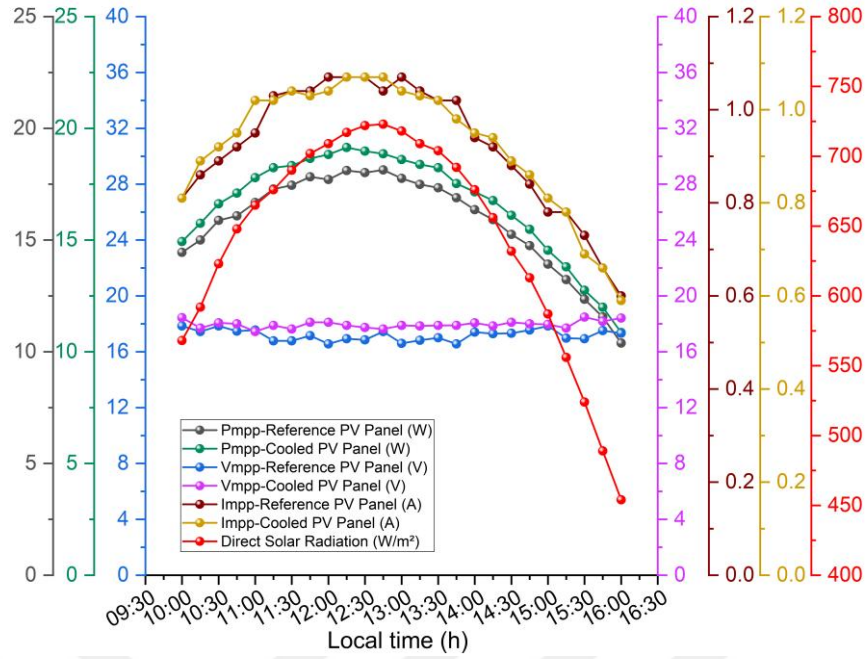


Figure 8.11. P_{mpp} , V_{mpp} , and I_{mpp} trends in comparison to DSR

Presented in **Figure 8.12** are the V_{oc} and I_{sc} characteristics of the reference and cooled PV panels, along with their association with the P_{mpp} attributes of the panel and DSR. Relative to the reference panel, the cooled panel had greater V_{oc} points through the measurement range, indicating improved voltage production. However, both panel's I_{sc} points were roughly equivalent. As the V_{oc} curves of the panels followed almost linear paths, the improved voltage production primarily resulted from temperature decrease owing to the EC. On the other hand, the I_{sc} variations were mainly due to the alterations in solar radiation. As a result, the improvement in power output of the panel was dependent on the enhancement of its I-V characteristics.

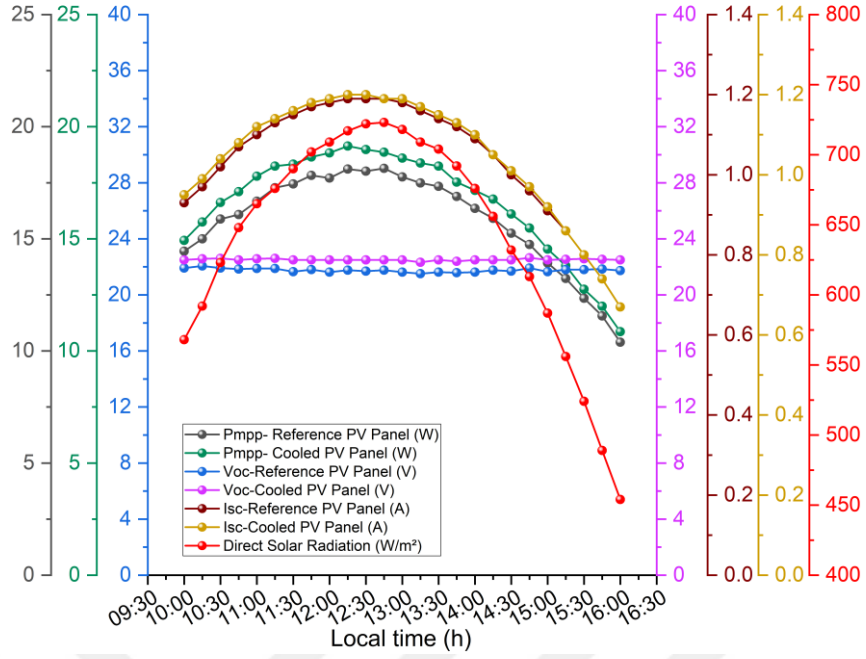


Figure 8.12. V_{oc} and I_{sc} trends in comparison to P_{mpp} and DSR

Figure 8.13 exhibits the distinction between the reference and cooled PV panels in terms of their panel and overall cell efficiencies and FF vlues. The panel and cell efficiencies of the cooled panel exceeded those of the reference panel at each measurement interval, underscoring the performance of the EC method and its constructive effects. Average panel efficiency was 16.42% for the reference panel and 17.22% for the cooled panel, while the corresponding overall cell efficiencies were 22.19% and 23.28%. As a result, average panel efficiency improved by 4.9%, while total average cell efficiency increased by 4.91%. There was a regular decrease in both panels' efficiencies as time progressed, which was probably because of elevated cell temperature caused by rising air temperatures. The FF values between the two panels had minimal differences, so the cooled panel's larger power output at the data collection intervals was on account of increased V_{mpp} and V_{oc} values arising from the EC, since the I_{mpp} and I_{sc} values for both panels were also approximately the same.

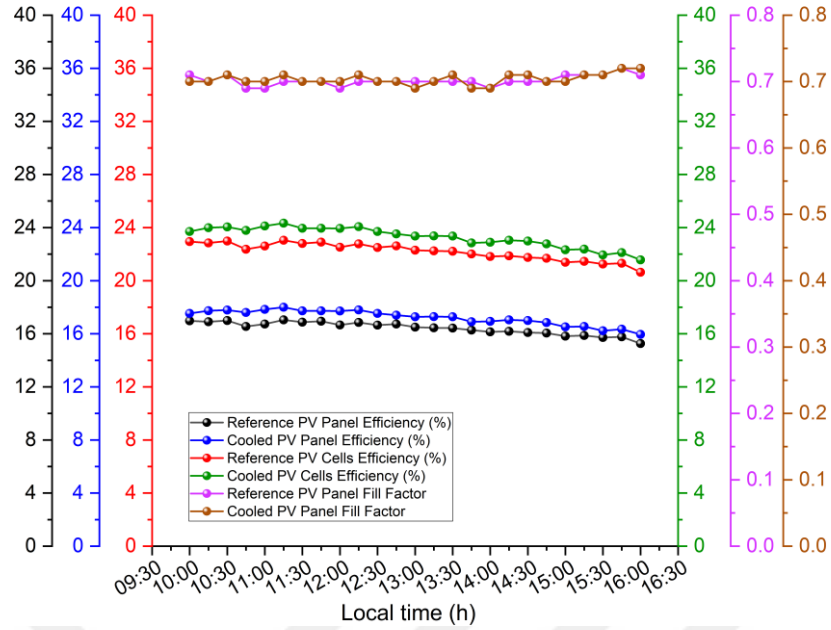


Figure 8.13. Cell and panel efficiencies and FF Readings

The energy outputs at registered points, cumulative energy outputs of the reference and cooled PV panels, and their association with the intensity of DSR are illustrated in **Figure 8.14**. The larger energy output readings were detected for the cooled panel throughout the entire experiment period. Consequently, there was a 4.95% advancement in cumulative energy of the cooled panel, regarding reference panel's cumulative energy output as the baseline.

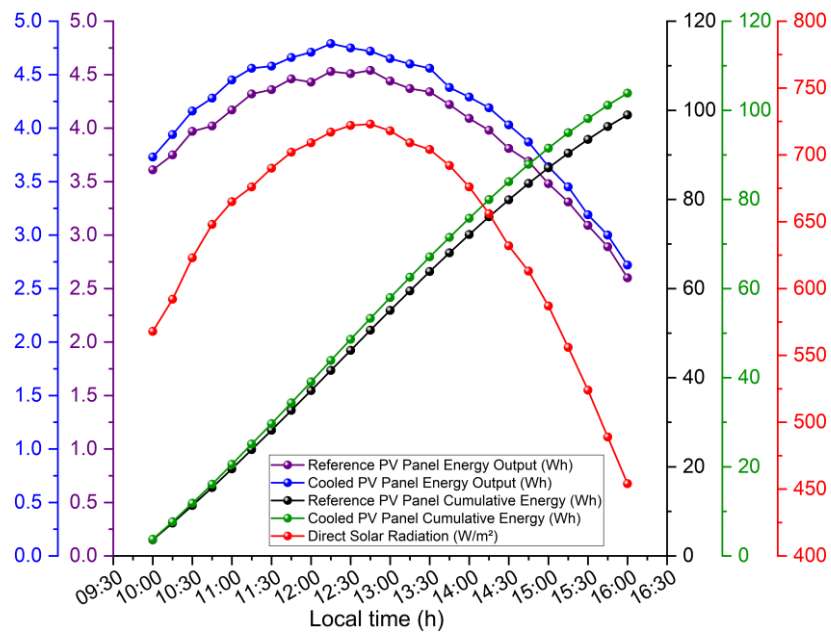


Figure 8.14. Energy and cumulative energy values, and DSR

Thermal camera pictures of the reference and cooled PV panels are arranged from earliest to latest at 30-min increments between 10:30 and 16:00 local time in **Figure 8.15**. From the thermal images, it is apparent that the reference panel operated at notably higher temperatures. Moreover, an evenly distributed cooling impact is visible when the thermal camera images are analyzed.

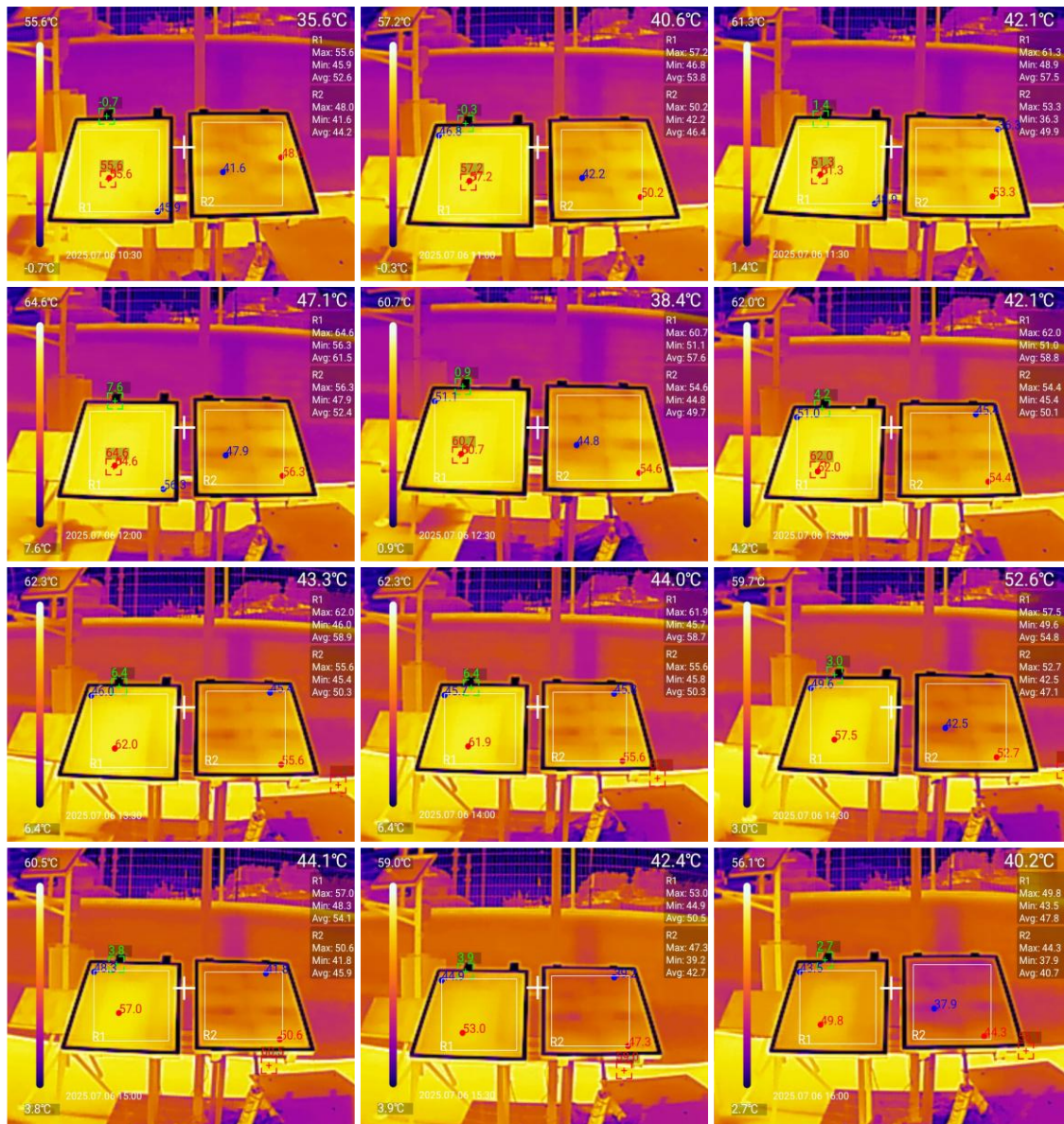


Figure 8.15. Thermal camera images of the reference (R1) and cooled (R2) panels at 30-min intervals from 10:30 to 16:00 local time

To conclude, the 1-s on/90-s off pump cycle had a slightly lower performance in terms of temperature reduction, efficiency, and energy production compared to the 1-s on/45-s off pump cycle. However, when the positive weather conditions, including higher

wind speeds, and lower air temperature, for the 1-s on/45-s off cycle are considered, their performances become more comparable. Hence, the 1-s on/90-s off pump cycle is the more water-efficient alternative.

8.1.3. Outcomes of the 1-s on/135-s off pump cycle

Throughout the 160 intervals from 10:00 to 16:00 local time, the pump delivered a total of 2512g of water to the CP affixed to the rear side of the panel. The liquid distribution system located under the pad evenly dispersed water across the pad surface, ensuring uniform cooling. During the period, 1740g of water was accumulated in the tray beneath the panel, whereas 772g of water evaporated, extracting excess heat from the panel surface.

Figure 8.16 illustrates the environmental factors, including wind direction, average wind speed, mean air temperature, humidity and average global solar radiation, retrieved from the weather station on the observation day (July 7, 2025). The wind direction was constant and came from the northwest, except at 13:15 local time, when it blew from the northeast. The wind speed was generally steady, reaching its maximum readings from 10:45 to 11:00 local time. Besides, it was relatively high from 12:00 to 13:00, when solar radiation was at its maximum. The relative humidity and mean air temperature had opposite trends: the relative humidity was constantly decreasing, while mean air temperature was steadily increasing. The average air temperature varied between 33 °C and 40 °C. Average global solar radiation readings closely matched their typical daily pattern.

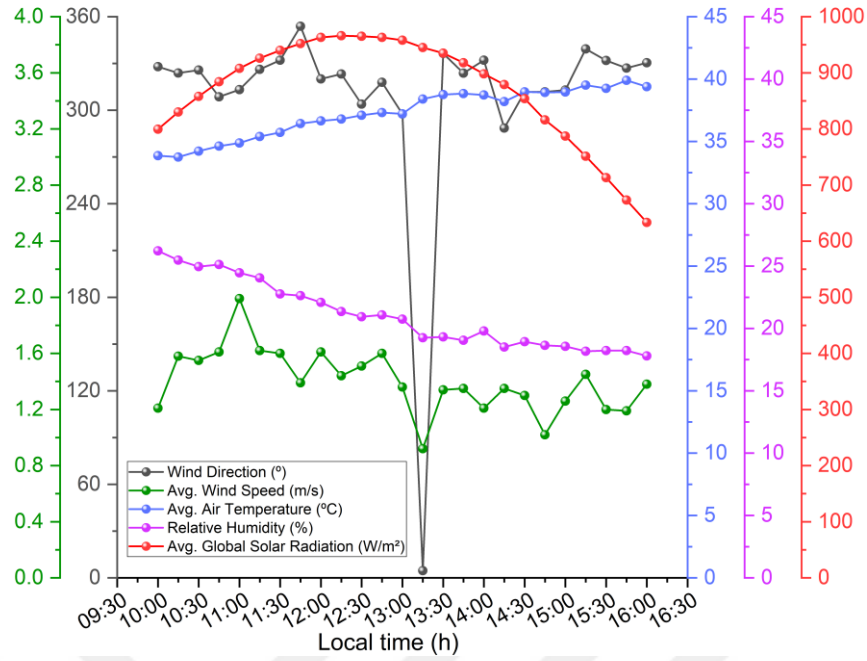


Figure 8.16. Environmental factors on the experimental day

The temperature fluctuations in the reference and cooled PV panels, temperature fall as a consequence of the cooling method, and their correlation to the DSR are demonstrated in **Figure 8.17**. The cooling method was sufficient to drop the panel's surface temperature over 5 °C, apart from the first reading recorded. The highest temperature drop of 8.2 °C was achieved at 13:15 local time, when wind shifted its direction from northwest to the northeast. Also, an equivalent drop was detected at 13:30 local time. There was a notable decline in both panels' surface temperature at 11:00 local time, which corresponded with a significant increase in the average wind speed, which was approximately 2 m/s. Although solar radiation declined considerably in the late afternoon, the temperature drops' values remained similar to those measured at midday period. This outcome was likely due to the rise in air temperature and the drop in relative humidity later in the day.

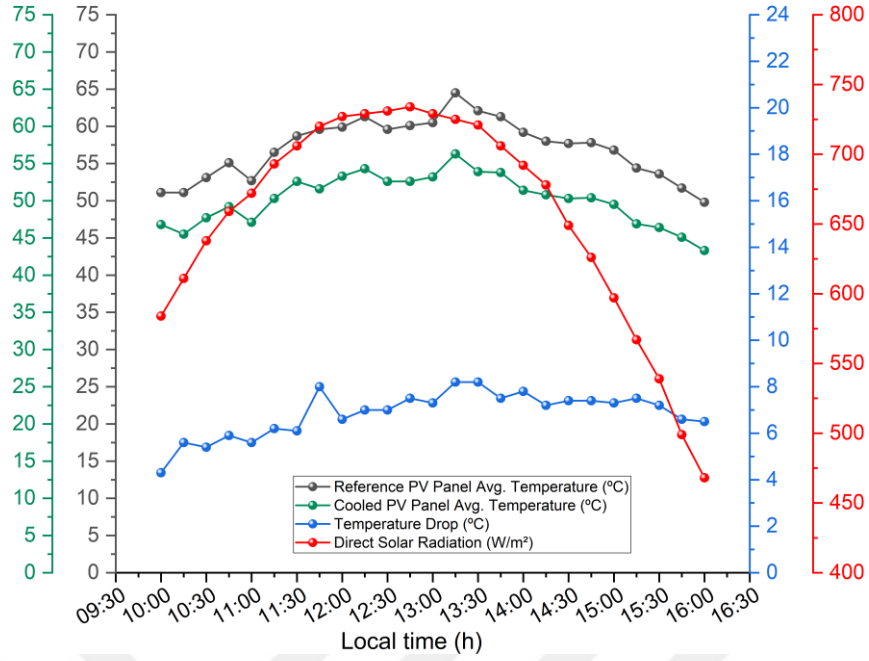


Figure 8.17. Temperature alterations, temperature reduction, and DSR

The P_{mpp} , V_{mpp} , and I_{mpp} outputs of the reference and cooled PV panels at each data point, and their behaviors under different solar radiation levels are evident in **Figure 8.18**. The P_{mpp} outputs were constantly higher for the cooled panel and the difference in the panels' P_{mpp} outputs were more visible between 11:30 and 13:45 local time, when they were exposed to the maximum solar radiation levels. In the early morning and later afternoon hours, the difference was smaller. The I_{mpp} values were nearly the same for both panels, but the cooled panel had elevated V_{mpp} outputs. This rise in voltage translated into a higher power output. The I_{mpp} outputs of the panels corresponded closely with solar radiation, with limited influence from the panels' thermal conditions. Meanwhile, the V_{mpp} outputs displayed linear patterns, largely driven by thermal effects. This is why the dominant factors influencing the P_{mpp} outputs were solar radiation and the thermal state of the panels.

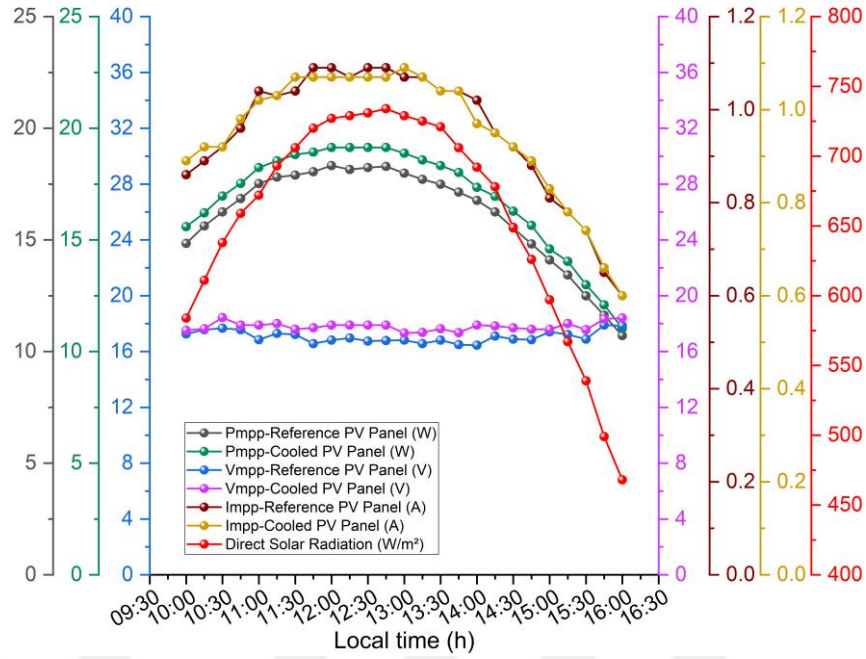


Figure 8.18. Interrelation of P_{mpp} , V_{mpp} , and I_{mpp} with DSR

The V_{oc} and I_{sc} characteristics of the reference and cooled PV panels, along with their dependence on solar radiation levels, and their influence on the P_{mpp} are presented in **Figure 8.19**. There was a voltage enhancement for the cooled panel since its V_{oc} values were constantly higher. This voltage improvement mainly resulted in larger P_{mpp} values, as the I_{sc} values for both panels were almost equivalent. For this reason, the drop in the panel's surface temperature had a larger impact on the V_{oc} instead of the I_{sc} . The panels' I_{sc} outputs were altered according to solar radiation levels, so solar radiation had a greater impact on the I_{sc} , rather than the surface temperature of the panels.

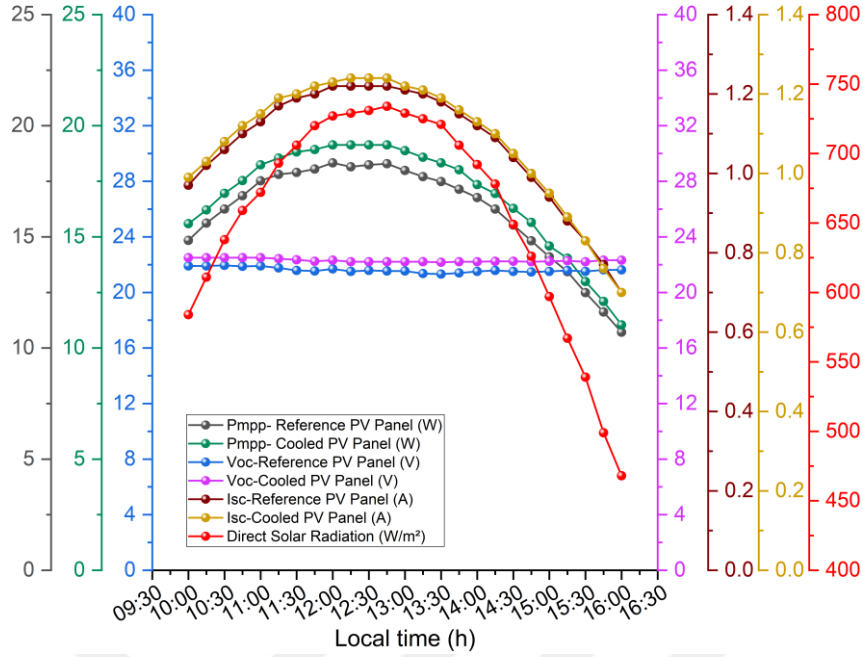


Figure 8.19. Interrelation of V_{oc} and I_{sc} with P_{mpp} and DSR

Figure 8.20 distinguishes the reference and cooled PV panels according to their panel and overall cell efficiencies and FF rates. At all measurement intervals, the cooled panel achieved higher panel and cell efficiencies than the reference panel, emphasizing the effectiveness of the cooling process and its favorable influence. The cooled panel achieved an average panel efficiency of 17.12% and total cell efficiency of 23.15%, whereas the reference panel had average panel and cell efficiencies of 16.39% and 22.15%, respectively. This led to a 4.45% enhancement in average panel efficiency and a 4.52% increase in total average cell efficiency. The efficiency of both panels fell progressively over the monitoring period, which was likely driven by the increase in air temperature. There were negligible differences in FF rates, which meant that the cooled panel's larger power output at the data collection intervals was on account of the boost in V_{mpp} and V_{oc} provided by EC process, since the I_{mpp} and I_{sc} values for both panels were approximately the same, as well.

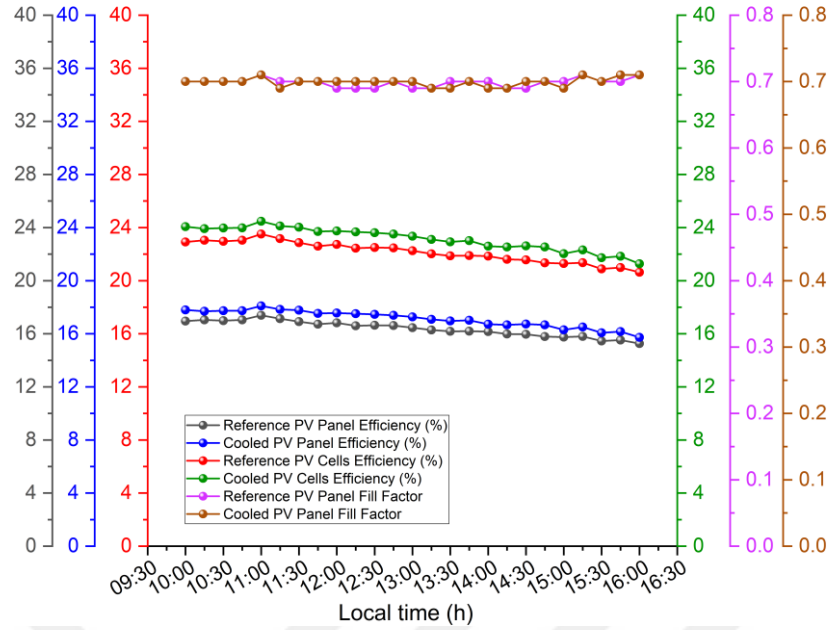


Figure 8.20. PV panel efficiency and FF analysis

Depicted in **Figure 8.21** are the energy outputs at the specified measurement times, the cumulative energy outputs for the reference and cooled PV panels, and their link with the DSR intensity. The cooled panel showed a sustained advantage in energy output across the entire experimental timeline. Accordingly, the cumulative energy output of the cooled panel increased by 4.52% advancement relative to cumulative energy of the reference panel.

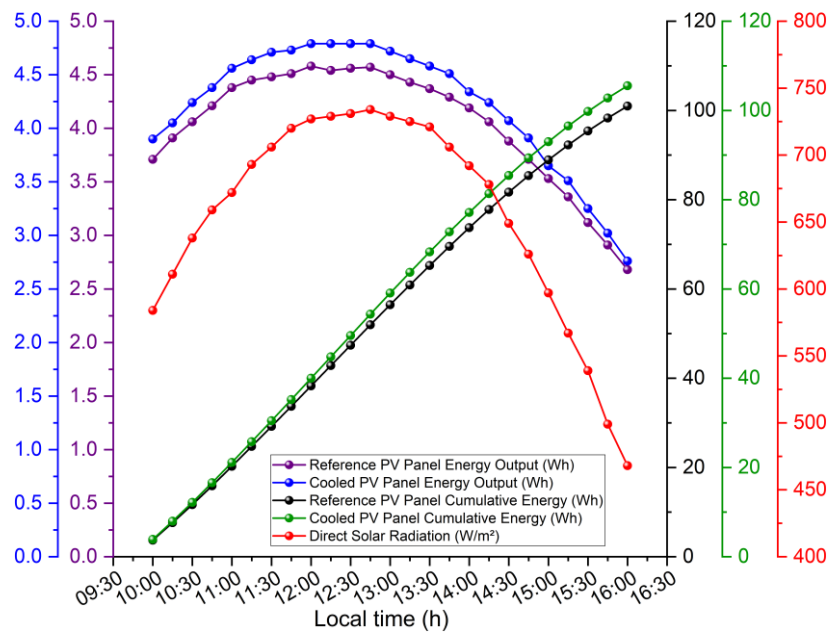


Figure 8.21. Energy yield, cumulative energy, and DSR

Thermal camera pictures of the reference and cooled PV panels are laid out in time order at 30-min increments between 10:30 and 16:00 local time in **Figure 8.22**. Thermal pictures revealed that the reference panel consistently experienced much higher temperatures. What's more, a uniformly distributed cooling effect is discernible in the thermal camera images.

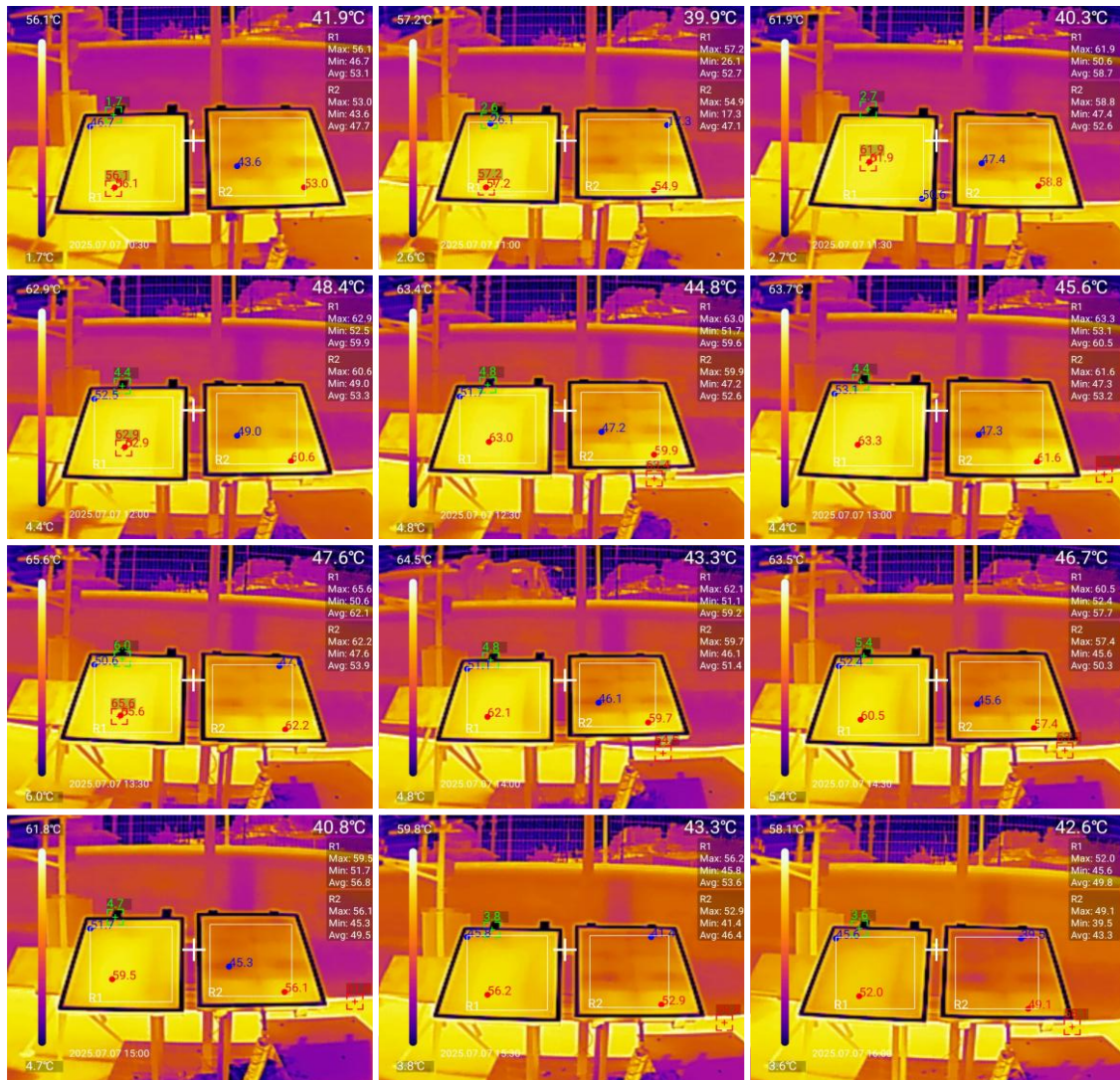


Figure 8.22. Thermal camera images of the Reference (R1) and Cooled (R2) Panels at 30-min intervals from 10:30 to 16:00 local time

To summarize, the 1-s on/135-s off pump cycle demonstrated slightly lower performance with respect to temperature reduction, efficiency, and energy production when compared to both the 1-s on/45-s off pump and 1-s on/90-s off pump cycles.

8.1.4. Outcomes of the 1-s on/180-s off pump cycle

In sum, 1884g of water was sent to the CP placed onto the back side of the PV panel over 120 cycles. An even spread of water on the pad was ensured by the liquid distribution system. The tray under the panel collected 1115g of water, while 769g of water evaporated, enabling heat removal. Subsequently, water collected was sent back to the underground tank by gravity.

The trends in wind direction, average wind speed, average air temperature, humidity and average global solar radiation recorded by the weather station on the day of the experiment (July 8, 2025) are defined in **Figure 8.23**. There were no drastic changes in the average wind speed during the day, with the wind mostly coming from the northwest and periodically shifting to the southeast. The average air temperature steadily rose throughout the day, with values between 35 and 41 °C. In contrast, the relative humidity decreased with occasional fluctuations during the day. A regular daily pattern was recorded in the average global solar radiation. Its maximum readings were detected from 12:00 to 13:00 local time.

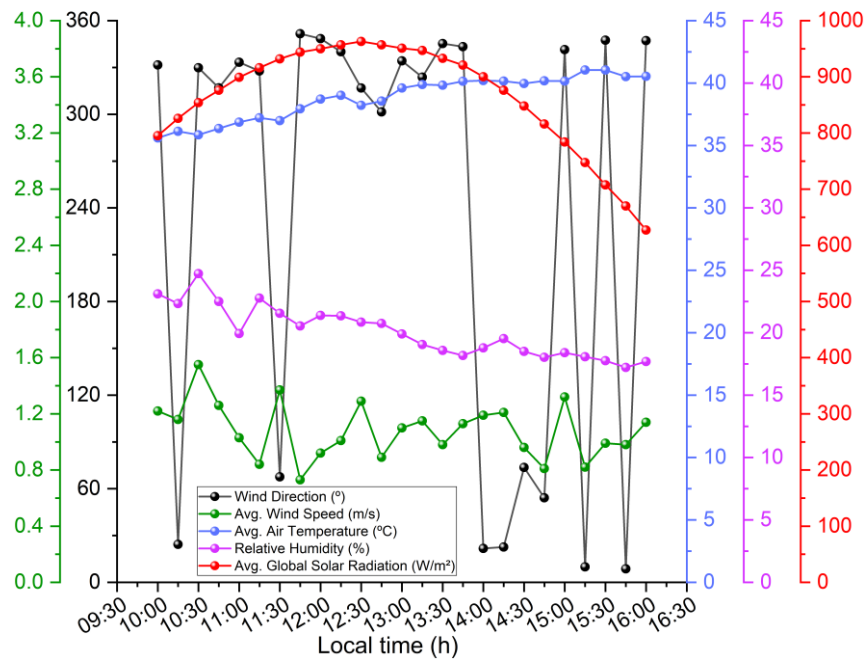


Figure 8.23. Environmental parameters on the test day

Figure 8.24 presents the temperature gradients of the reference and cooled PV panels, temperature reduction achieved through the cooling process, and DSR. The EC

lowered the panel's temperature by a minimum of 4.2 °C and a maximum of 8.8 °C. The reference panel's temperature rose as high as 65.5 °C, whereas the cooled panel's temperature remained below 59 °C. Except for early morning hours, this cooling configuration sustained a temperature difference greater than 6 °C. The temperature drop readings in the late afternoon were comparable to those during the midday period, though there was a significant decline in solar radiation. This can be related to the increased air temperature and reduced relative humidity in late afternoon.

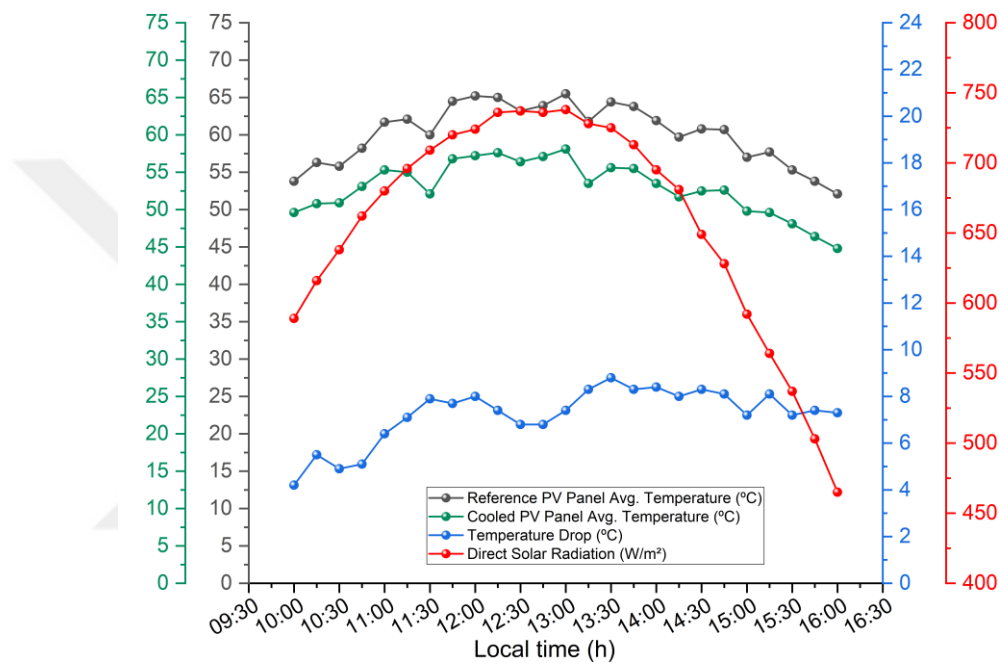


Figure 8.24. Temperature gradients, temperature decrease, and DSR

Figure 7.25 contrasts the P_{mpp} , V_{mpp} , and I_{mpp} readings of the reference PV panel with those of the cooled PV panel, along with their correlation with the DSR. The cooled panel demonstrated greater P_{mpp} values throughout all assessed points, which is attributable to higher V_{mpp} values at those points brought about by the EC effect. The I_{mpp} readings for both panels were nearly equal, so they were not greatly affected by the EC. Nonetheless, solar radiation has a significant influence on I_{mpp} readings, as their curves show a strong resemblance. The V_{mpp} curves of both panels were linear with minor variations, suggesting no significant effect from solar radiation.

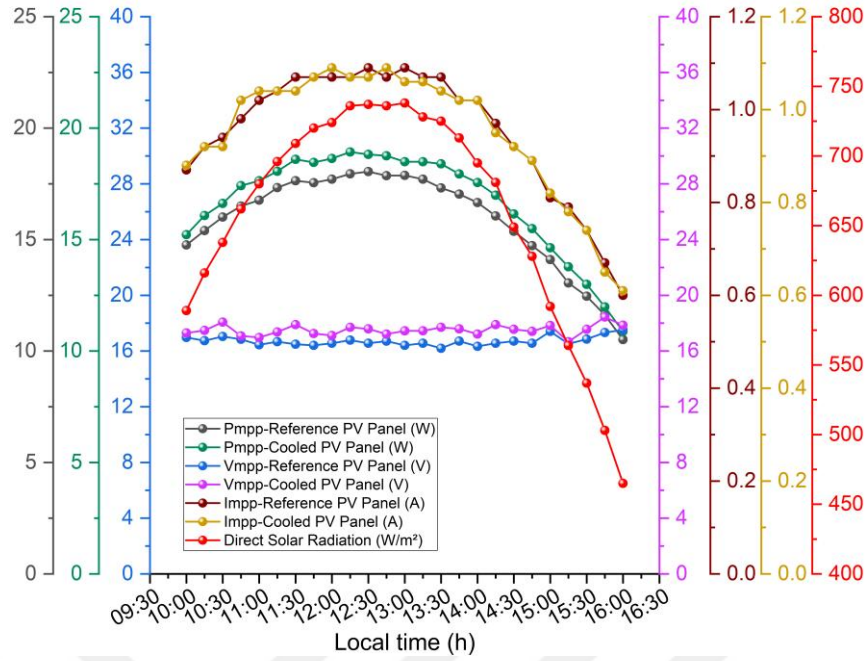


Figure 8.25. Variations of P_{mpp} , V_{mpp} , and I_{mpp} with DSR

The V_{oc} and I_{sc} measurements of the reference and cooled PV panels, and their interrelation with the P_{mpp} and DSR are summarized in **Figure 8.26**. Following the parallel pattern of the V_{mpp} curves, the panels' V_{oc} curves were linear, and the measurements were lower for the reference panel across all data points. On the contrary, the panels' I_{sc} measurements were almost identical, and their curves tracked the variation in solar radiation, as consistent with I_{mpp} curves. Considering the findings, the EC predominantly influenced the V_{oc} measurements, as well as the V_{mpp} readings, and solar radiation had the greatest effect on the I_{sc} values, similar to the I_{mpp} readings.

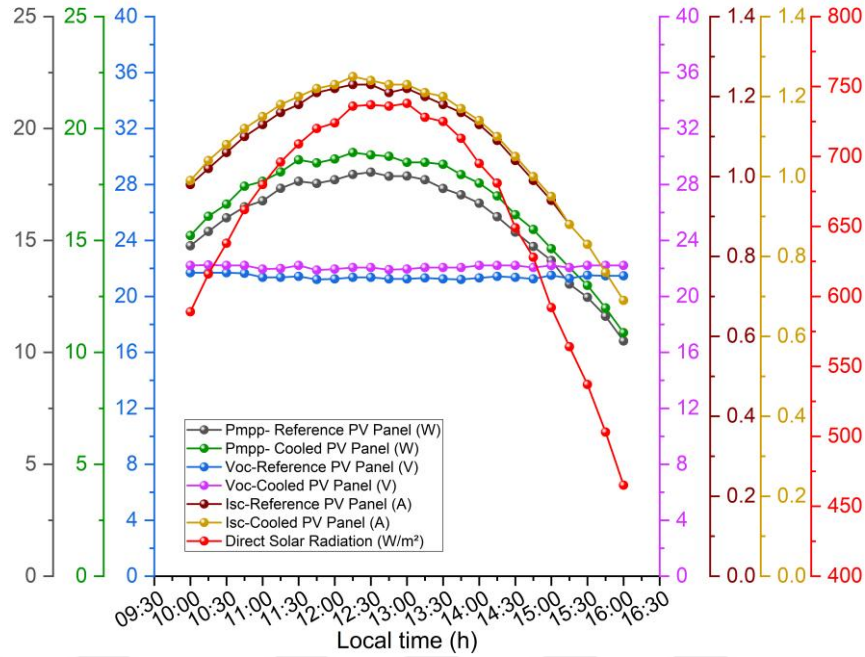


Figure 8.26. Variations of V_{oc} and I_{sc} with P_{mpp} and DSR

Figure 8.27 compares the reference and cooled PV panels based on their panel and overall cell efficiencies and FF values. The cooled panel's panel and cell efficiencies surpassed those of the reference panel in every measurement, outlining the effectiveness of the EC setup. The cooled panel showed average efficiencies of 16.86% for the panel and 22.79% for the overall cell, compared with 16.10% and 21.76% for the reference panel. As a consequence, average panel efficiency was enhanced by 4.72%, while total average cell efficiency increased by 4.63%. The efficiencies of both panels went down gradually during the full span of the experiment, which was possibly caused by an increase in cell temperature due to the elevation in air temperature. The panels' FF values differed by negligible values, suggesting that the greater power output readings of the cooled panel were because of the rise in voltage production, as the current values for both panels were matching closely.

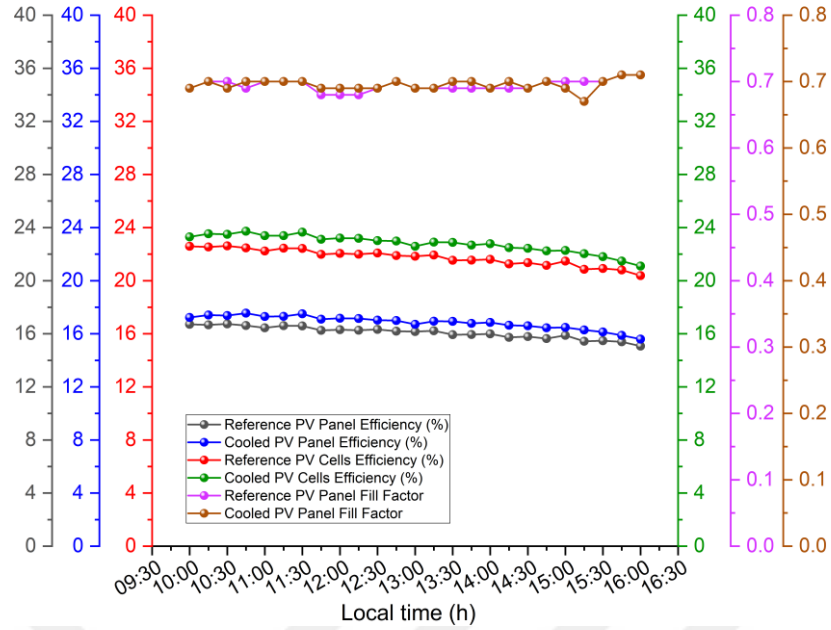


Figure 8.27. Reference panel vs. cooled panel in terms of efficiency and FF

The energy outputs of the reference and cooled PV panels at the designated measurement points, their cumulative energy outputs, and the relationship between these outputs and the magnitude of DSR are shown in **Figure 8.28**. The cooled panel's energy output continued to be higher than that of the reference panel during the whole experimental day. Thus, the cumulative energy yielded by the cooled panel exceeded that of the reference panel by 4.77%.

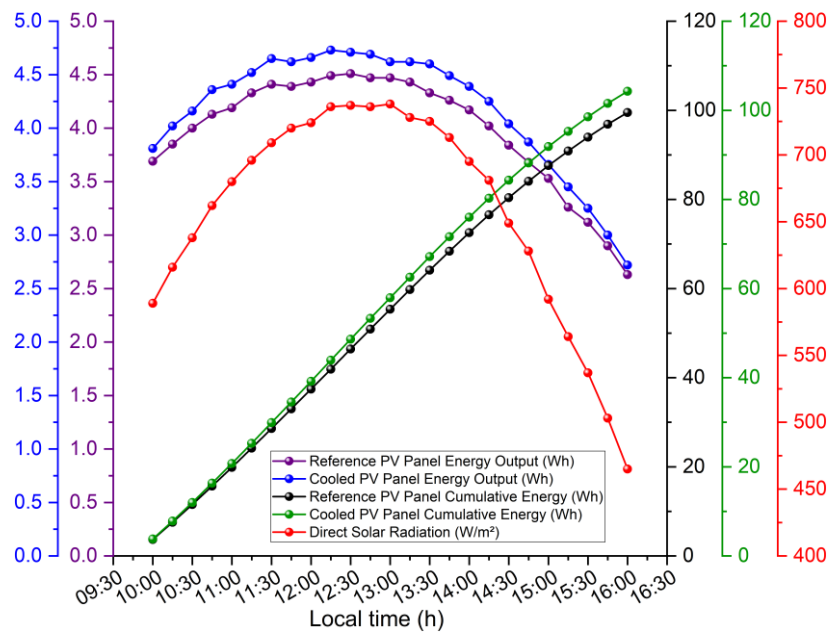


Figure 8.28. Reference panel vs. cooled panel based on their energy outputs, with DSR

Thermal camera pictures of the reference and cooled PV panels are sequenced by their capture times at 30-min increments between 10:30 and 16:00 local time in **Figure 8.29**. The thermal views distinctly indicated that the reference panel functioned at much higher temperatures. Furthermore, the thermal views revealed a nearly uniform cooling effect across the panel surface.

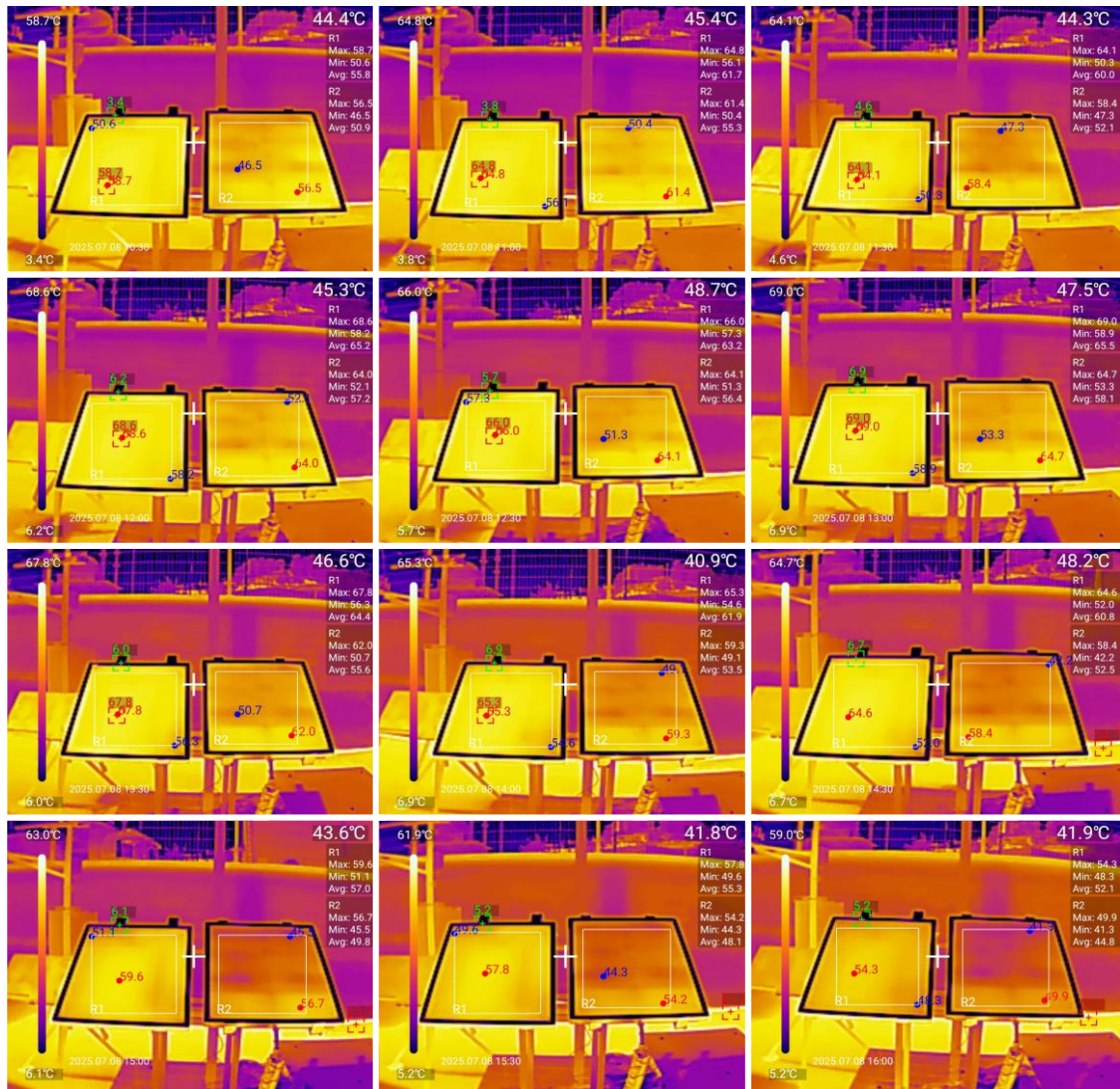


Figure 8.29. Thermal camera pictures of the reference (R1) and cooled (R2) panels at 30-min periods from 10:30 to 16:00 local time

In conclusion, the 1-s on/180-s off pump cycle delivered marginally better performance regarding temperature reduction, efficiency, and energy production compared to the 1-s on/135-s off pump cycle, and comparable results to 1-s on/90-s off

pump cycles. Therefore, the 1-s on/180-s off pump cycle appears to be more advantageous for regions with limited water resources than the 1-s on/135-s off pump cycle.

8.1.5. Outcomes of the 1-s on/300-s off pump cycle

In total, 1130.4g of water was transferred within 72 cycles by the pump to the CP integrated on the rear side of the PV panel during the timeframe of the test day. The liquid distribution system provided homogeneous coolant distribution on the pad. The tray beneath the panel accumulated 420 g of water, while 710.4 g of water evaporated, lowering the panel temperature. The water gathered in the tray was redirected to the underground tank by gravity.

Figure 8.30 details the variations in the wind direction, mean wind speed, mean air temperature, humidity and average global solar radiation calculated by the weather station throughout the experimental day (July 9, 2025). The wind direction largely originated from the northwest, with occasional changes to the southwest. The average wind speed was greater between 12:00 and 13:30 local time, when solar radiation was higher as well, compared to the rest of the observation periods. The average air temperature elevated during the day, with minor fluctuations. The readings for the average air temperature were between 33 and 42 °C. The relative humidity was notably lower after 12:00 local time, varying between 14% and 19%. The average global solar radiation followed a trend of a standard day, ascending its peaks from 12:00 and 13:30 local time.

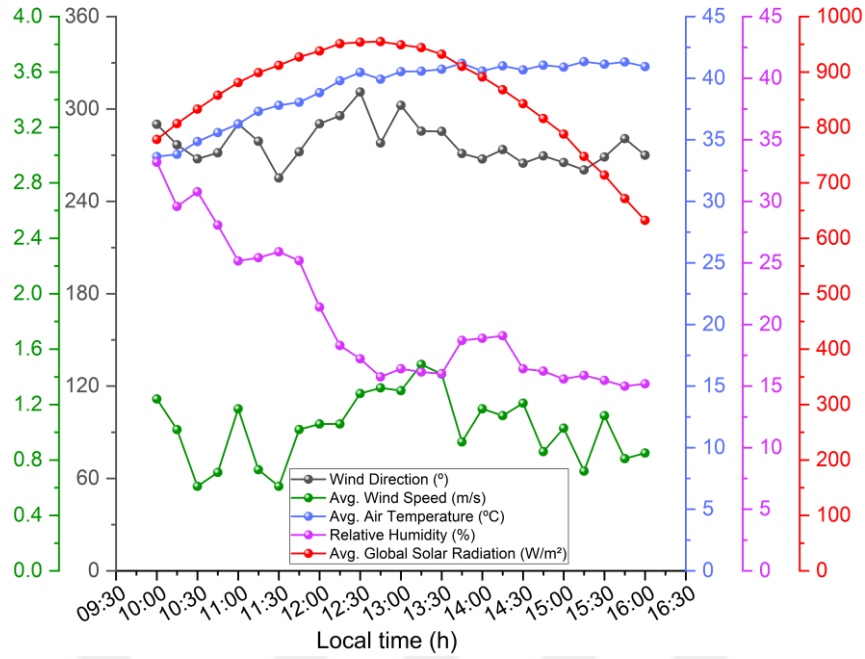


Figure 8.30. Environmental conditions on the experimental day

The temperature deviation of the reference and cooled PV panels, temperature decrease as a result of the EC, and the DSR are shown in **Figure 8.31**. The cooling procedure brought about a temperature decrease in the panel throughout the testing duration, keeping the temperature of the panel below 59 °C. The reference panel's temperature went up to 64 °C. Apart from the period before noon, the temperature reduction of over 5 °C was sustained by the cooling technique. The maximum temperature difference between the panels was 7 °C. The largest temperature reduction was monitored from 12:45 to 13:45 local time, when the solar radiation was at its optimum, and average wind speed at its highest. Despite lower solar radiation in the late afternoon, the temperature difference remained comparable that observed at midday, owing to higher air temperatures and decreased relative humidity.

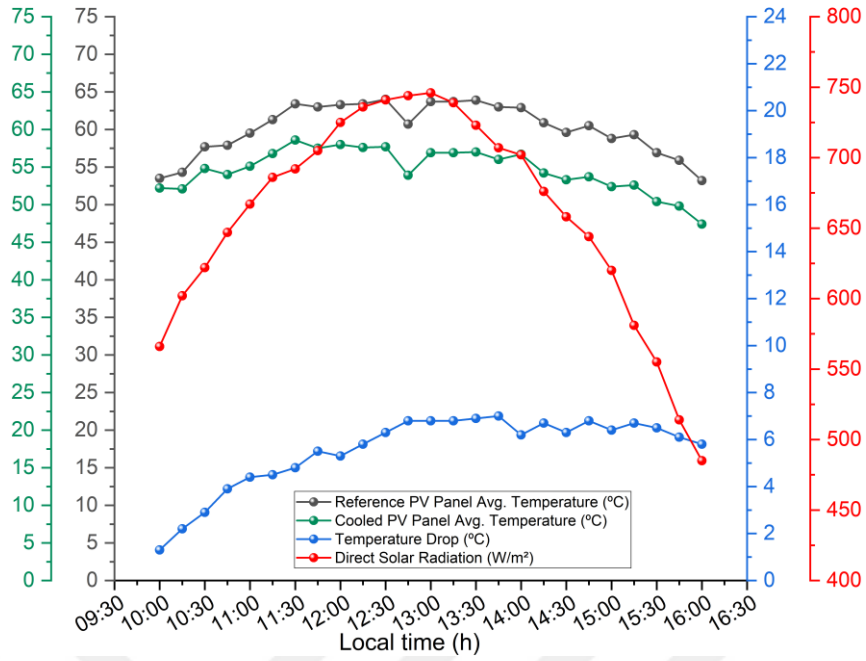


Figure 8.31. Temperature profiles, temperature drop, and DSR

Figure 8.32 presents a comparison between the P_{mpp} , V_{mpp} , and I_{mpp} values of the reference panel and those of the cooled panel, together with DSR. The EC improved the P_{mpp} values at every measurement point; however, the values remained similar in the early morning and late afternoon due to lower solar radiation. The V_{mpp} measurements for both panels displayed a nearly linear trend, with the cooled panel registering higher values at measurement points. Thus, the V_{mpp} measurements were slightly influenced by solar radiation but mainly affected by the temperature drop as a consequence of the EC. Yet, the EC did not primary impacted the I_{mpp} measurements, as they were almost equivalent. Nevertheless, their curves approximately mirrored that of the DSR curve, implying that solar radiation was the dominant factor affecting them.

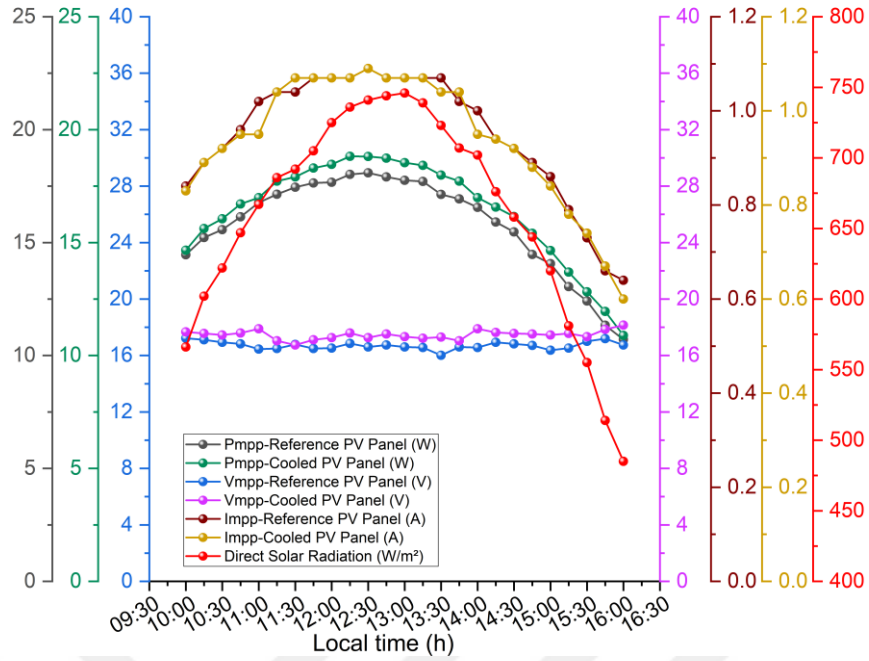


Figure 8.32. P_{mpp} , V_{mpp} , I_{mpp} and their dependence on DSR

The V_{oc} and I_{sc} data of the reference and cooled PV panels with respect to their P_{mpp} data, and DSR are indicated in **Figure 8.33**. As with the V_{mpp} curves, the V_{oc} curves were linear for both panels, and the cooled panel had higher data relative to the reference panel. On the other hand, similar to the I_{mpp} curves, the I_{sc} curves reflected the same path as the solar radiation curve, and both panels showed almost identical I_{sc} data. Overall, these outcomes suggest that the cooling method mainly impacted the V_{oc} data, thereby increasing the voltage generation, rather than changes in solar radiation. The I_{sc} data of both panels were primarily impacted by the changes in solar radiation.

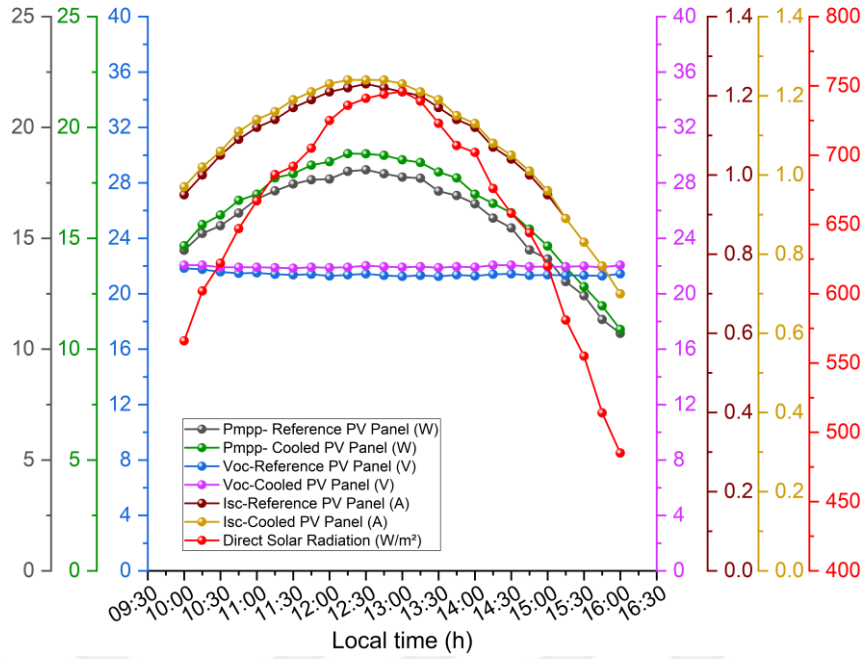


Figure 8.33. V_{oc} and I_{sc} variation with respect to P_{mpp} and DSR

The panel efficiencies of reference and cooled PV panels, their aggregate cell efficiencies, and their FF values are displayed in **Figure 8.34**. In all measurements, the cooled panel achieved higher panel and cell efficiencies than the reference panel, demonstrating the effectiveness of the EC setup. Average panel and overall cell efficiency for the cooled panel were 16.57%, and 22.4%, respectively, exceeding the reference panel values of 15.97% and 21.59%. This resulted in a 3.76% improvement in average panel efficiency and a 3.72 % increase in overall average cell efficiency. The efficiencies of both panels progressively declined over the course of the experiment, primarily due to the increase in cell operation temperature caused by the rise in air temperature. The FF values of the panels showed only minor differences, indicating that the cooled panel's higher power output resulted from increased voltage generation, since the current production of both panels were nearly identical.

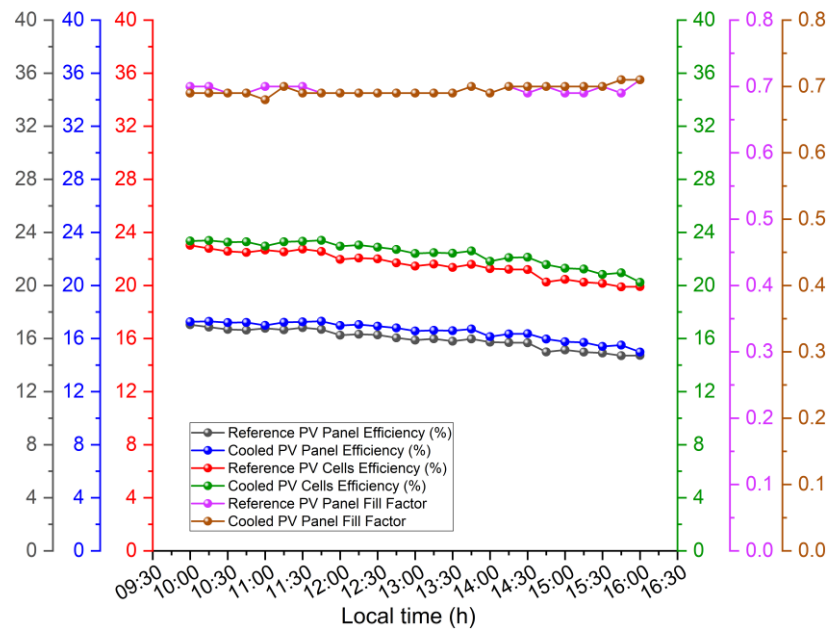


Figure 8.34. Illustration of cell Efficiency, panel Efficiency, and FF

Figure 8.35 demonstrates the energy outputs of the reference and cooled PV panels at the set measurement intervals, their cumulative energy production, and the correlation between the energy measurements and DSR. The EC system contributed to the energy generation throughout testing period in the panel; therefore, the cumulative energy output of the cooled panel rose by 3.62% relative to the reference panel's cumulative energy.

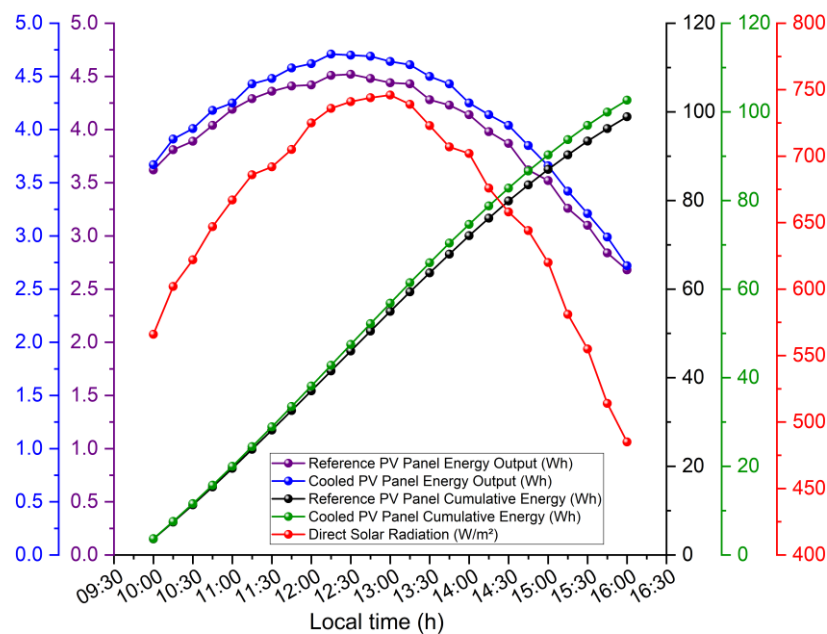


Figure 8.35. Reference and Cooled Panel's Energy Outputs, and DSR

Thermal camera images of the reference and cooled PV panels, ordered according to their subsequent times at 30-min intervals between 10:30 and 16:00 local time, are shown in **Figure 8.36**. It is apparent from the images that the cooling technique was effective, as there was a pronounced temperature increase in the reference panel. What's more, the cooling effect is nearly uniformly distributed over the panel surface.

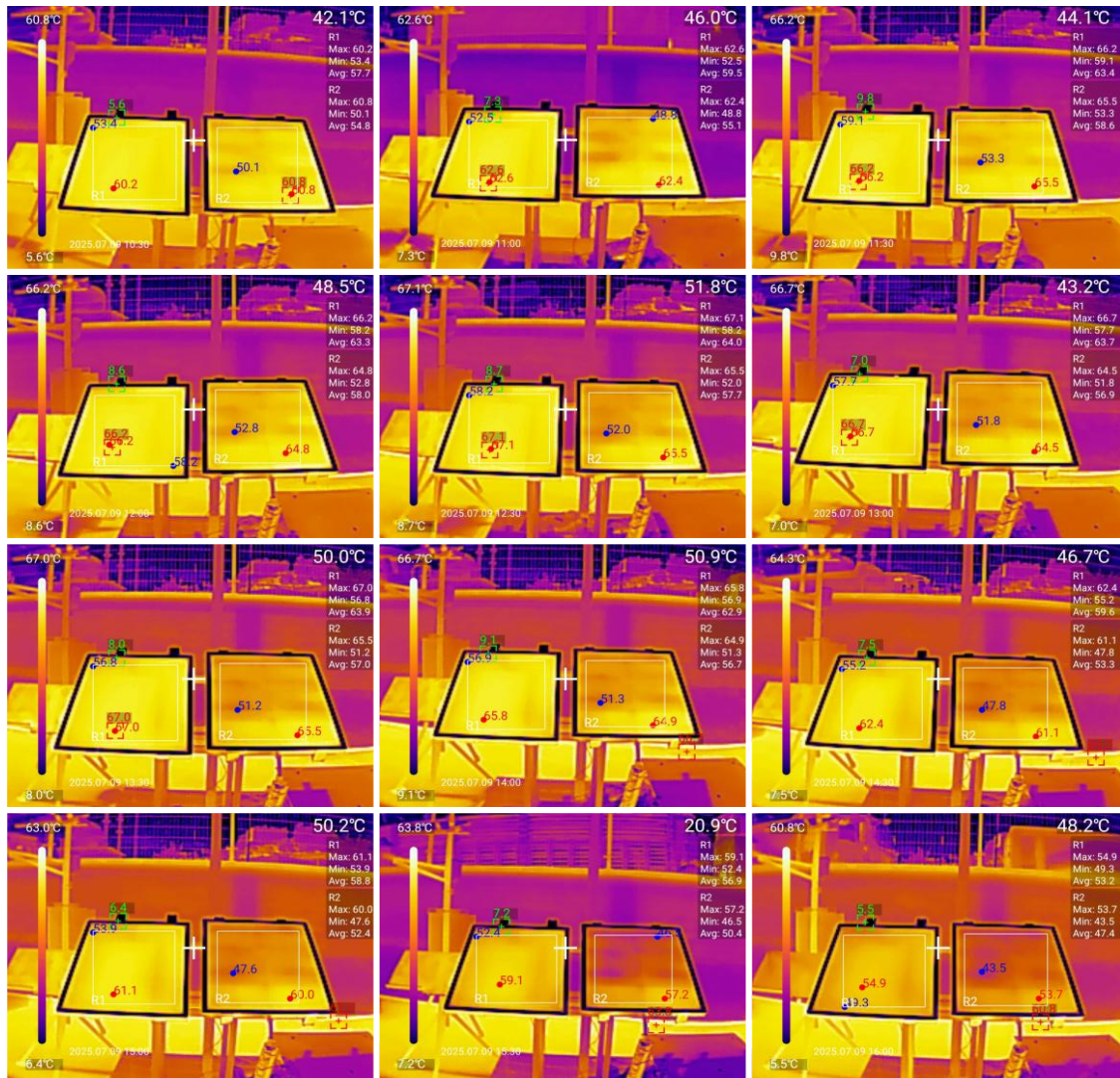


Figure 8.36. Thermal camera images of the reference (R1) and cooled (R2) panels at 30-min time points from 10:30 to 16:00 local time

Overall, the temperature reduction, efficiency, and energy production performance of the 1-s on/300-s off pump cycle was lower than those of the other pump cycles applied with the CP. Increasing off time of the pump beyond 300 s may not deliver

adequate temperature reduction and, consequently, may not enhance the panel's performance output.

8.1.6. Outcomes of the manual spraying

An average of 96g of water was manually sprayed onto the CP mounted on the back side of the panel every 30 min, extracting unwanted heat.

Figure 8.37 details weather condition parameters, which comprise of wind direction, average wind speed, mean air temperature, humidity and average global solar radiation, during the test day (July 10, 2025), measured by the weather station. The wind direction occasionally shifted to the southwest, but it predominantly blew from the northwest on the day of the experiment. After 12:00 local time, average wind speed recorded higher values, whereas relative humidity varied between 12% and 20%. The average air temperature ranged between 33 and 43 °C, demonstrating gradual increase until 14:45 local time. The patten of the average solar radiation was typical, attaining its maximum levels between 12:00 and 13:30 local time.

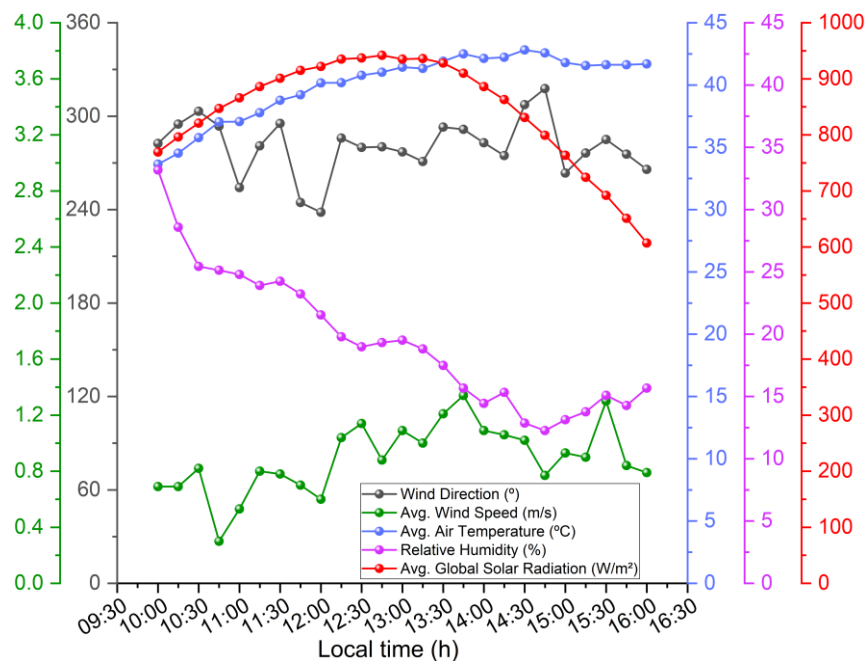


Figure 8.37. Weather conditions on the test day

The temperature variation of the reference and cooled PV panels, temperature reduction resulting from the EC, and the DSR are illustrated in **Figure 8.38**. The cooling

process led to a sustained temperature reduction in the panel during the experimental timeframe. The temperature of the reference panel escalated to 67.4 °C, while the temperature of the cooled panel maintained below 59 °C. The cooling process lowered the temperature of the panel by up to 10.1 °C, considering the reference panel temperature as the baseline. Although solar radiation was weaker in the late afternoon, the temperature drop values during late afternoon period were comparable to those in the midday hours due to an increase in wind speed and air temperature, coupled with a reduction in relative humidity. Apart from early morning hours, the manual spraying of approximately 96g water sustained a temperature difference above 6 °C. Nonetheless, this cooling technique may not be advantageous over extended timeframes.

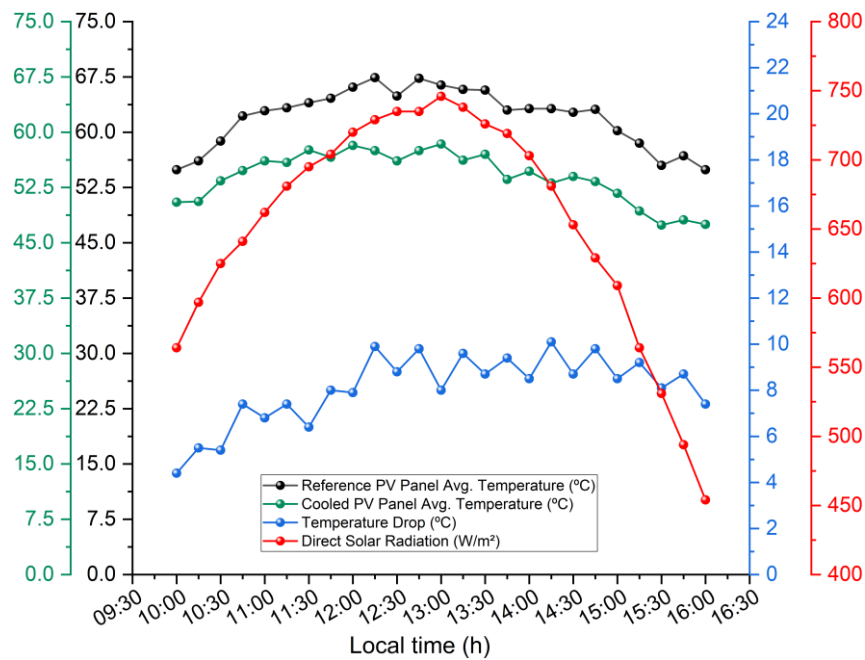


Figure 8.38. Temperature profiles, temperature drop, and DSR

Figure 8.39 compares the MPP parameters of the reference panel with those of the cooled panel, along with the DSR. Although the cooling process enhanced the P_{mpp} values at all measurement points, these values remained close in the early morning and late afternoon because of reduced solar radiation. The V_{mpp} readings for both panels followed a linear pattern, with the cooled panel showing higher values at all recorded points. Therefore, solar radiation had a minor effect on the V_{mpp} readings, and the improvement in the V_{mpp} values of the cooled panel was largely caused by the temperature decrease brought about by the EC system. The temperature decrease did not largely

influence the I_{mpp} readings since they were nearly equal. However, their curve tracked the path of the solar radiation curve, so they were mainly influenced by solar radiation.

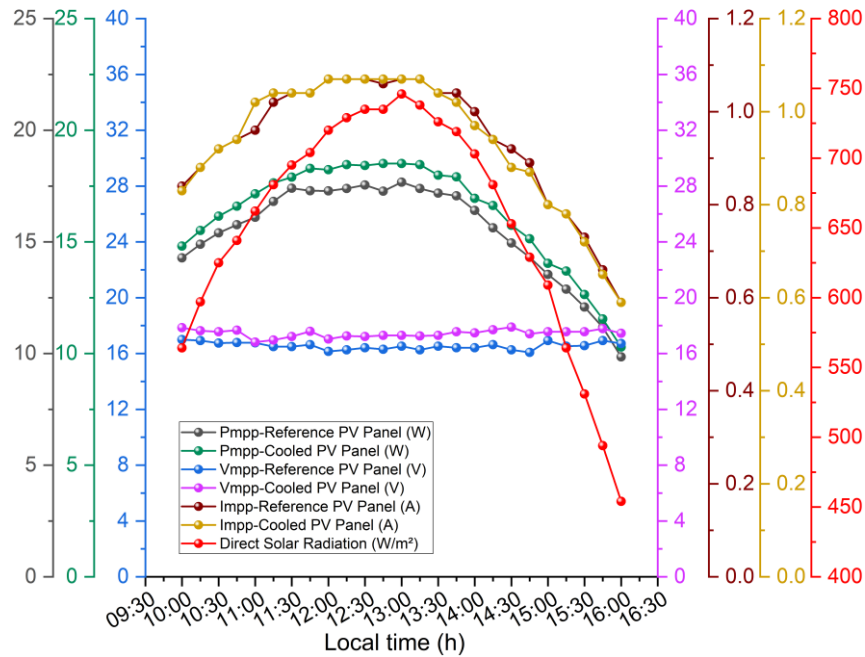


Figure 8.39. P_{mpp} , V_{mpp} , I_{mpp} with respect to DSR

The V_{oc} and I_{sc} measurements of the reference and cooled PV panels in comparison with their P_{mpp} measurements, and DSR are reported in **Figure 8.40**. The V_{oc} measurements for both panels had linear curves, with the cooled panel possessing larger rates at all measurement points. By contrast, the I_{sc} measurements for both panels closely matched, and the paths of their curves were the same as the solar radiation curve. Thus, the manual spraying mainly influenced the V_{oc} measurements, improving the voltage production, as opposed to alterations in solar radiation. The variation in solar radiation primarily affected the I_{sc} measurements.

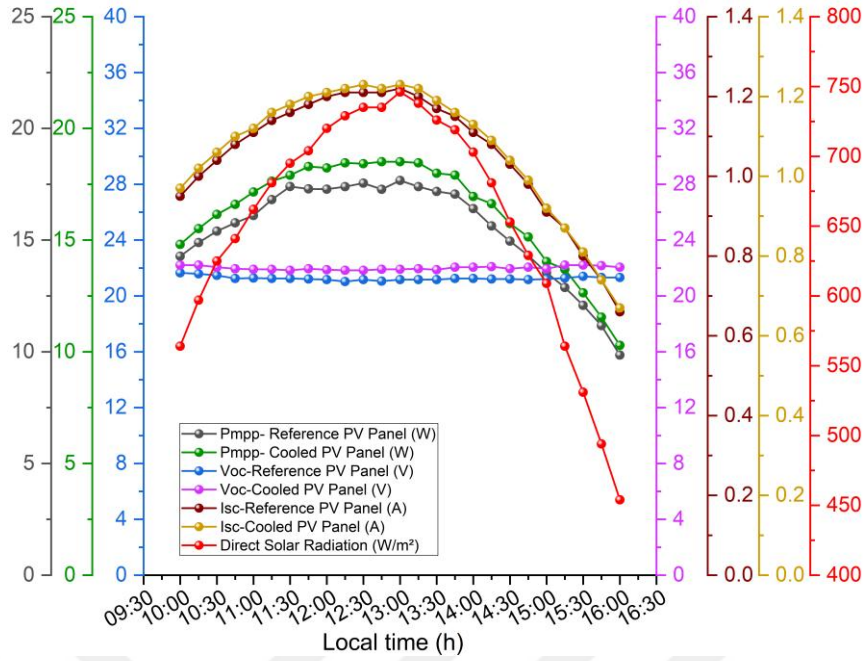


Figure 8.40. V_{oc} and I_{sc} in comparison with P_{mpp} and DSR

Figure 8.41 conveys the cell and panel efficiency of the reference and cooled PV panels, with their correlation with the respective FF rates. The cooling process considerably improved the panel and cell efficiency throughout the measurement range. The cooled panel performed with an average panel efficiency of 16.59% and a cell efficiency of 22.42%, compared to 15.79% and 21.35% for the reference panel. There was an average 5.07% increase in panel efficiency and 5.01% improvement in total cell efficiency as a result of the EC process. Nevertheless, the FF readings were linear and nearly identical for the panels. The panel and cell efficiency of the cooled panel was higher because lower cell temperatures led to higher V_{oc} and V_{mpp} , thereby resulting in greater energy output, and higher panel and cell efficiency, even though I_{sc} and I_{mpp} or FF readings remained relatively unchanged.

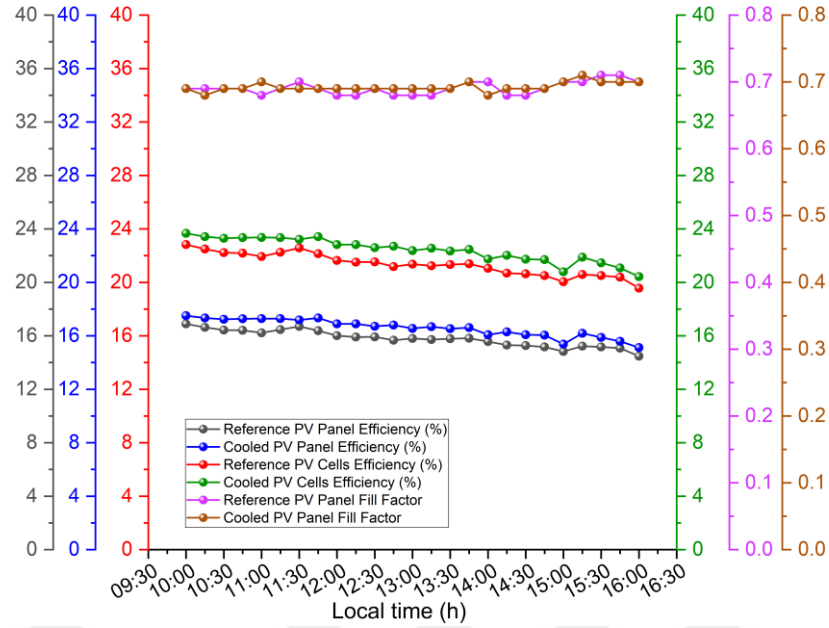


Figure 8.41. Cell efficiency, panel efficiency, and FF

The energy output at all observation points and calculated cumulative energy of the reference and cooled PV panels, along with the DSR are arranged in **Figure 8.42**. The manual spraying onto the CP boosted the energy output of the panel. This resulted in a 5.07% improvement in cumulative energy. The enhancement in energy output resulted from the increased V_{oc} and V_{mpp} values caused by the EC process, as the I_{sc} , I_{mpp} and FF measurements for both panels were nearly equivalent.

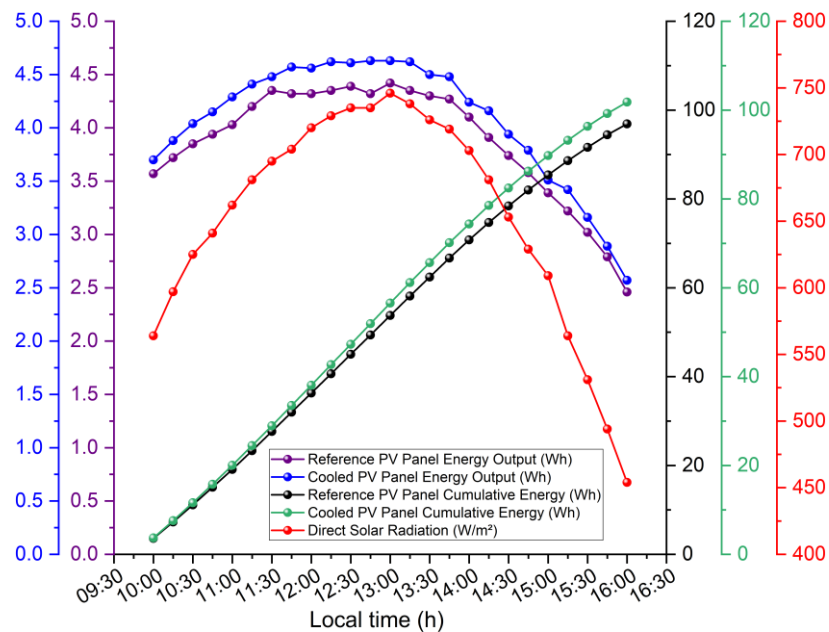


Figure 8.42. Energy output at the measurement points, Cumulative Energy, and DSR

Thermal camera views of the reference and cooled PV panels acquired at the specified local times (10:45, 11:00, 11:45, 12:00, 12:45, 13:00, 13:45, 14:00, 14:45, 15:00, 15:45, and 16:00) are illustrated in **Figure 8.43**. The images prove that the manual spraying onto the rear side of the panel was effective in uniformly mitigating the panel's surface temperature.

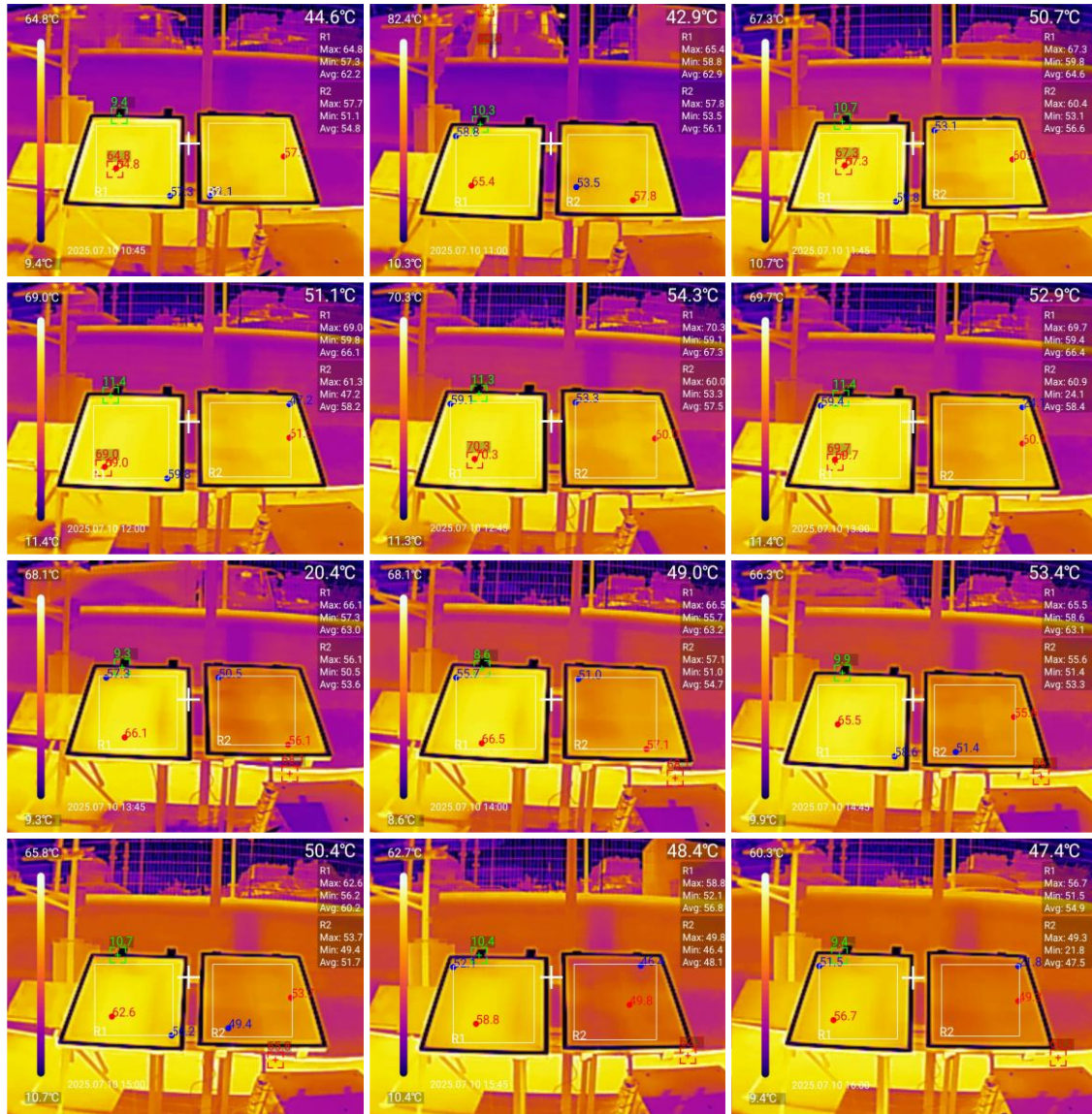


Figure 8.43. Thermal views of the reference (R1) and cooled (R2) panels at appointed hours between 10:00 and 16:00 local time

To sum up, the manual spraying on the CP secured a higher cumulative energy improvement ratio, and higher temperature reduction relative to the 1-s on/90-s off, 1-s on/135-s off, 1-s on/180-s off, and 1-s on/300-s off pump cycles, despite the more

advantageous environmental conditions, including higher wind speeds and lower average air temperatures, on the days when those pump cycles were operated.

8.1.7. Summary of outcomes of the EC system using CP and underground cooling

The following highlights a summary of the outcomes of the EC technique using CP and underground cooling:

- All six implementations of the EC with the CP and underground cooling proved feasible in dry and extremely hot climates.
- The cooling implementations steadily lowered the PV panel's surface temperature throughout the experiments, increasing the panel's efficiency and energy generation, and improving its I-V characteristics.
- The cooling implementations provided uniform cooling over the panel's surface, as evidenced by the thermal camera images. Therefore, they inhibited potential hotspots, current mismatch issues, and prolonged structural damage.
- The maximum temperature reduction for the 1-s on/45-s off pump cycle, 1-s on/90-s off pump cycle, 1-s on/135-s off pump cycle, 1-s on/180-s off pump cycle, 1-s on/300-s off pump cycle and manual spraying were 10.3 °C, 9.1 °C, 8.2 °C, 8.8 °C, 7.0 °C and 10.1 °C, respectively.
- The average percentage increase in panel efficiencies for the 1-s on/45-s off pump cycle, 1-s on/90-s off pump cycle, 1-s on/135-s off pump cycle, 1-s on/180-s off pump cycle, 1-s on/300-s off pump cycle and manual spraying were 5.38%, 4.90%, 4.45%, 4.63%, 3.72%, 5.07%, respectively, in comparison to the reference panel.
- The average improvement in overall cell efficiencies was 5.33%, 4.91%, 4.52%, 4.72%, 3.76%, 5.01%, respectively, relative to the reference panel.
- The 1-s on/45-s off pump cycle resulted in a continuous temperature reduction exceeding 6 °C during the experimental timeframe. Furthermore, it yielded a 5.46% increase in cumulative energy output compared to the reference panel. This increase was larger than that of the rest of the setups used for the CP.
- The 1-s on/90-s off pump cycle ensured a temperature drop higher than 7 °C over the course of the experimental day, excluding the measurements at 10:00 and 10:15 local time. Additionally, it secured a 4.95% enhancement in cumulative energy output,

which was higher than those of the 1-s on/135-s off and 1-s on/180-s off pump cycles, using the reference panel's cumulative energy output as the reference point.

- The 1-s on/135-s off and 1-s on/180-s off pump cycles resulted in comparable improvements in cumulative energy percentage relative to the reference panel, with increases of 4.52% and 4.77%, respectively. Furthermore, the 1-s on/135-s off and 1-s on/180-s off pump cycles led to similar temperature drops, both consistently exceeding 5 °C, and these reductions were consistently greater at all measurements points than those achieved by the 1-s on/300-s off pump cycle. Consequently, the 1-s on/300-s off pump cycle yielded a lower cumulative energy enhancement ratio, compared to the 1-s on/135-s off and 1s on/180-s off pump cycles, based on the cumulative energy output of the reference panel as the baseline.
- The 1-s on/300-s off pump cycle maintained a temperature difference greater than 4 °C throughout the experimental day, excluding the early morning hours.
- Extending the pump's off-time beyond 300 s when using the CP as the cooling material may not provide sufficient temperature reduction, thus may not improve performance output of the panel.
- Despite the unfavorable environmental conditions, including lower wind speeds and higher mean air temperatures, the manual spraying achieved a higher cumulative energy improvement ratio than that of the 1-s on/135-s off, 1-s on/180-s off, and 1-s on/300-s off pump cycles and ensured a temperature difference greater than 6 °C during a 30-min timeframe, except for the early morning hours. Moreover, its cumulative energy improvement ratio was slightly higher than that of the 1-s on/90-s off pump cycle, despite the more favorable weather conditions such as stronger wind speeds and lower average air temperature readings, on the day when the 1-s on/90-s off pump cycle was employed. Nevertheless, this cooling technique may not offer advantages over extended durations. Therefore, the spraying interval can be shortened to 15-min intervals or lower to enhance the effectiveness of the cooling approach.
- The manual spraying on the CP provided more uniform cooling across the panel relative to the 1-s on/135-s off, 1-s on/180-s off, and 1-s on/300-s off pump cycles, as validated by the thermal camera images.
- Although the total amounts of water delivered to the CP by the 1-s on/90-s off pump cycle and 1-s on/180-s off pump cycles were substantially different, the temperature reduction and cumulative energy improvement ratio values for both cycles were

comparable because the CP has a certain retention capacity, causing any excess water to simply drip into the tray.

- Slightly more water evaporated with the 1-s on/180-s off pump cycle than with the 1-s on/300-s off pump cycle, which is expected because the 1-s on/180-s off pump cycle produced a greater temperature reduction at all measurements points, as more water needed to evaporate to achieve a larger temperature reduction. In addition, the amount of water evaporated during the 1-s on/135-s off pump and 1-s on/180-s off pump cycles were similar, as both generated comparable temperature reductions under similar meteorological parameters.
- When the 1-s on/90-s off pump cycle was operated, the quantity of water evaporated was greater than the amounts evaporated during 1-s on/135-s off pump and 1-s on/180-s off pump cycles because it mostly yielded higher temperature reduction at each monitoring point.
- During the 1-s on/45-s off pump cycle, more water evaporated with respect to 1-s on/90-s off pump cycle, as it generally led to a larger drop in temperature across the measurement intervals.
- The CP was more effective in dissipating surplus heat from the panel surface under conditions of higher temperature, stronger wind speeds, and lower relative humidity. Therefore, the cooling effect provided by the CP was still effective in the late afternoon despite the decreased solar radiation, as the air temperature was higher, the relative humidity was lower, and wind speed was stronger or comparable during that period on the day of the experiments.

8.2. Finding for the EC System with CWs and Underground Cooling

The findings for the EC system with CWs and underground cooling are outlined in the section below:

8.2.1. Findings from the 1-s on/180-s off pump cycle

Overall 1884g of water was transferred to the CWs assembled on the back side of the PV panel in 120 cycles by the pump, and a uniform distribution of water on the CWs was achieved via the liquid distribution system. Throughout the process, 1024g of water

was gathered in the tray positioned below the cooled PV panel and conveyed to the underground tank by gravity. In the meantime, 861g of water evaporated, carrying away surplus heat from the panel.

Figure 8.44 laid out the environmental variables assessed by the weather station throughout the day of the experiment (July 16, 2025), covering wind direction, average wind speed, mean air temperature, humidity and average global solar radiation. The wind direction varied at times between northwest and southwest. Elevated wind speeds were measured from 11:30 to 15:00 local time. The mean air temperature remained nearly constant, mostly fluctuating between 38 and 40 °C. There were periods of cloud formation in the sky; therefore, the average global solar radiation did not follow a regular daily trend.

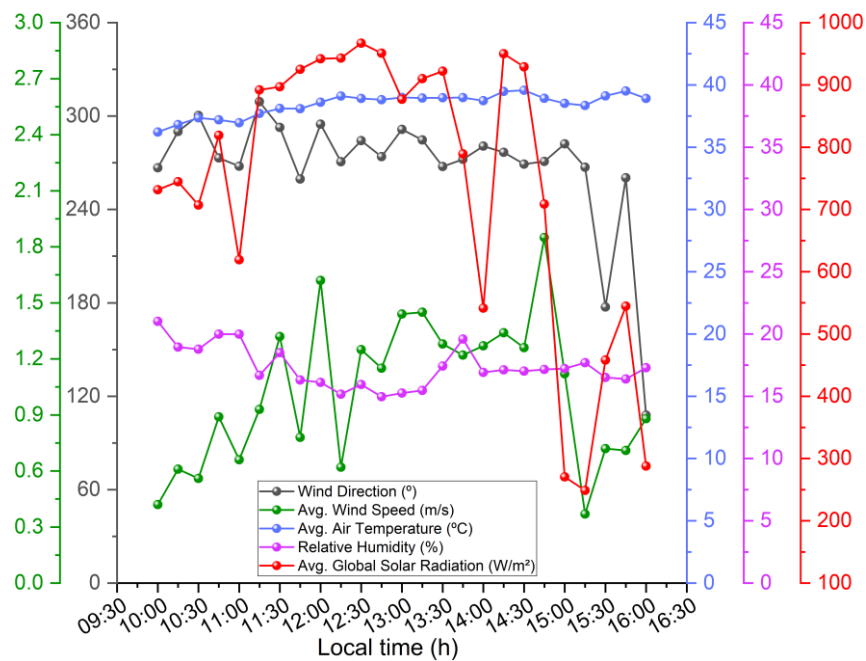


Figure 8.44. Environmental parameters recorded on the test day.

Variation of average temperature for the reference and cooled PV panel, the decrease in temperature due to the EC, and DSR are elaborated in **Figure 8.45**. The panel that underwent the cooling process showed exceptionally lower temperatures compared to the reference panel. Solar radiation was the main factor affecting panel temperatures and the pattern of temperature reduction. During periods of cloud formation, the temperature of both panels and the temperature decrease experienced a decline. For instance, there was a notable decrease in solar radiation from 13:45 to 14:00 local time, as

the temperature of the panels and the temperature decrease underwent a reduction. Regardless of this, the EC technique accomplished impressively large temperature reductions, reaching 22.7 °C between 11:15 and 14:30 local time. Factors responsible for this temperature reduction were higher solar radiation, except during periods of cloud formation, and relatively larger wind speeds. During this period, wind direction, average air temperature and relative humidity did not show drastic changes. The temperature of the reference panel exceeded 69 °C. Nevertheless, the panel exposed to the cooling process consistently remained below 47 °C.

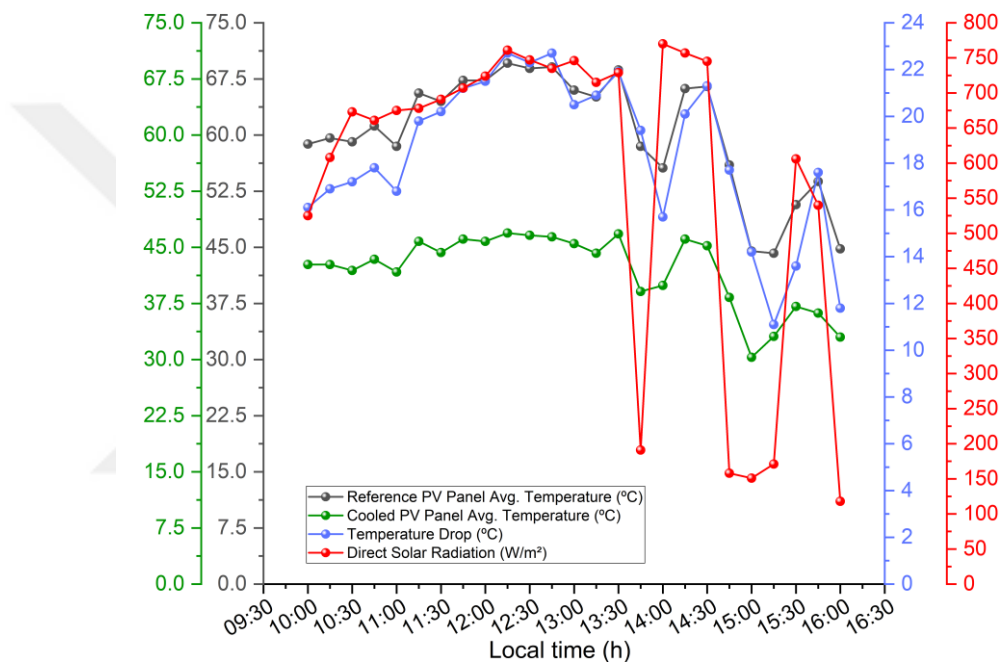


Figure 8.45. Variations of temperature, temperature decrease and DSR

Figure 8.46 demonstrates the P_{mpp} , V_{mpp} , and I_{mpp} outputs of the reference and cooled PV panels at each measurement interval, and their responses to variations in solar radiation. When compared to the reference panel, the cooled panel produced higher P_{mpp} readings, particularly between 12:15 and 13:00 local time, when subjected to the optimum solar radiation. Furthermore, there was a parallel increase in the P_{mpp} difference between 11:30 and 12:00, even though the solar radiation was lower. This increase can be linked to a rise in average wind speed during that time. Solar radiation and thermal conditions were the dominant parameters impacting the P_{mpp} readings. The I_{mpp} readings for both panels largely were equivalent, whereas the V_{mpp} readings were higher for the cooled panel. Thus, the increase in voltage readings was manifested as larger power output. The

I_{mpp} readings of the panels tracked the solar radiation curve, showing limited reactions to the thermal condition. On the other hand, the V_{mpp} readings had linear curves, primary influencing from the thermal condition.

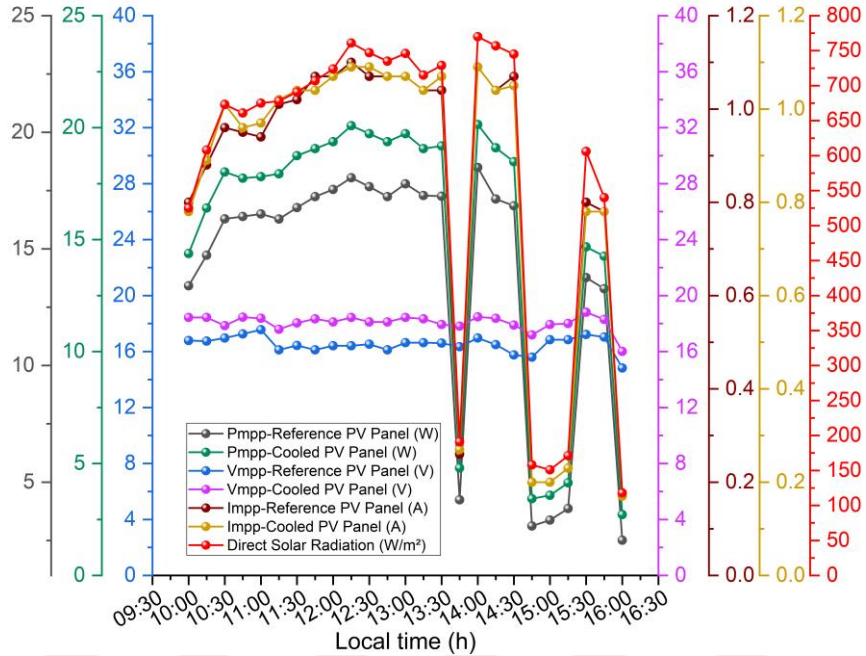


Figure 8.46. P_{mpp} , V_{mpp} , and I_{mpp} Parameters Relative to DSR

The V_{oc} , I_{sc} , and P_{mpp} characteristics of the reference and cooled PV panel and DSR are plotted in **Figure 8.47**. The cooled panel showed higher V_{oc} levels than those of the reference panel. This confirms that the V_{oc} levels were predominantly influenced by temperature and were largely unaffected by solar radiation. As a consequence, the EC had a positive effect on the voltage generation. The I_{sc} levels for both panels were mostly equivalent. Accordingly, unlike voltage output, the current output of the panels was not significantly influenced by temperature; instead reflecting the fluctuations in solar radiation.

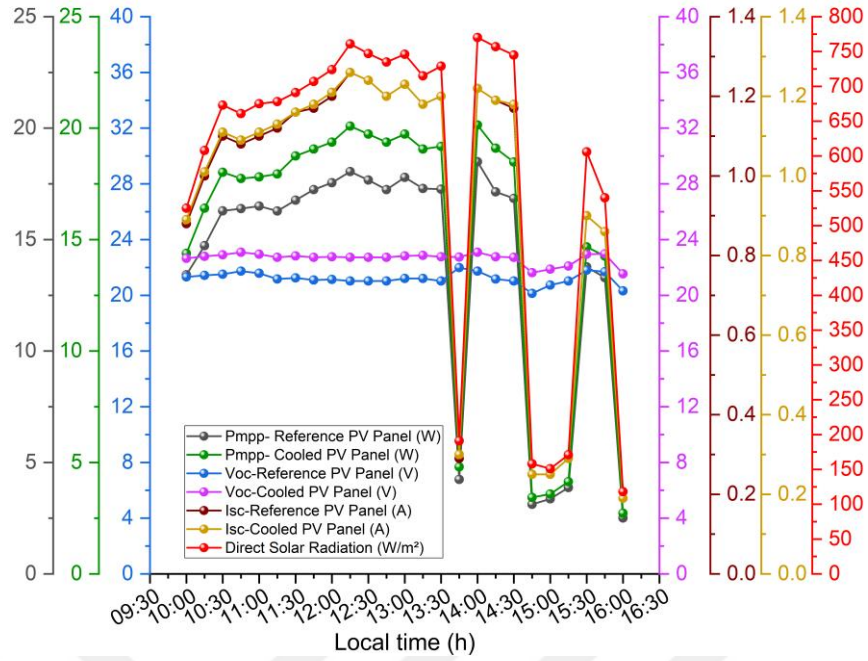


Figure 8.47. V_{oc} and I_{sc} trends and their relationship with P_{mpp} and DSR

Figure 8.48 defines cell efficiencies, panel efficiencies, and FF rates for the reference and cooled PV panels. The panel and cell efficiency were considerably enhanced by the EC method. Additionally, the FF rates were increased by the cooling effect, improving the I-V behavior. There were sharp and sudden drops in efficiency and FF readings for both panels during cloud formation at the time of measurement. The efficiency of both panels gradually declined over time with fluctuations because there was an increase in cell operating temperature due to elevated air temperatures. The cooled panel exhibited an average panel efficiency of 17.2%, and an average overall cell efficiency of 23.26%, in contrast to 15.67% and 21.19% observed in the reference panel. Ultimately, despite the unsteady findings due to the cloud formation, the cooling approach employing CWs with the incorporated liquid distribution system running on a 1-s on/180-s off pump cycle improved both average panel and total cell efficiency by 9.77%.

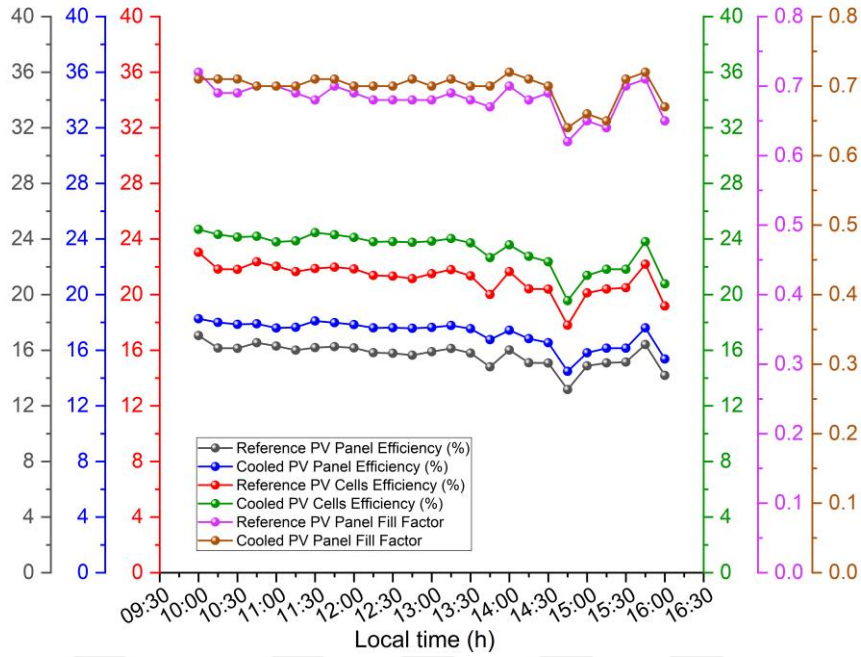


Figure 8.48. Performance indicators of reference and cooled panels

Figure 8.49 distinguishes the energy output and cumulative energy behaviors of the reference and cooled PV panel, and their connection to the DSR. Higher energy output was observed at all measurements intervals for the cooled panel. This resulted in a 10.04% improvement in cumulative energy. The energy output of both panels reached its peak between 12:15 and 13:00 local time, as was the difference in their energy outputs, during the period of highest solar radiation on the experiment day. At 11:30, there was a minor increase in the energy output difference between the panels due to the sudden rise in wind speed. Furthermore, there were sharp and rapid drops in energy output for both panels during cloud formation at the time of measurement. This affected the linearity of the cumulative energy curves, causing a slight drop at the measurement points when solar radiation was blocked by clouds.

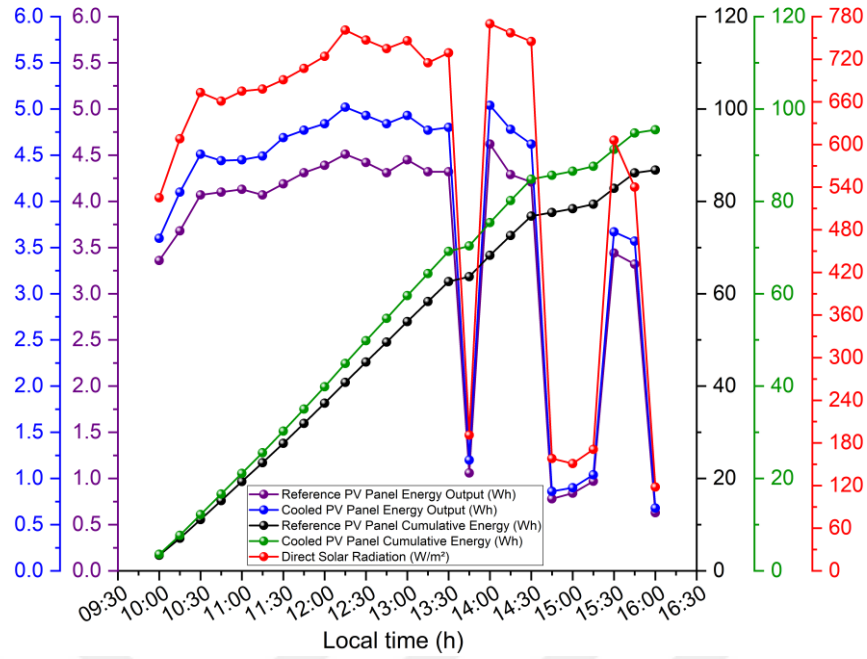


Figure 8.49. Energy and cumulative energy production, and DSR

Figure 8.50 illustrates the thermal camera images of the reference and cooled PV panels, organized by their recording times at 30-min increments between 10:30 and 16:00 local time. The images serve as visual confirmation of the effective and uniform operation of the EC system, which was applied via a liquid distribution setup on CWs operating with a pump cycle of 1-s on/180-s off.

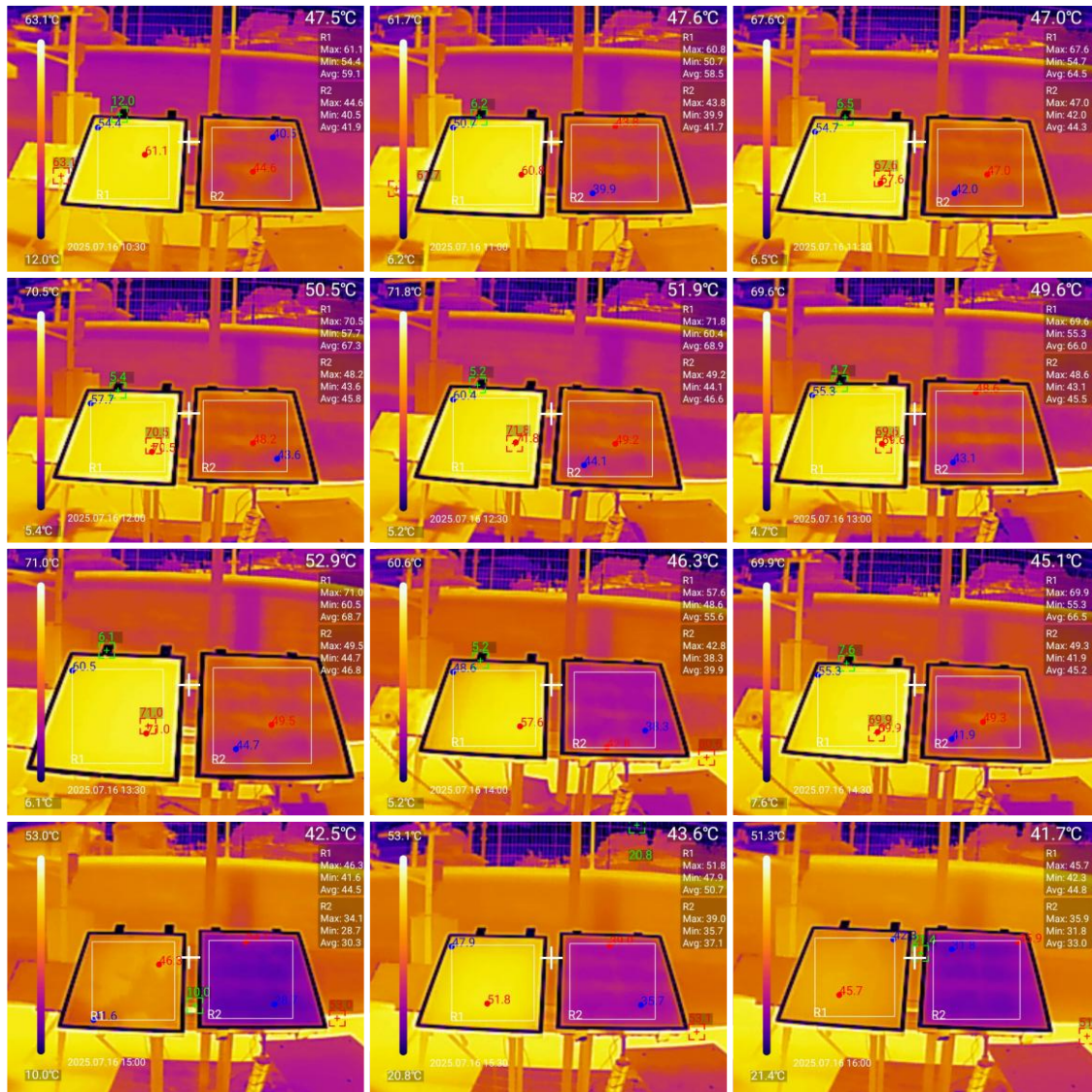


Figure 8.50. Thermal camera images of the reference (R1) and cooled (R2) panels at 30-min increments from 10:30 to 16:00 local time

8.2.2. Findings from the 1-s on/300-s off pump cycle

A total of 1130.4g of water was delivered by the pump to the CWs installed on the rear side of the PV panel over the course of 72 intervals between 10:00 and 16:00 local time, with the liquid distribution system ensuring even dispersion. During the process, 474g of water was recovered in the tray below the cooled PV panel and returned to the underground tank through gravitational flow. Meanwhile, 656.4g of water evaporated, eliminating heat buildup on the panel.

Environmental parameters computed by the weather station during the test day (July 17, 2025), encompassing wind direction, average wind speed, average air

temperature, humidity and average global solar radiation, are set forth in **Figure 8.51**. The wind direction was mostly stable, originating from the northwest. The average wind speed was higher between 12:45 and 14:30 local time. There was a gradual increase in average air temperature until 15:30 local time, when the average wind speed was elevated. In contrast, there was a steady decline in relative humidity until 15:30 local time, as the average wind speed rose. Overall, the average air temperature was between 32 and 41°C. The average global solar radiation adhered to a typical daily cycle, reaching its optimum from 12:00 to 13:00 local time.

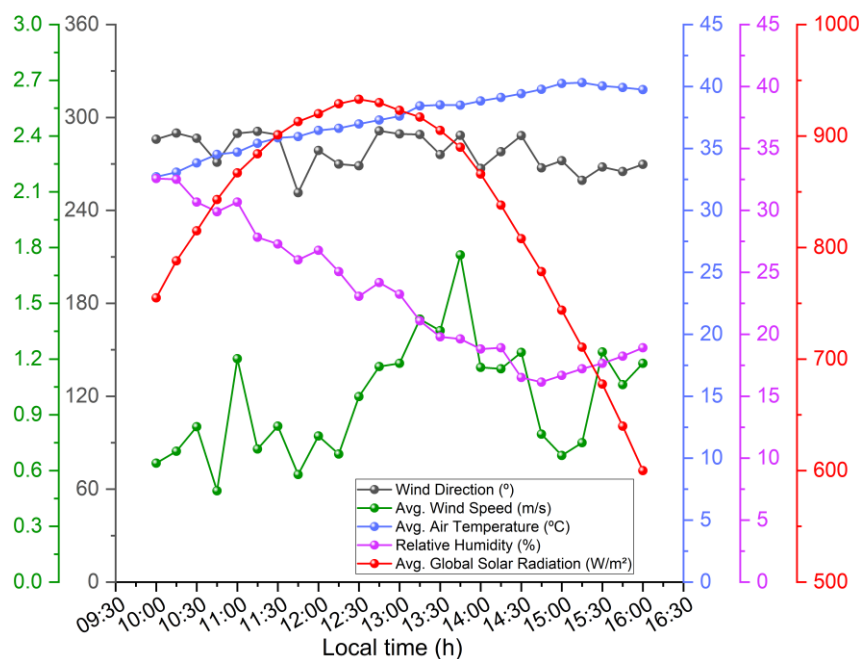


Figure 8.51. Weather-related measurements on the day of experiment

Figure 8.52 visualized a comparison of the average temperature trends of the reference and cooled PV panels, the temperature reduction because of the EC effect, and the DSR. The panel subjected to the EC exhibited distinctly lower temperature values with relative formation to those of the reference panel. The temperature profiles of both panels were not greatly influenced by the wind direction. The EC system achieved a remarkable temperature drop ranging from 19.3 °C to 21.1 °C between 11:30 and 15:15 local time. Contributing factors to this temperature decrease include increased solar radiation between 11:30 and 13:45, relatively strong wind speeds, and reduced relative humidity between 12:30 and 15:15. The temperature of the reference panel surpassed 68

°C. Nonetheless, the temperature of the cooled panel was below 49 °C across the monitoring duration.

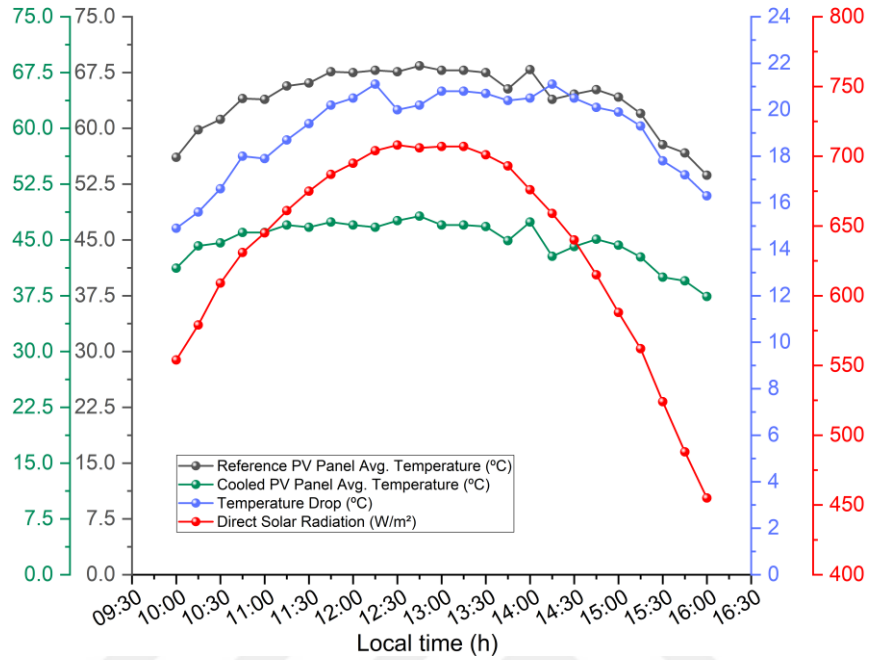


Figure 8.52. Comparison of panel temperature, temperature reduction, and DSR

Optimal operating point values, which are composed of P_{mpp} , V_{mpp} , and I_{mpp} , of the reference and cooled PV panels in correspondence with solar radiation are expressed in **Figure 8.53**. In comparison to the reference panel, the panel subjected to the EC consistently yielded higher P_{mpp} values, notably between 12:00 and 13:15 local time, when it was exposed to the maximum solar radiation. Additionally, there was a corresponding increase in the P_{mpp} difference at 11:00 local time, which can be attributed to a sudden rise in average wind speed. It was apparent that solar radiation and the thermal condition were the main factors influencing the P_{mpp} . There was a rise in the V_{mpp} values of the cooled panel, and the V_{mpp} curves displayed a linear pattern. However, the I_{mpp} values of the cooled panel mostly were equal to those of the reference panel. Hence, the enhancement in voltage output on account of the EC was reflected as an improvement in power output. The I_{mpp} curves of both panels aligned well with the solar radiation curve, showing limited sensitivity to thermal variations.

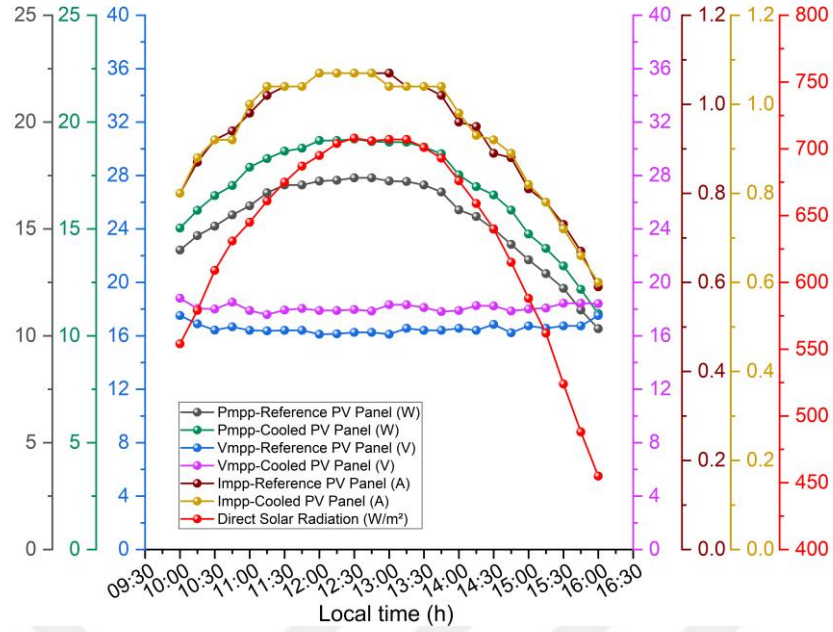


Figure 8.53. P_{mpp} , V_{mpp} , and I_{mpp} variations, and their relation to DSR

The V_{oc} and I_{sc} measurements for the reference and cooled PV panel and their association with the P_{mpp} and solar radiation are presented in **Figure 8.54**. A linear trend was observed in the V_{oc} measurements, with the panel under the EC showing increased values. Therefore, the temperature played a crucial role in the voltage generation of the panels. Conversely, the I_{sc} values of the panels were mostly the same, and unaffected by temperature; instead, greatly influenced by the solar radiation.

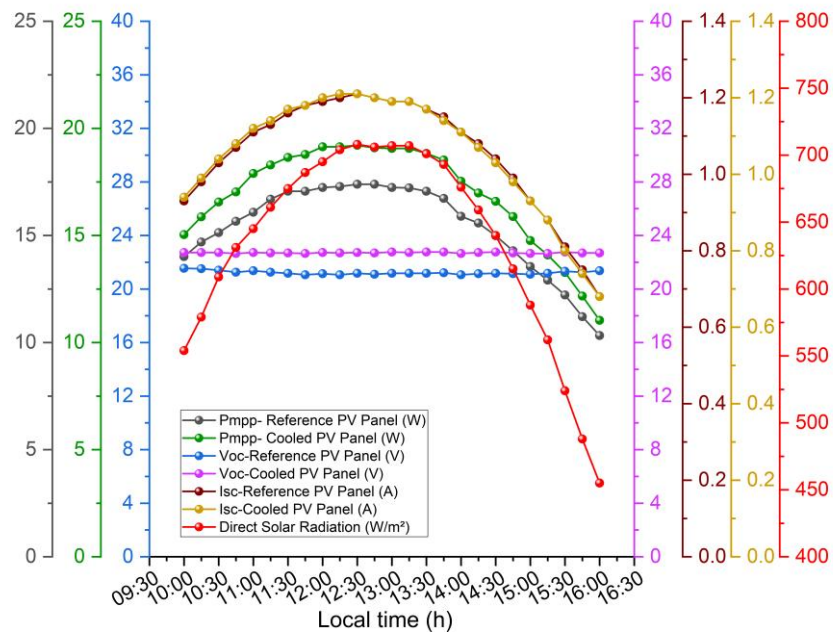


Figure 8.54. V_{oc} and I_{sc} and their correlation with P_{mpp} and DSR

Figure 8.55 differentiates cell efficiencies, panel efficiencies, and FF rates for the reference and cooled PV panels. The EC system substantially improved the panel and overall cell efficiency. In comparison with the reference panel, which possessed average efficiencies of 16.14% (panel) and 21.82% (cells), the cooled panel attained greater values of 17.7% and 23.93%. Therefore, both the average panel and total cell efficiencies enhanced by 9.67% owing to the EC system. Moreover, the cooling process rose the FF readings, optimizing the I-V characteristics. On the other hand, the efficiency of both panels gradually dropped over time, exhibiting some fluctuations, which can be attributed to higher cell operating temperatures induced by higher air temperatures. Besides, between 10:45 and 11:00 local time, the difference in efficiency experienced an increase due to the sudden rise in average wind speed. To summarize, the cooling technique using CWs with the integrated liquid distribution system on a 1-s on/300-s off pump interval was distinctly promising in enhancing panel and cell efficiency.

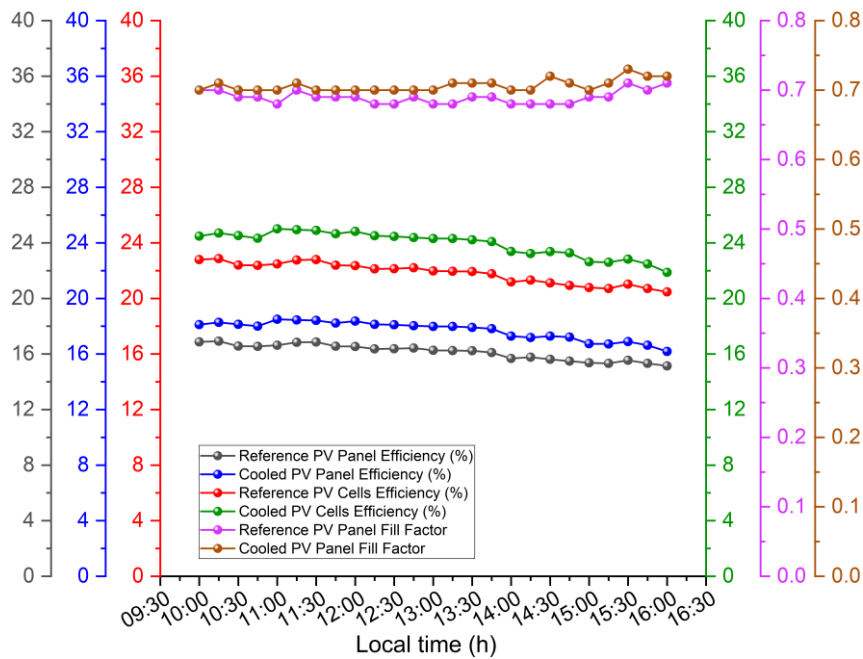


Figure 8.55. Performance metrics: cell Efficiency, panel Efficiency, and FF

The energy output at each measurement point for the reference and cooled PV panel, their cumulative energy, and solar radiation are shown in **Figure 8.56**. The panel operating under the EC regularly yielded higher energy output on test day. This led to a 9.76% enhancement in cumulative energy. The energy output for both panels was at its

maximum between 12:00 and 13:30 local time, as did the difference in their energy outputs, coinciding with the peak in solar radiation.

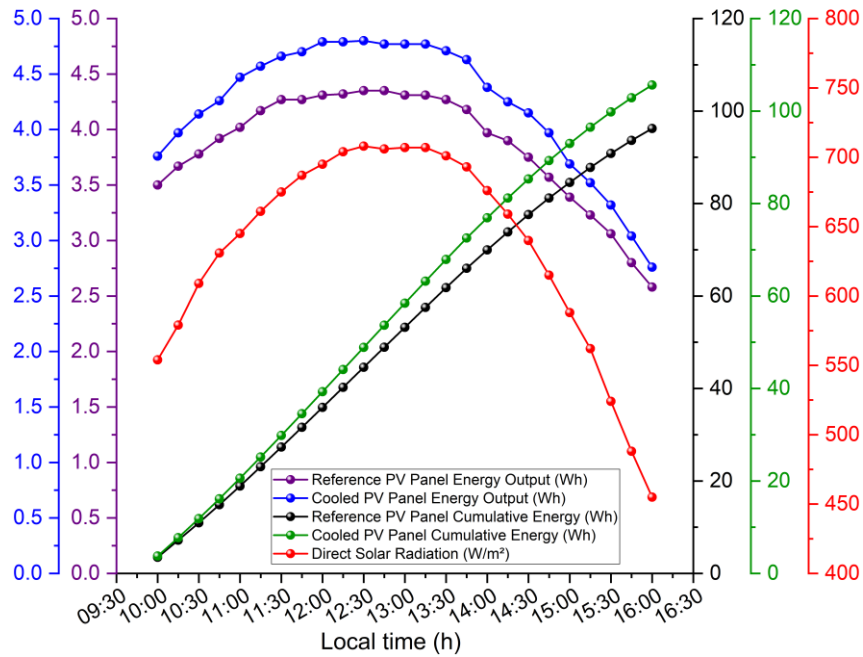


Figure 8.56. Energy and cumulative energy yield, and DSR

Thermal camera images of the reference and cooled PV panels, arranged based on their recording times at 30-min increments between 10:30 and 16:00 local time, are displayed in **Figure 8.57**. These images provide visual proof for the temperature reduction, substantially efficiency increase and cooling uniformity of the EC system, which was implemented using the liquid distribution system on the CWs with employing the pump cycle of 1-s on/300-s off.

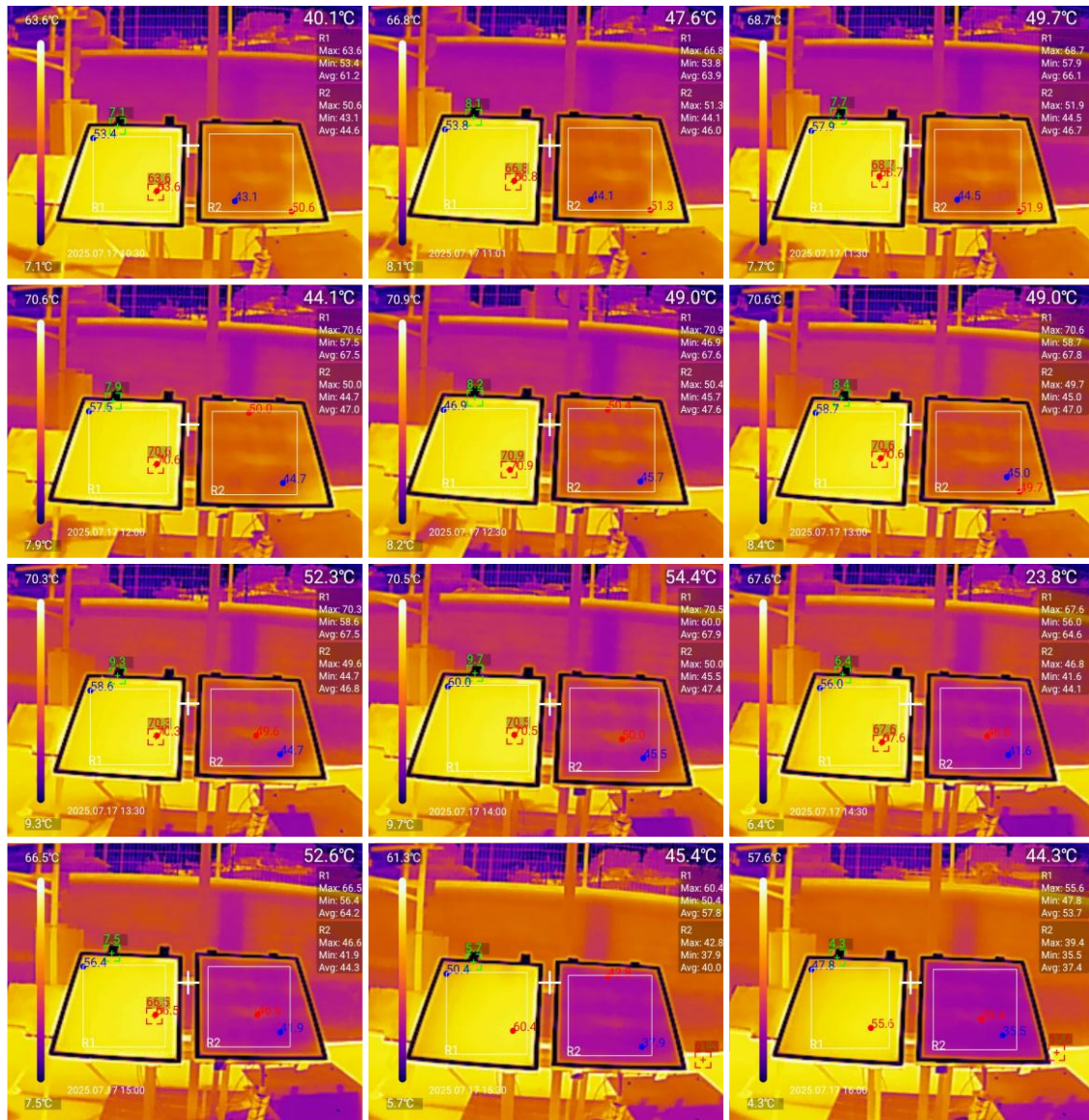


Figure 8.57. Thermal camera images of the reference (R1) and cooled (R2) panels at 30-min intervals from 10:30 to 16:00 local time

As a result, operating the 1-s on/300-s off pump cycle offered slightly lower performance based on the temperature reduction and improvement in cumulative energy production than the 1-s on/180-s off pump cycle. Nevertheless, the analysis of the meteorological data suggests that its lower performance compared to the 1-s on / 180-s off pump cycle could be attributed to lower wind speeds, reduced solar radiation, and higher humidity during its experimental day. Therefore, it can be implied that the 1-s on/300-s off pump cycle achieved similar performance and demonstrated superior water efficiency.

8.2.3. Findings from the manual spraying

Every 30 min, an average of 92g of water was manually sprayed onto the CWs affixed to the rear side of the panel, dissipating the surplus heat from the panel.

Weather-related factors, involving wind direction, average wind speed, average air temperature, humidity and average global solar radiation, quantified by the weather station across the experimental day (July 18, 2025) are elaborated in **Figure 8.58**. The wind consistently blew from the northwest throughout the experimental day, with no significant changes in direction. The average wind speed was generally mild and steady, except between 15:15 and 16:00 local time, when the highest values were computed. Likewise, the average air temperature was at its peak during the same period, which was approximately 41 °C. The relative humidity was reduced after 13:15 local time, fluctuating between 16% and 18%. The average global solar radiation aligned with a standard daily pattern, reaching its peak midday hours from 12:00 to 13:00 local time.

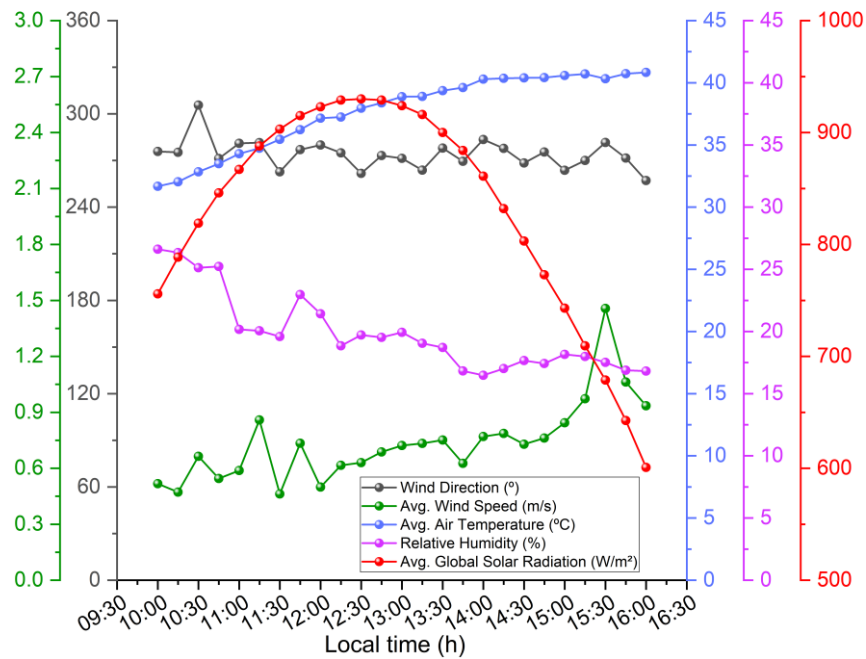


Figure 8.58. Meteorological measurements over the experimental timeframe

The temperature variation of the reference and cooled PV panels, and temperature decrease on account of the EC effect and DSR are included in **Figure 8.59**. The temperature of the cooled panel was substantially reduced with respect to that of the reference panel. The wind direction, average wind speed and relative humidity did not

majorly influence the temperature variations on the panels. The temperature differences between the two panels reached 20.5 °C at 12:15 and 12:45 local time when solar irradiance was at its highest intensity. A similar temperature difference also occurred at 13:45 and 14:15 local time, when relatively high solar irradiance and average air temperature were measured. The temperature of the reference panel rose up to 70.5 °C. Yet, the temperature of the cooled panel was below 53 °C over the monitored period. An average of 92g of manual water spraying sustained a large temperature difference for 30 min. However, during certain intervals, a slight decrease in the magnitude of the temperature drop, ranging from 0.5 °C to 1.4 °C, was detected. Despite this, the cooling approach shows promise for maintaining its cooling performance over prolonged interval, potentially 45 min to 1 h.

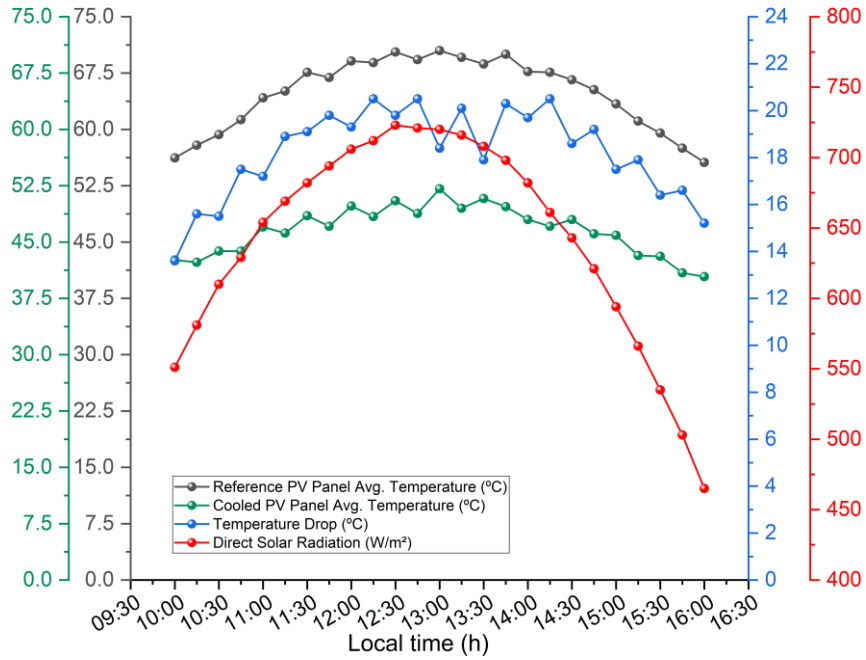


Figure 8.59. Temperature distribution, temperature reduction and DSR

Figure 8.60 introduces optimal power output characteristics, which are composed of P_{mpp} , V_{mpp} , and I_{mpp} , of the reference and cooled PV panels, along with their dependence on the DSR. The cooled panel markedly demonstrated greater P_{mpp} values versus those of the reference panel, demonstrably between 12:15 and 12:45 local time under peak solar radiation conditions. It was obvious that solar radiation and thermal state were the key parameters affecting the P_{mpp} . The I_{mpp} values for both panels were mostly the same and exhibited a similar pattern to the P_{mpp} and solar radiation. Therefore, the

increase in P_{mpp} values of the cooled panel was due to the improvement in voltage output of the cooled panel, underscoring the beneficial effect of the EC system on voltage production.

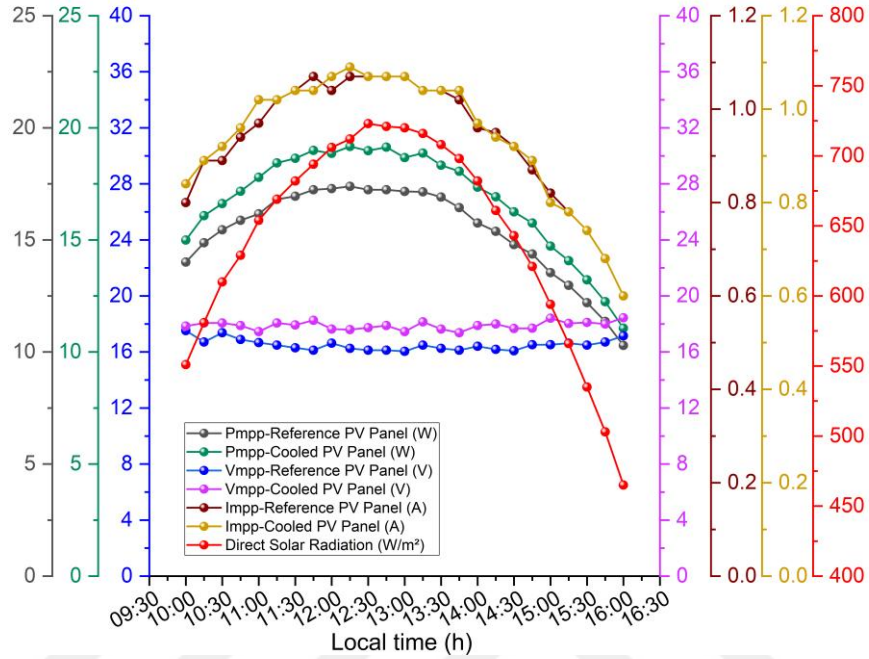


Figure 8.60. Evaluation of the P_{mpp} , V_{mpp} , and I_{mpp} in correlation with DSR

The aspects related to V_{oc} and I_{sc} for the reference and cooled PV panels, and their variation with the P_{mpp} and solar radiation are given in **Figure 8.61**. The I_{sc} values for both panels were largely identical, signifying that they are not influenced by thermal conditions. Conversely, they were aligned with the trend of solar radiation and P_{mpp} curves. The V_{oc} values of the cooled panel were higher compared to those of the reference panel, revealing that the EC system had a favorable impact on the voltage production. The nearly linear trends in **Figure 8.61** suggest that solar radiation had a minimal influence on the V_{oc} .

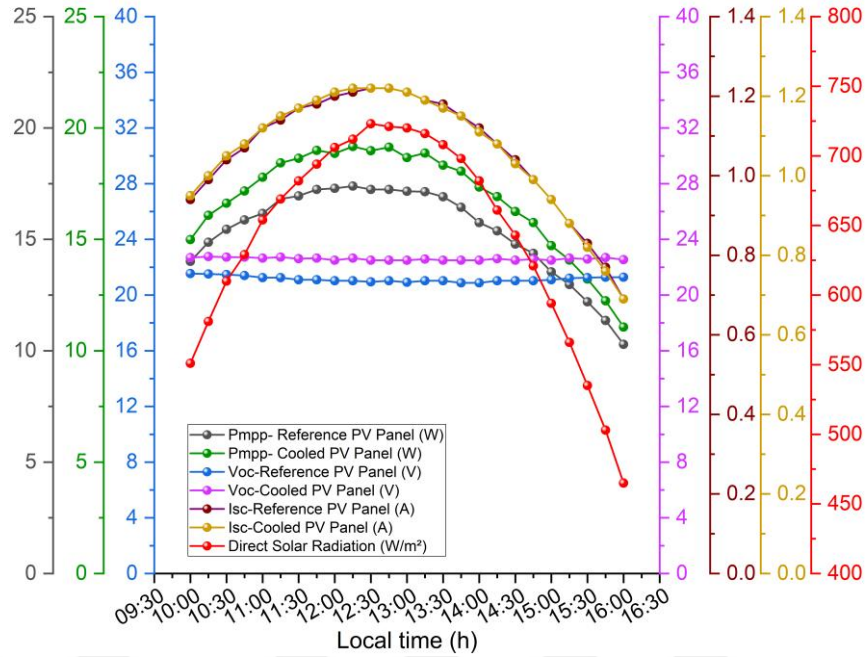


Figure 8.61. Comparative evaluation of V_{oc} , and I_{sc} parameters in relation to P_{mpp} and DSR

Figure 8.62 details the efficiency of the reference and cooled PV panels, the overall cell efficiency for both panels and their FF rates. In comparison to the reference panel, the cooled panel had an improved panel efficiency, cell efficiency and FF during the whole test day due to the EC effect on its rear side. While the reference panel demonstrated an average panel and cell efficiencies of 15.97% and 21.59%, respectively, the cooled panel delivered improved results of 17.43% and 23.57%. Thus, average panel efficiency was enhanced by 9.18%, whereas total average cell efficiency increased by 9.11%. However, there was a decrease in both panels' efficiency and their overall cell efficiency over time, which can be related to the rise in air temperature. The FF values for both panels were regular during the full span of the experiment day, but the panel under the EC consistently established moderately higher FF values, which implies that the cooling improved the I-V characteristics of the panel.

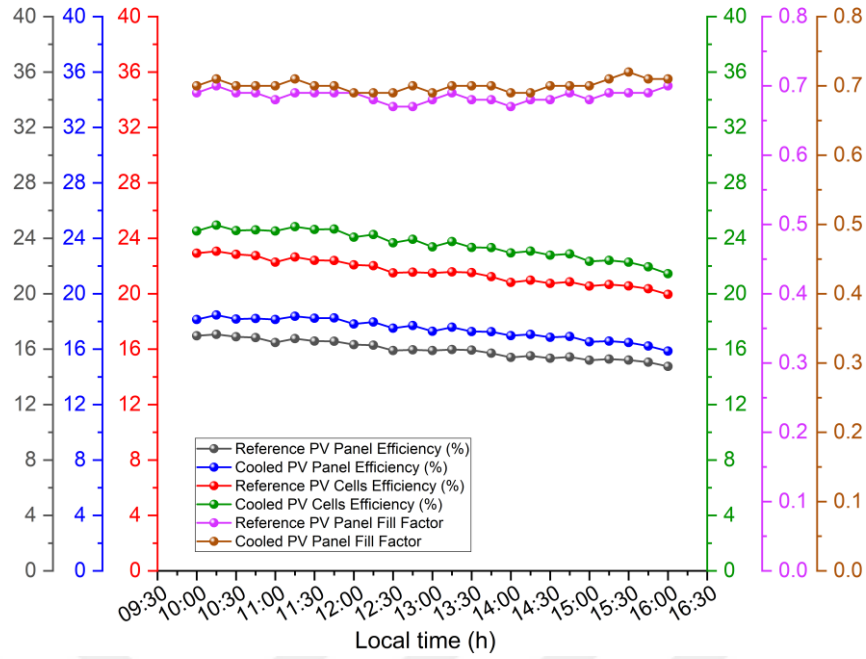


Figure 8.62. Comparative analysis of overall cell efficiency, panel efficiency, and FF

The energy output at each recorded time step, and cumulative energy of the reference and cooled PV panels and their connection with the DSR are exhibited in **Figure 8.63**. The energy output of both panels was linked to the trajectory of the DSR, with the cooled panel consistently yielding higher output. As a result, the EC effect generated by the manual spraying on the CWs contributed to a 9.24% improvement in cumulative energy output, regarding the cumulative energy output of the reference panel as the reference point.

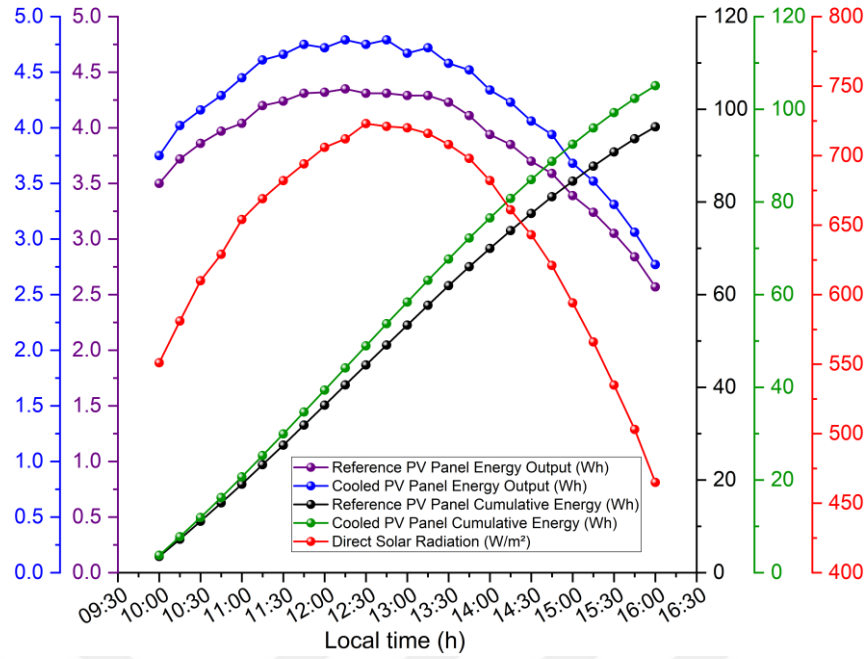


Figure 8.63. Evaluation of instantaneous and cumulative energy generation in correlation with DSR

Figure 8.64 displays the thermal camera pictures of the reference and cooled PV captured at the following local times: 10:45, 11:00, 11:45, 12:00, 12:45, 13:00, 13:45, 14:00, 14:45, 15:00, 15:45, and 16:00. These pictures evidently validate the effectiveness of the manual spraying on the CWs mounted on the back side of the panel in maintaining uniformly lower temperature distributions.

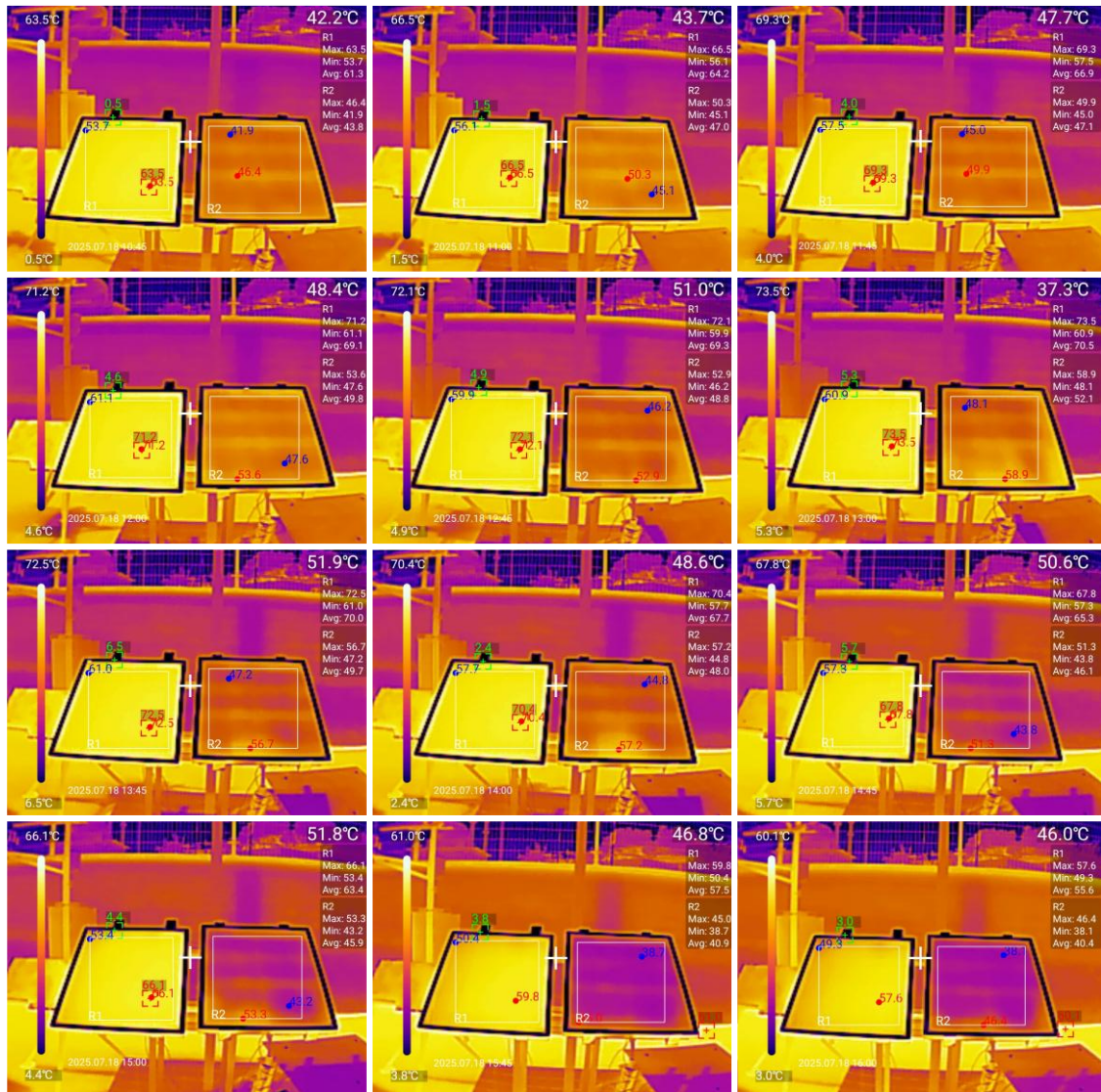


Figure 8.64. Thermal camera pictures of the reference (R1) and cooled (R2) panels at designated hours between 10:00 and 16:00 local time

To sum up, the manual spraying on CWs provided slightly lower performance parameters, including lower percentage improvement in cumulative energy, lower temperature reduction, compared to the cooling setups using the pump cycles of 1-s on/300-s off and liquid distribution system under comparable meteorological conditions. Nonetheless, it delivered a small enhancement in cooling uniformity.

8.2.4. Summary of findings from the EC method incorporating CWs and underground cooling

A summary of the results of the EC system incorporating CWs and underground cooling is outlined as follows:

- All three setups of the EC using CWs and underground cooling proved promising in dry and intensely hot environments.
- The cooling setups constantly decreased the surface temperature of the PV panel throughout the testing periods, boosting its efficiency, energy output and electrical performance.
- According to the thermal camera views, the cooling setups achieved a uniform cooling effect across the panel's surface, preventing possible hotspots formation, current mismatch issues, and long-term structural damage.
- The highest temperature reduction assessed were 22.7, 21.1, and 20.5 °C for the 1-s on/180-s off pump cycle, 1-s on/300-s off pump cycle, and manual spraying, respectively.
- With the implementation of the EC technique, panel and cell efficiencies improved on average by 9.77% for the 1-s on/180-s off pump cycle, and by 9.67% for the 1-s on/300-s off pump cycle, relative to the reference panel. Also, there was a 9.18% enhancement in average panel efficiency and 9.11% increase in average total cell efficiency for the manual spraying, compared to the reference panel.
- The cooling approach operating with the pump cycle of 1-s on/180-s off delivered the highest cumulative energy enhancement of 10.04%, followed by the approach employing 1-s on/300-s off pump cycle with a 9.76% enhancement, and manual backside spraying at 30-min increments with a 9.24% improvement, with the cumulative energy output of the reference panel regarded as the baseline.
- The cooled panel consistently outperformed the reference panel in both panel and cell efficiency across all three EC setups, although these efficiency values gradually declined throughout the testing day due to reduced solar irradiance and rising ambient temperatures.
- A greater amount of water evaporated when the 1-s on/180-s off pump pattern was used to dissipate excess heat from the panel compared to the 1-s on/300-s off cycle.

On the day the 1-s on/180-s off pattern was applied, solar radiation was higher, relative humidity was lower, and average air temperature and wind speed were greater, especially around midday, than on the day the 1-s on/300-s off cycle was employed. As a result, so as to eliminate the surplus heat, more water was needed to evaporate.

- Among all three setups, the pump cycle of 1-s on/180-s off stands out as a favorable option for regions with plentiful water resources, as it delivered the largest temperature drop, and the highest ratio of cumulative energy improvement. However, considering the meteorological data, its superior performance compared to the 1-s on/300-s off pump cycle may have resulted from higher wind speeds, greater solar radiation and lower humidity on its experimental day. As a result, the 1-s on and 300-s off cycle demonstrates comparable performance and is a more water-efficient option.
- The manual backside spraying on CWs maintained a large temperature difference for 30 min. Nevertheless, there was a minor reduction in temperature at the measurements acquired after 15 minutes to the first spraying. Despite that, this cooling technique has potential to retain its effectiveness over a longer timeframe, estimated at 45 minutes to 1 hour.
- Among the three cooling setups, thermal camera images revealed that the manual spraying provided a marginally better cooling uniformity.

8.3. Results of the EC System with HRs and Underground Cooling

The following sections present the results of the EC system configured with HRs and underground cooling:

8.3.1. Results of the 1-s on/180-s off pump cycle

From 10:00 and 16:00 local time, the pump supplied a total of 1884g of water over 120 cycles to the HRs positioned at the rear side of the PV panel. The water was evenly dispersed through the liquid distribution system. Throughout that period, 1270g of water was accumulated in the tray below the cooled panel and drained back into the underground tank by gravity, whereas 614g of water evaporated, effectively extracting unwanted heat from the back side of the panel.

The weather parameters assessed by the weather station on the test day (July 20, 2025), which include wind direction, average wind speed, mean air temperature, humidity and average global solar radiation, are visualized in **Figure 8.65**. The wind blew from the northwest until 13:00 local time; afterward, the wind direction became unstable, shifting between northeast, southeast, and southwest. The wind speed ranged from 0.49 to 1.44 m/s, with the highest values were measured between 15:00 and 15:30 local time, when the air temperature was comparatively high and relative humidity was relatively low. The average air temperature ranged from 34 to 44 °C, typically increasing steadily throughout the day. The relative humidity was lower after 13:00, varying from 11% to 15% during that period. The average global solar radiation followed a typical daily pattern except at 14:45 local time due to the cloud formation in the sky.

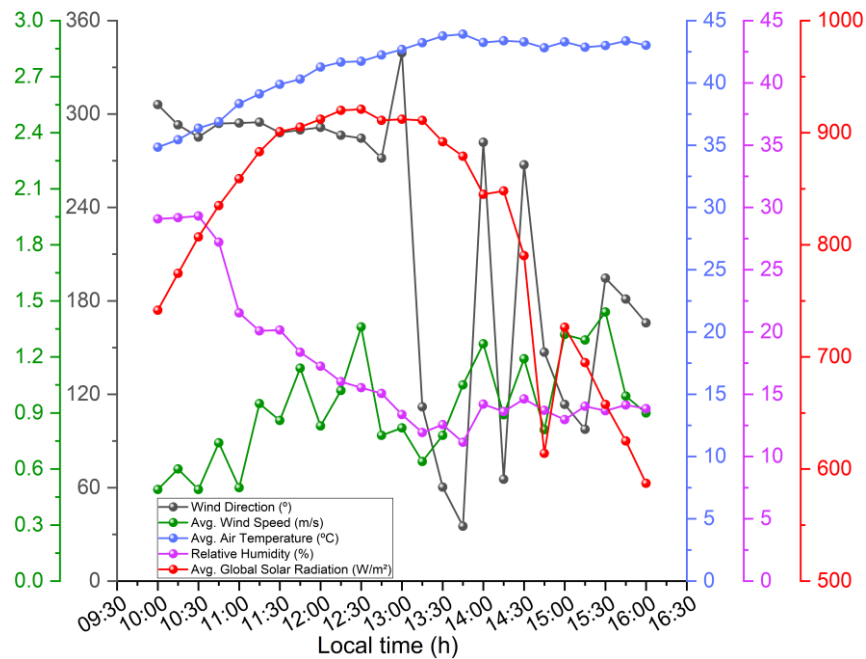


Figure 8.65. Weather parameters measured on the test day

The average temperature profiles of the reference and cooled PV panels, the temperature drop owing to the EC effect, and DSR are provided in **Figure 8.66**. There was an unexpected decline in the solar radiation at 13:45 due to the cloud formation in the sky at the time of measurement. Throughout the observation period, the temperature of the cooled panel was remarkably lower than that of the reference panel, particularly between 12:00 and 14:00, with temperature differences ranging from 19.9 to 22.1 °C during the period of highest solar intensity and elevated air temperature. The temperature

drop profile was not affected despite changes in wind direction. The average temperature of the reference panel elevated up to 72.9 °C. In contrast, the cooled panel temperature prolonged below 52 °C throughout the whole test day. The highest temperature drop of 22.1 °C was reached at 13:30 and 13:45 local time, when the air temperature peaked near 44 °C, and both relative humidity and wind speed were relatively low. Thus, the applied EC system configuration was sufficient to maintain the panel temperature within its optimal operational limits.

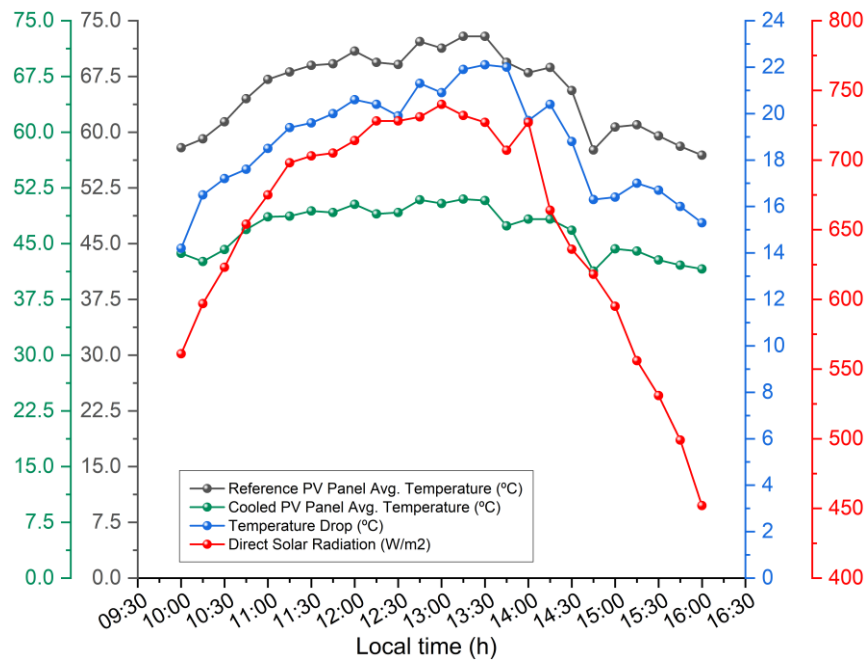


Figure 8.66. Temperature profiles, temperature drop and DSR

A comparison of the performance indicators at MPP, consisting of P_{mpp} , V_{mpp} , and I_{mpp} , of the reference and cooled PV panels, and their relationship to the DSR are introduced in **Figure 8.67**. The P_{mpp} values of the cooled panel were substantially superior to those of the reference panel, notably between 12:45 and 13:30 local time, when solar radiation was at its peak. It is evident that the P_{mpp} values were affected by both solar radiation and thermal conditions of the panels. The P_{mpp} values experienced an unexpected decrease at 13:45 local time due to cloud presence during the measurement. The I_{mpp} values for both panels typically tracked the P_{mpp} and solar radiation trends and showed minimal difference. Therefore, temperature differences on the panels had little impact on the I_{mpp} . Nevertheless, the V_{mpp} values of both panels followed a regular pattern, though the cooled panel consistently showed significantly higher values than the

reference one, highlighting the positive effect of reduced panel temperature on voltage output.

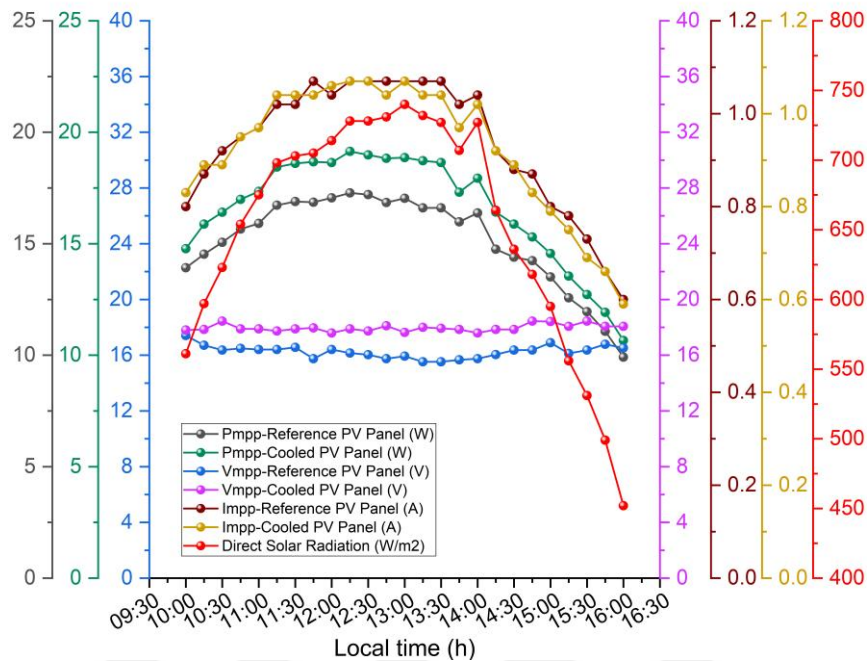


Figure 8.67. Comparison of P_{mpp} , V_{mpp} , and I_{mpp} values of the panels, and their correlation with DSR

Figure 8.68 outlines a comparison of V_{oc} and I_{sc} traits for the reference and cooled PV panels and their associations with the P_{mpp} and DSR. The V_{oc} values appeared to be influenced more by the temperature than solar radiation, as they were usually stable over the experimental timeframe, with the cooled panel maintaining higher readings. Hence, the cooling system optimized the panel temperature and improved the voltage production. Conversely, the I_{sc} values for panels tracked parallel pattern with the P_{mpp} values and DSR, with minimal differences between the two panels. Thus, the I_{sc} values are mainly impacted by solar radiation and minimally influenced by the temperature.

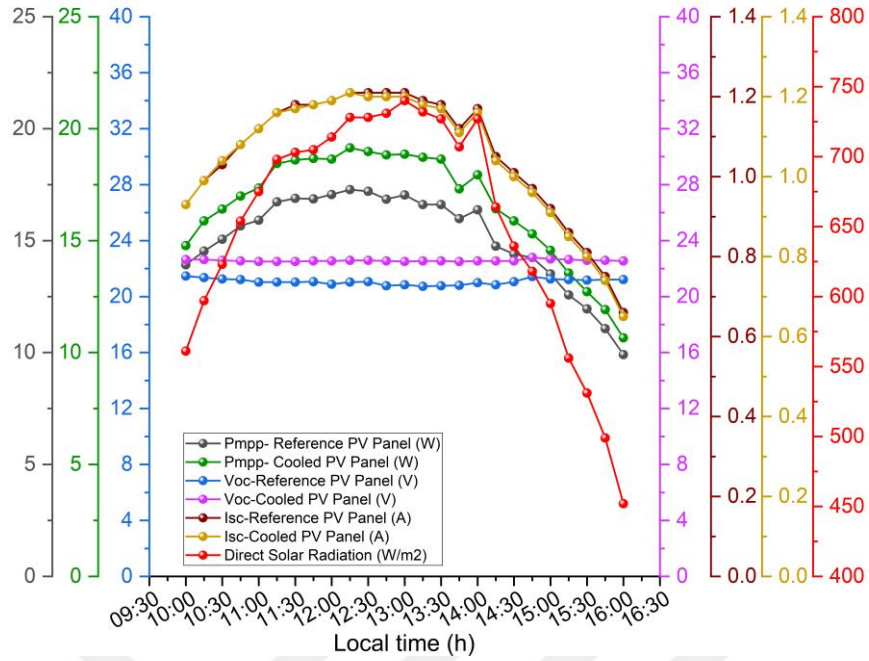


Figure 8.68. V_{oc} , and I_{sc} characteristics of the Panels in Relation to P_{mpp} and DSR

A comparison of overall cell efficiencies, panel efficiencies, and FF readings for both the reference and cooled PV panels is highlighted in **Figure 8.69**. The panel and cell efficiencies of the cooled panel surpassed that of the reference panel at all observed times, reflecting the positive impact of the cooling system. The cooled panel's average panel and total cell efficiencies were 16.94% and 22.91%, respectively, whereas the reference panel's average panel and overall cell efficiencies were 15.46%, and 20.94%, respectively. Accordingly, average panel efficiency experienced a 9.57% improvement, while total average cell efficiency showed a 9.41% increase, owing to the EC method. The efficiency of both panels gradually declined over time, with some fluctuations, which can be linked to the elevated cell operating temperature associated with higher air temperature. The fill factor values of both panels remained stable over time, with slightly higher values observed in the cooled panel, signifying more efficient I-V dynamics. Accordingly, the findings verify the success of the cooling approach involving HRs and a liquid distribution system operating on a 1-s on/80-s off pump cycle.

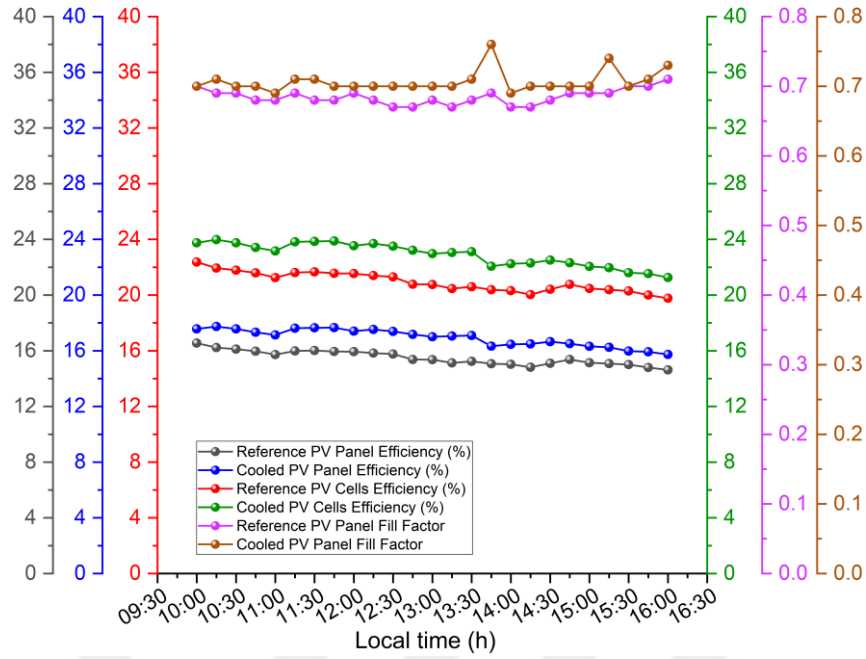


Figure 8.69. Comparison of overall cell efficiencies, panel efficiencies, and FF

Figure 8.70 depicted the energy output at each measurement interval, cumulative energy of the reference and cooled PV panels, and DSR. The energy output of both panels correlated with the profile of DSR. There was a 9.56% enhancement in the cumulative energy when the liquid distribution system with HRs was operated with the pump cycle of 1-s on/180-s off. The cooled panel continually produced greater energy output than the reference panel. Both panels generated greater energy output during the peak solar radiation period between 12:15 and 13:30 local time, and their energy output difference was most significant during this timeframe.

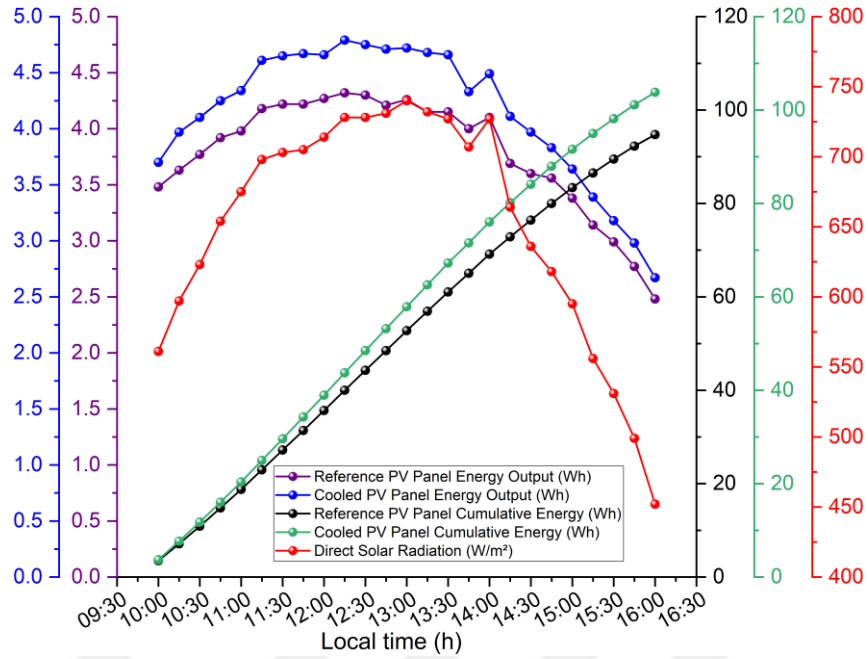


Figure 8.70. Comparative assessment of energy output and cumulative energy of the Panels, and DSR

The thermal camera shots of the reference and cooled PV panels, acquired at 10:30, 11:00, 11:30, 12:00, 12:30, 13:00, 13:30, 14:00, 14:30, 15:00, 15:30 and 16:00, are arranged sequentially in **Figure 8.71**. The thermal camera shots provide clear visual proof of a uniform cooling effect achieved through the EC by the HRs and liquid distribution system operating with the pump cycle of 1-s on/180-s off.

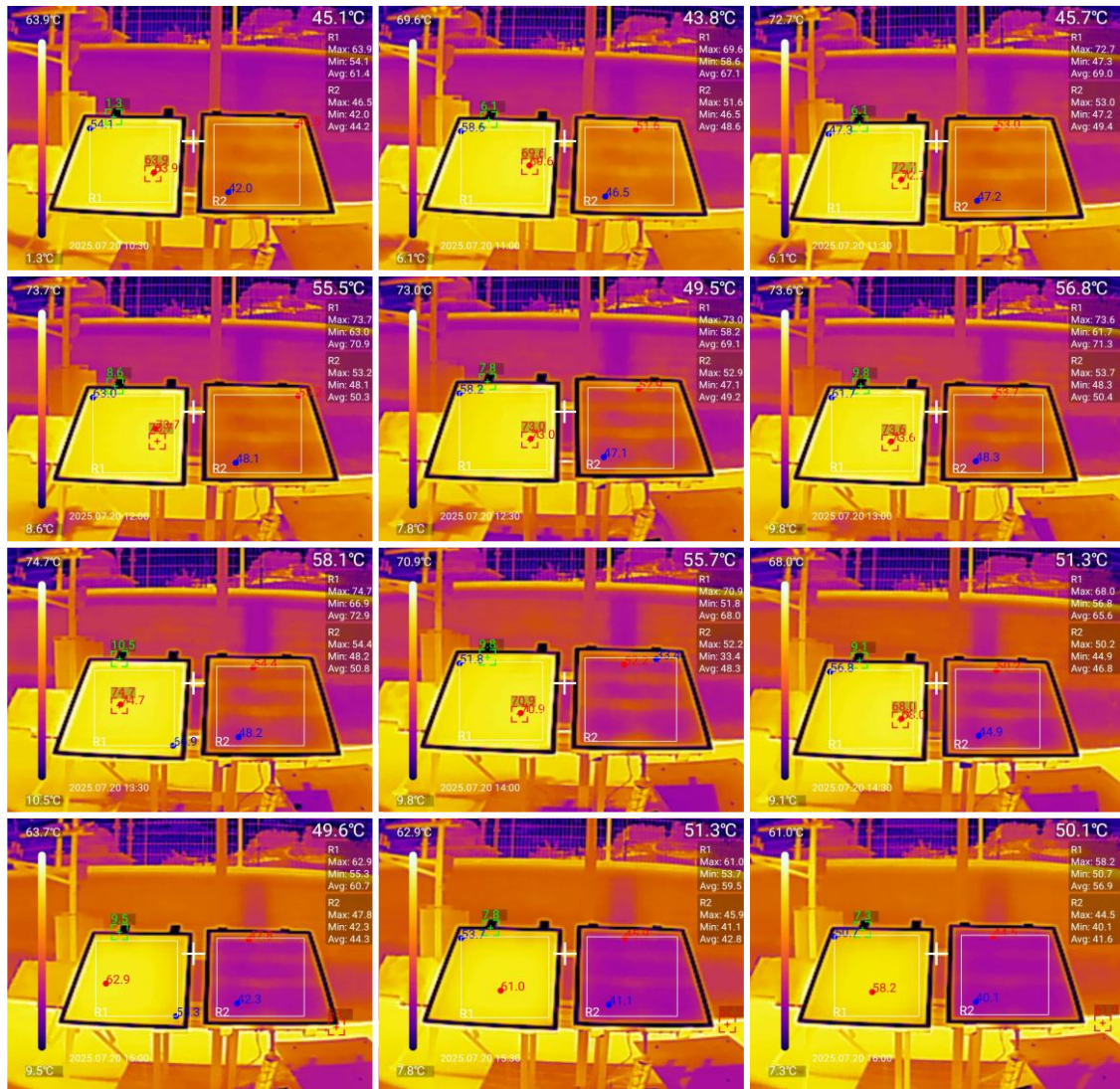


Figure 8.71. Thermal camera shots of the Reference (R1) and cooled (R2) panels acquired at half-hour intervals from 10:30 to 16:00 local time

8.3.2. Results of the 1-s on/300-s off pump cycle

The pump delivered 1130.4g of water in 72 intervals to the HRs attached to the back side of the PV panel, with underground water being distributed evenly through the liquid distribution system between 10:00 and 16:00 local time. During that time, 696g of water was collected in the tray beneath the cooled PV panel and returned to the underground tank by gravity, while 434.5g evaporated, removing excess heat from the rear side of the panel.

Figure 8.72 presents the meteorological parameters measured by the weather station on the day of experiment (July 21, 2025), which comprise wind direction, average wind speed, average air temperature, humidity and average global solar radiation. During

the experimental day, the wind direction mostly remained from the northwest. The wind speed ranged from 0.37 to 1.57 m/s, with usually higher values recorded 12:30 and 14:00 local time, when air temperature and solar radiation were relatively high, and relative humidity was comparatively low. The average air temperature varied from 34 to 43 °C, generally exhibiting a steady increase over the course of the day. The relative humidity was lower after 12:00, ranging from 13% to 19% during that period. The average global solar radiation showed a typical daily pattern, peaking between 11:30 and 13:00.

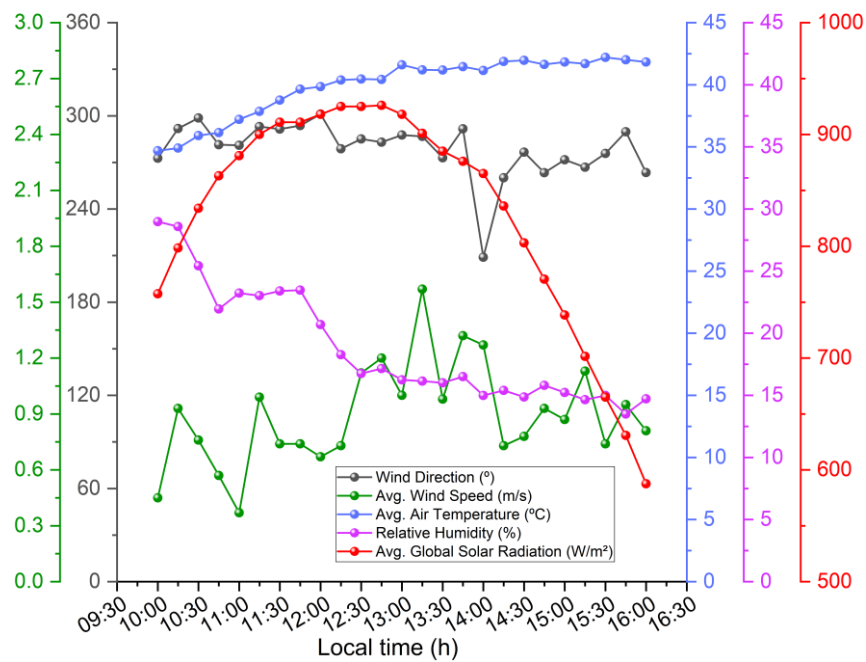


Figure 8.72. Meteorological conditions recorded on the experimental day

Figure 8.73 depicts the average temperatures of the reference and cooled PV panels, the temperature drop resulting from the EC, and DSR. Throughout the experimental day, the cooled panel remained at lower temperatures compared to the reference panel, especially between 12:00 and 13:30 local time when solar radiation levels were at their highest. The average temperature of the reference panel was as high as 70.6 °C, while the average temperature of the cooled panel maintained below 52 °C throughout the experimental day. The temperature of the cooled panel was lower by as much as 20.4 °C at 12:15 local time compared to the reference panel, when the solar radiation was at its peak, wind speed was relatively low, and the average air temperatures exceeded 40 °C. These results validate the effectiveness of the EC system under elevated thermal conditions. Additionally, it confirmed that decreasing the pump cycle from 1-s

on/180-s off to 1-s on/300-s off did not reduce effectiveness of the liquid distribution system, considering similar meteorological parameters acquired in testing days; instead, it demonstrated that comparable amount of temperature reduction can be achieved employing less water.

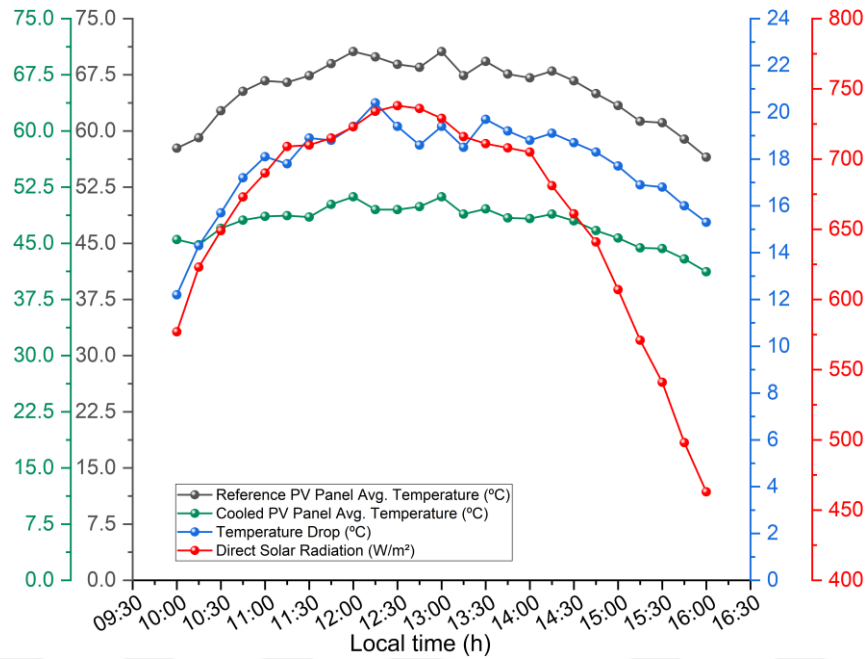


Figure 8.73. Average temperatures, associated temperature reduction, and DSR

Figure 8.74 displays the MPP point characteristics, including P_{mpp} , V_{mpp} , and I_{mpp} of the reference and cooled PV panels, along with the DSR. The P_{mpp} values of the cooled panel were consistently greater than those of the reference panel during the experimental day, with the distinct differences observed between 12:00 and 13:00, likely due to elevated solar radiation during that period. The I_{mpp} values of both panels were closely matched and followed a similar pattern to the P_{mpp} and solar radiation. In addition, the V_{mpp} values of both panels were steady, with cooled panels being considerably greater than those of the reference panel. Therefore, the improved panel temperature conditions contributed to voltage generation.

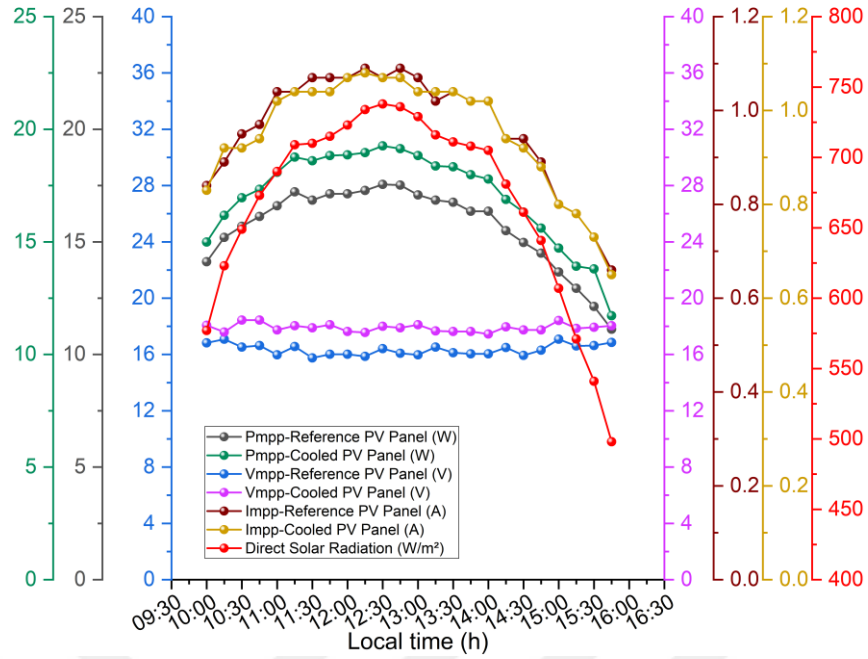


Figure 8.74. MPP parameters, along with DSR

Figure 8.75 includes a comparison of the P_{mpp} , V_{oc} , and I_{sc} values for both the reference and cooled PV panels, as well as the DSR. The cooled panel consistently possessed slightly higher V_{oc} values with respect to those of the reference panel. These V_{oc} appeared to be largely influenced by temperature variations and only minimally affected by changes in solar radiation. On the contrary, the I_{sc} values of the cooled panel were roughly equal to those of the reference panel. Accordingly, the I_{sc} was not greatly impacted by the temperature increase but primary influenced by solar radiation. Consequently, the cooling system improved the thermal conditions for the panel and contributed positively to voltage generation.

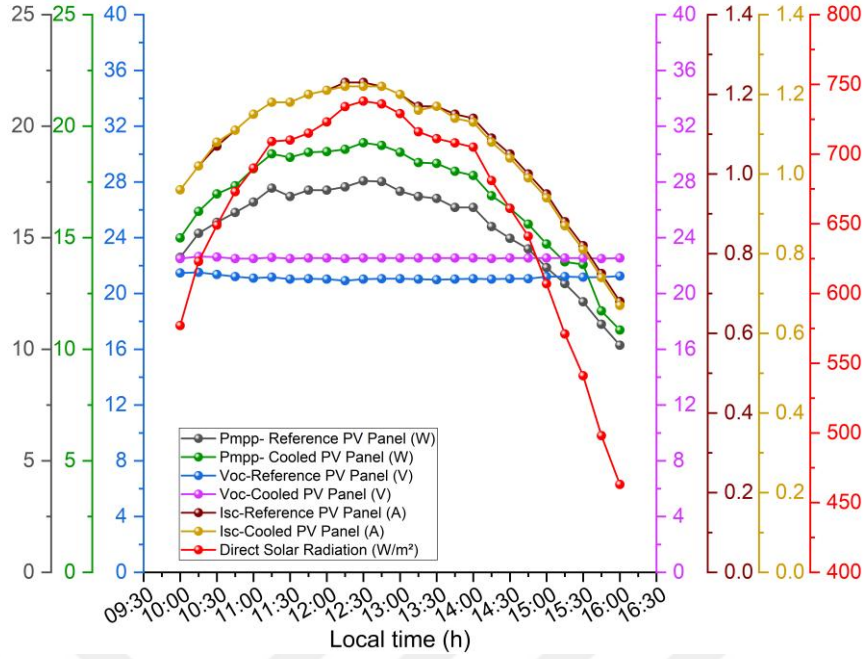


Figure 8.75. V_{oc} , and I_{sc} with P_{mpp} and DSR

The efficiencies of the reference and cooled PV panels, the overall cell efficiencies of both panels, and their FF values are shown in **Figure 8.76**. The cooled panel maintained higher efficiency than the reference panel at all recorded time intervals, pointing out the effectiveness of the cooling system. With average panel and total cell efficiencies of 16.96% and 22.93%, the cooled panel outperformed the reference panel, which achieved 15.6% and 21.08%, respectively. As a consequence, an improvement of 8.42% was observed in average panel efficiency, alongside an 8.79% increase in total average cell efficiency. There was a decline in the efficiency of both panels over the course of time, which can be attributed to the increased cell temperature prompted by larger air temperature. The FF values for both panels remained relatively constant over time. They were marginally greater for the cooled panel, suggesting improved I-V behavior. Thus, these findings confirm that using the liquid distribution system with HRs, operating on the pump pattern of 1-s on, 300s off, enhanced both the efficiency and electrical performance of the panel, validating the effectiveness of this cooling strategy.

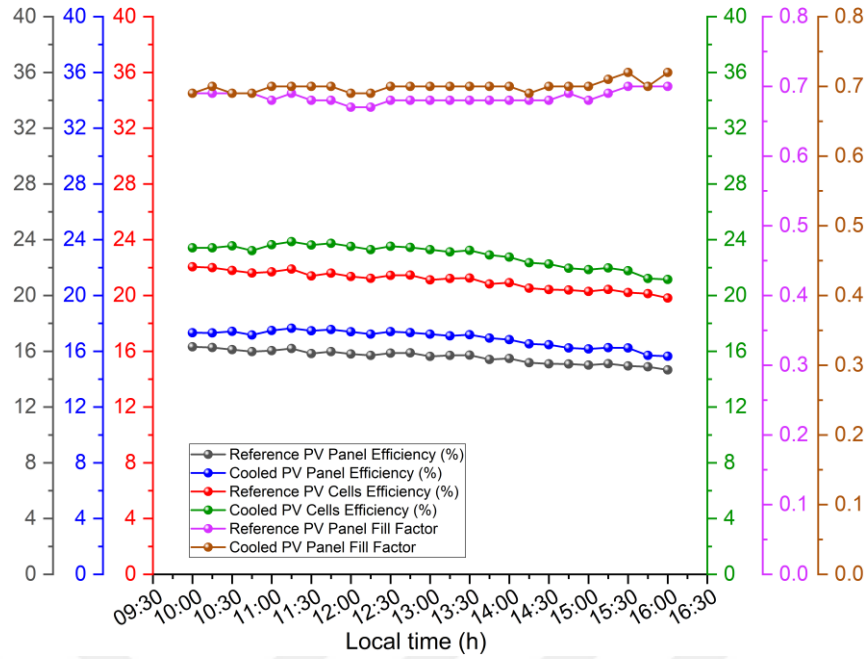


Figure 8.76. Comparison of efficiencies and FF

The energy output at the measurement points, cumulative energy of the reference and cooled PV panels, and DSR are outlined in **Figure 8.77**. There was an 8.86% improvement in cumulative energy using the liquid distribution system with HRs, employing the pump cycle of 1s on, 300s off. Throughout the test day, the cooled panel consistently generated higher energy output than the reference panel. Energy output for both panels corresponded with the pattern of DSR, with the cooled panel delivering more energy, particularly during the noon period when thermal impacts were the strongest.

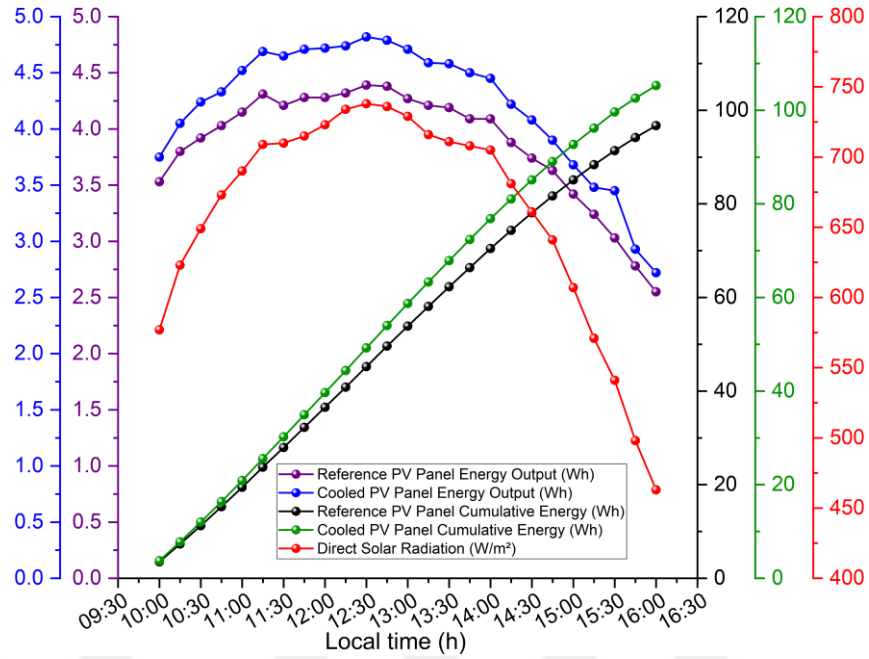


Figure 8.77. Comparison of energy and cumulative energy outputs, along with DSR

Figure 8.78 presents thermal camera views of the reference and cooled PV panels, recorded at 10:30, 11:00, 11:30, 12:00, 12:30, 13:00, 13:30, 14:00, 14:30, 15:00, 15:30 and 16:00. The thermal camera images clearly show a uniform cooling effect achieved through the EC provided by the liquid distribution system on the HRs, using the pump pattern of 1-s on/300-s off, offering visual evidence for the effectiveness of the cooling system.

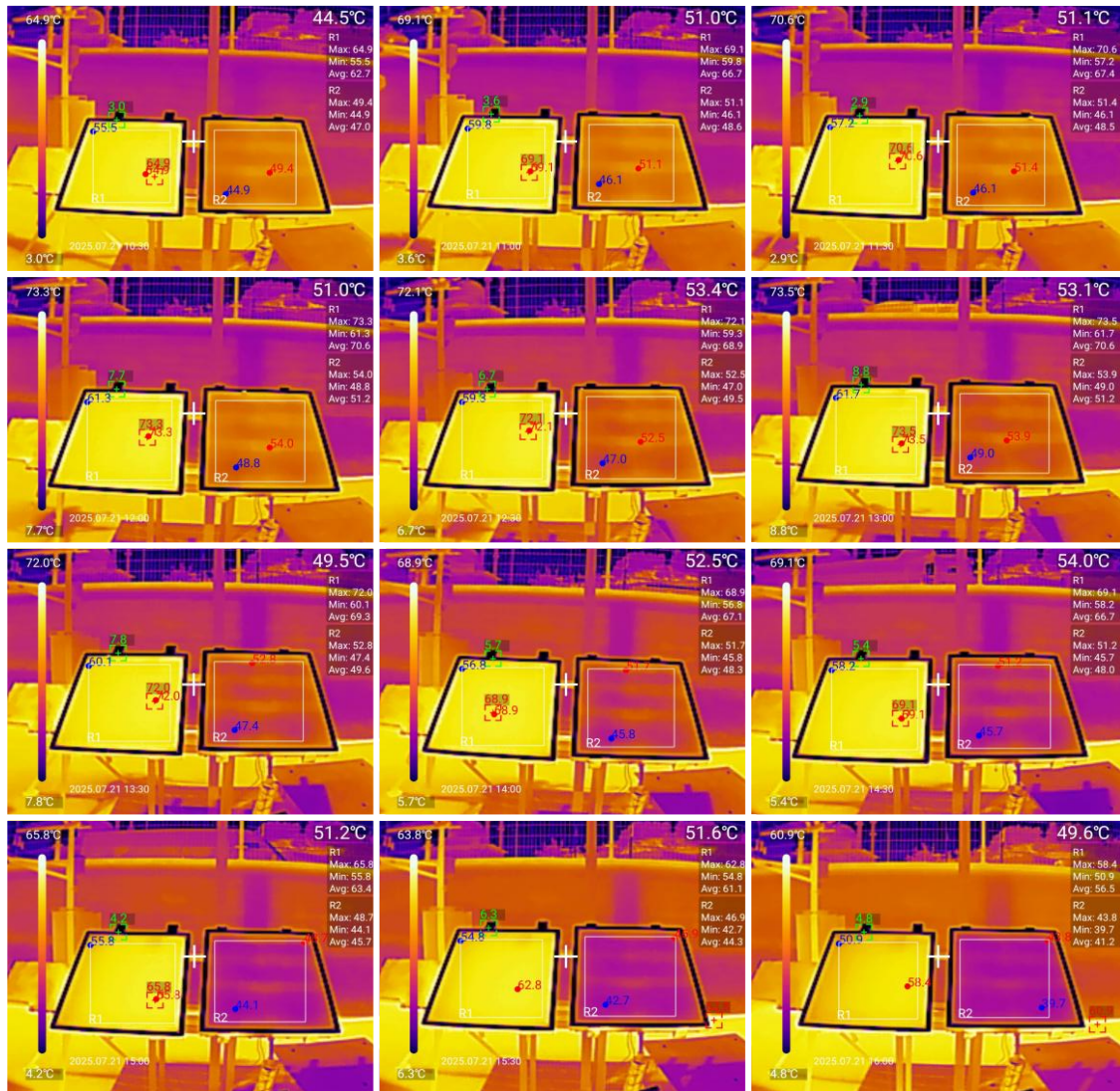


Figure 8.78. Thermal camera views of the reference (R1) and Cooled (R2) panels, provided every 30 Min between 10:30 and 16:00 local time

To conclude, the 1 s-on/300-s off pump cycle attained efficiency and cumulative energy output improvements similar to those of the 1-s on/180-s off cycle, but with lower water consumption, making it a more sustainable choice for areas facing water shortages.

8.3.3. Results of the manual spraying

An average of 115g of water was manually sprayed on the HRs attached at the back of the panel every 30 min, facilitating the removal of excess heat from its rear side.

The meteorological variables, including wind direction, average wind speed, average air temperature, humidity and average global solar radiation, recorded on the experimental day (July 22, 2025) by the weather station, are illustrated in **Figure 8.79**.

The wind direction remained stable throughout the experimental day, blowing from the northwest. There were no drastic changes in wind speed, which ranged from 0.6 to 1.2 m/s. The air temperature averaged between 34 and 43 °C, showing a gradual increase throughout the day. The relative humidity ranged from 14% to 32%, with the lowest values recorded between 13:15 and 14:00. The average global solar radiation followed the expected pattern, with maximum radiation occurring between 12:00 and 13:00.

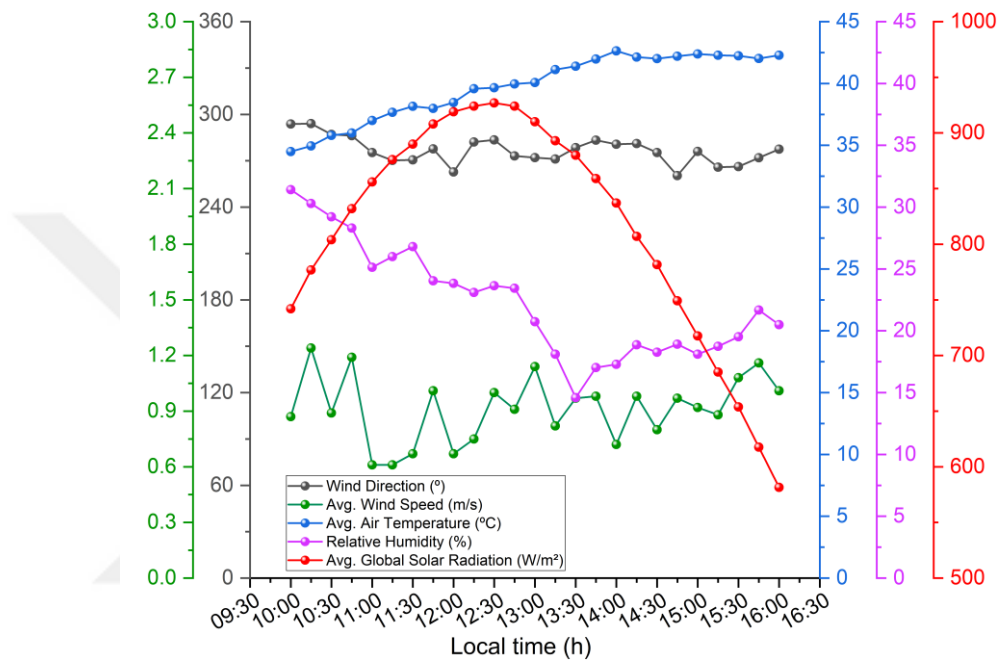


Figure 8.79. Meteorological parameters detected on the experimental day

The average temperatures of the reference and cooled PV panel, temperature drop due to the EC, and DSR are shown in **Figure 8.80**. The cooled panel maintained at lower temperatures than the reference panel during the experimental day. The temperature differences were significant at midday period when solar radiation was elevated. The average temperature of the reference panel reached 69.8 °C at 13:45, probably due to the relatively high air temperature, low wind speed and reduced relative humidity at that time, while the average temperature of the cooled panel maintained below 52 °C throughout the day. According to the average temperature measurements obtained 15 and 30 min after the back-side spraying, the temperature of the cooled panel was reduced by up to 19.2 °C compared to the reference panel at 13:15 and 13:45 local time, when the average air temperature and solar radiation was relatively high. This confirms that the EC system is effective under intense thermal conditions. Furthermore, an average of 115 grams of

water spraying maintained the temperature difference for 30 min, which confirms that this cooling method has the potential to remain effective over extended periods, such as 1 or even 2 hours. This also indicates that HRs have high water absorption and retention capacities, so release moisture slowly as the panel temperature increases. Consequently, this figure supports that the manual spraying on the rear side of the panel covered with HRs is simple, practical and effective technique for thermal control in arid conditions and extremely high temperatures.

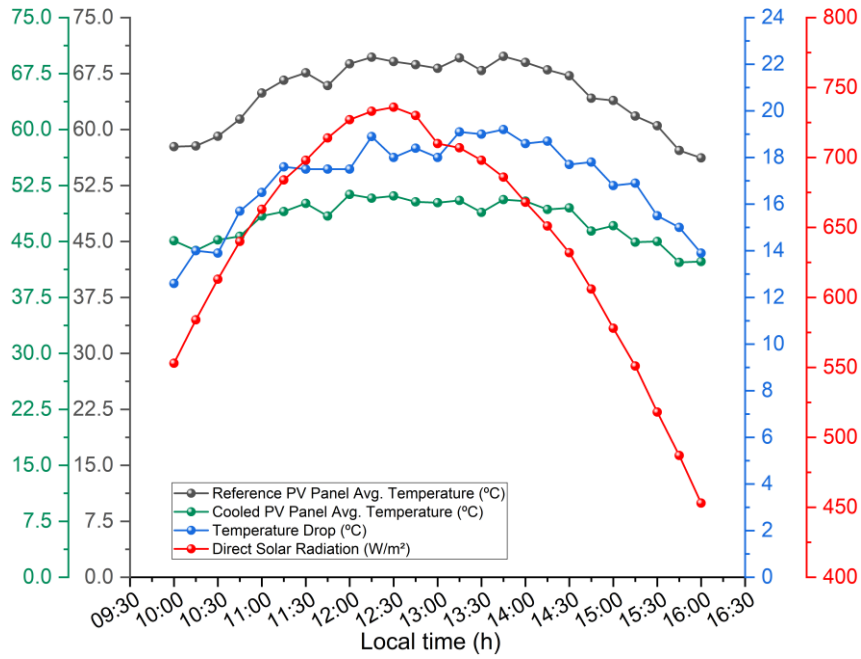


Figure 8.80. Panel's Surface Temperatures, corresponding temperature drop and DSR

The MPP parameters, including P_{mpp} , V_{mpp} , and I_{mpp} , of the reference and cooled PV panel, along with the DSR are given in **Figure 8.81**. Compared to P_{mpp} of the reference panel, the cooled panel achieved higher P_{mpp} values throughout day, particularly between 11:30 and 13:15, possibly because of the high solar radiation during that period. The I_{mpp} values of both panels were nearly equal and displayed a similar trend with the DSR and P_{mpp} curves, suggesting that they were mostly influenced by solar radiation rather than temperature. Conversely, the V_{mpp} of the cooled panel was considerably higher than that of the reference panel. Overall, the cooling effect enhanced the V_{mpp} values for the cooled panel, thereby increasing its P_{mpp} values.

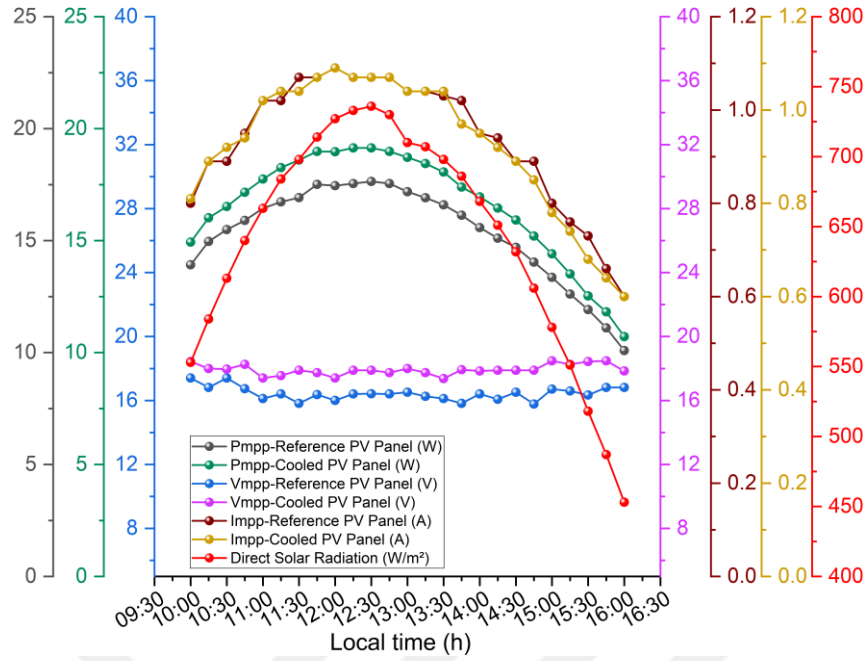


Figure 8.81. MPP of the Panels, and DSR

Figure 8.82 demonstrates the V_{oc} , and I_{sc} values of reference and cooled PV panels, together with the P_{mpp} and DSR. As presented in **Figure 8.82**, the I_{sc} values of both panels were roughly equal and closely aligned due to receiving the same solar radiation and being identical panels, which clearly shows that I_{sc} is not greatly influenced by the temperature. On the other hand, the V_{oc} values of the cooled panel were marginally higher compared to those of the reference panel throughout the entire measurement period. This difference can be attributed to the lower operating cell temperatures of the cooled panel, which reduced thermal losses and thereby sustained a higher voltage output.

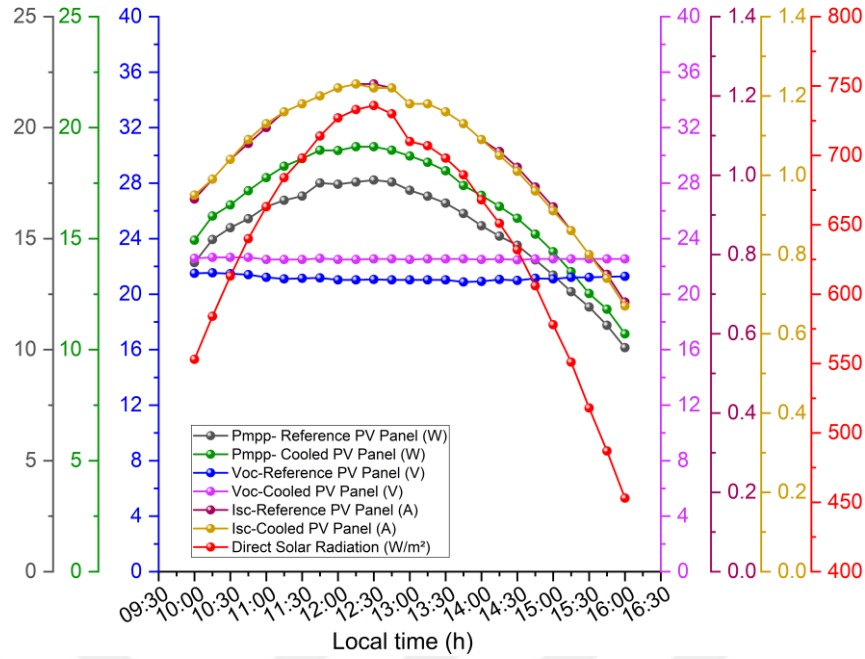


Figure 8.82. Comparison of V_{oc} and I_{sc} Values with P_{mpp} Readings, with DSR

The efficiency of the reference and cooled PV panels, the total cell efficiency for both panels and their FF rates are presented in **Figure 8.83**. The cooled panel demonstrated greater efficiency compared to the reference panel at all measured time intervals, highlighting the effectiveness of the cooling system. In terms of average efficiency, the cooled panel achieved 17.21% at the panel level and 23.27% at the cell level, while the reference panel reached 15.94% at the panel level and 21.54% at the cell level. Therefore, the average panel efficiency was boosted by 7.97%, with the total average cell efficiency gaining 7.90%. Both panels showed a decline in efficiency as the day progressed due to a decrease in power output resulting from the higher cell operating temperature brought about by the rise in air temperature. As clearly observed, both panels sustained relatively stable FF rates throughout the entire testing period. The cooled panel exhibited slightly higher FF values, which is indicative of enhanced I-V characteristics. As a result, the manual significantly improved both efficiency and electrical power output of the panel, demonstrating the effectiveness of the cooling system.

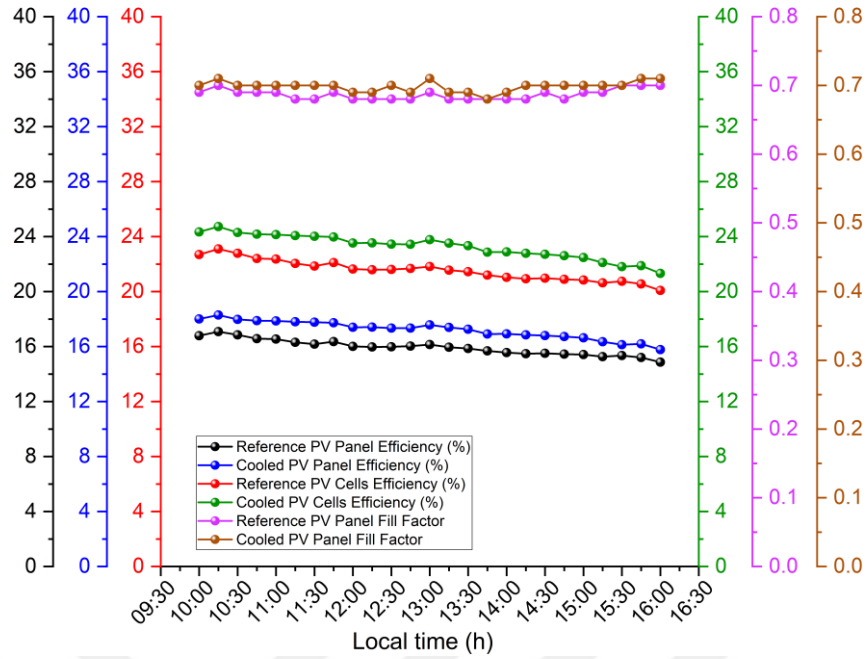


Figure 8.83. Efficiencies and FF rates of the Panels

Figure 8.84 displays the energy output at measurement points, the cumulative energy of the reference and cooled PV panels, and DSR. The manual spraying on the HRs mounted on the back side of the panel led to an 8.13% improvement in cumulative energy. During the entire measurement period, the cooled panel produced greater energy output in comparison to the reference panel. The energy outputs for both panels followed the DSR profile, and the cooled panel generated considerably more energy, especially throughout the midday hours when thermal effects were more substantial.

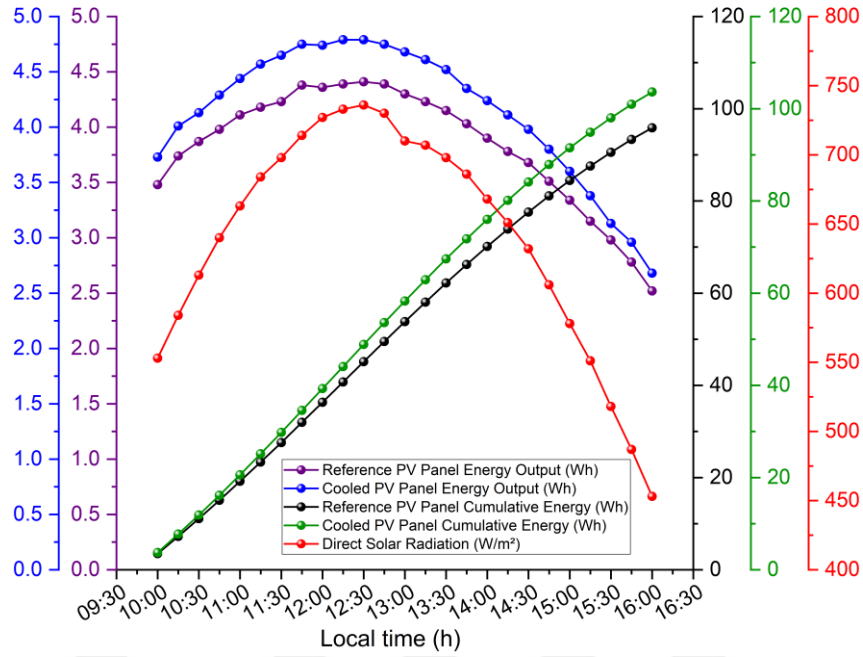


Figure 8.84. Energy output and cumulative energy output, and DSR

Thermal camera images of the reference and the cooled PV panels, taken at 10:45, 11:00, 11:45, 12:00, 12:45, 13:00, 13:45, 14:00, 14:45, 15:00, 15:45, and 16:00 local time are shown in **Figure 8.85**. These images evidently validate the thermal performance of the cooling system. Furthermore, as observed in the thermal camera images, a uniform cooling effect is evident with using the manual spraying on the HRs attached to the rear side of the PV panel.

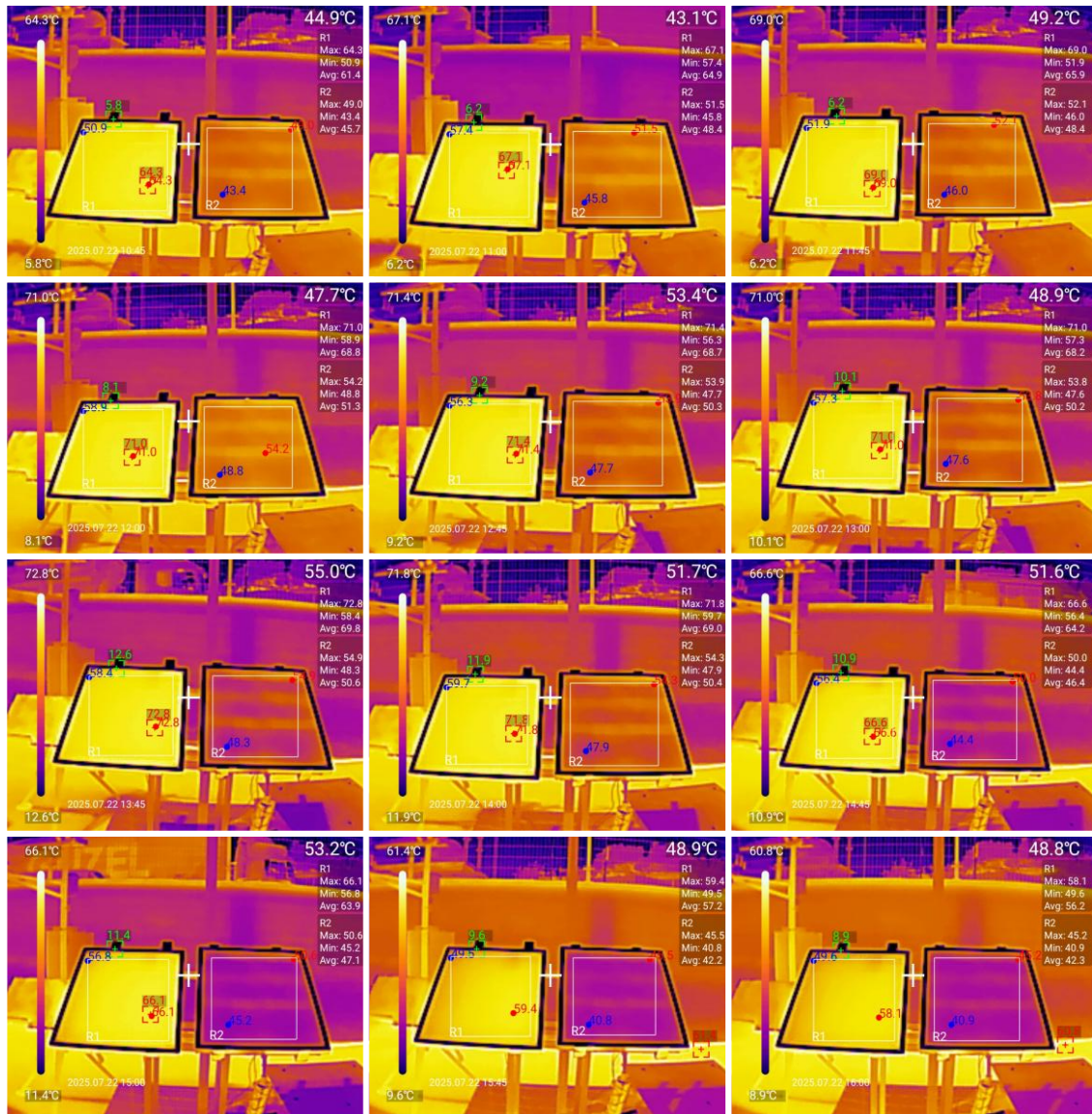


Figure 8.85. Thermal camera images of the reference (R1) and cooled (R2) panels, presented at selected times between 10:00 and 16:00 local time

Consequently, the manual spraying on HRs yielded slightly lower performance parameters, including lower percentage improvement in cumulative energy, lower temperature reduction, relative to the cooling configuration using the pump cycles of 1-s on/300-s off and liquid distribution system under comparable environments. Nevertheless, it achieved a minor improvement in cooling uniformity.

8.3.4. Summary of results of the EC technique with HRs and underground cooling

The results from the EC system using HRs and underground cooling are summarized as follows:

- All three configurations of the EC employing HRs and underground cooling proved effective in arid and extremely hot climates.
- The cooling configurations consistently reduced the PV panel's surface temperature during the entire duration of the experiments, improving the panels' efficiency, energy production and I-V characteristics.
- Thermal camera images provided clear visual proof of a uniform cooling effect resulting from the cooling configurations, reducing the occurrence of severe issues such as hotspots, current mismatch problems, and lasting structural damage.
- The maximum temperature drops for the 1-s on/180-s off pump cycle, 1-s on/300-s off pump cycle, and manual spraying were 22.1, 20.4, and 19.2 °C, respectively.
- The EC process led to an average improvement in panel efficiency of 9.57% for the 1-s on/180-s off pump cycle, 8.42% for the 1-s on/300-s off pump cycle, and 7.97% for the manual spraying. On the other hand, there was a 9.41%, 8.79%, and 7.90% increase in cell efficiency for the 1-s on/180-s off pump cycle, the 1-s on/300-s off pump cycle, and the manual spraying, respectively, when compared to the reference panel.
- Employing the 1-s on/180-s off pump pattern achieved the highest cumulative energy improvement of 9.56%, followed by the 1-s on and 300-s off ump cycle, with an 8.86% increase, and manual spraying, with an 8.13% increase, relative to the reference panel's cumulative energy output as the baseline.
- The panel under the EC setups demonstrated superior panel and cell efficiencies in comparison to the reference panel at the measurement times, though these values decreased over time due to the decline in solar radiation and the increase in air temperature on the experimental days.
- More water was evaporated when the 1-s on/180-s off pump pattern was used compared to when the 1-s on/300-s off cycle was operated. This was partly due to consistently higher average air temperatures on the day the 1-s on/180-s off cycle was applied, which promoted greater evaporation.
- The 1-s on/180-s off pump cycle achieved the highest temperature drop, even under slightly higher average air temperature readings at measurement intervals, compared to the 1-s on/300-s off cycle and manual spraying. Therefore, this setup may be preferable in regions with extremely hot climates and sufficient water resources.

- The 1-s on and 300-s off pump pattern demonstrated comparable effectiveness to the 1-s on, 180-s off pump pattern, while requiring less water to achieve comparable improvements in panel efficiency and cumulative energy output. Consequently, it presents a more sustainable option for regions experiencing water scarcity.
- An analysis of thermal camera images from the three configurations revealed that the manual spraying resulted in slightly more uniform cooling.
- The manual spraying sustained the temperature drop for 30 min, thanks to water absorption and retention capacity of the HRs. This implies that the method could remain efficient over longer periods, such as 1 or even 2 hours.

8.4. General Discussion

In terms of temperature reduction performance during the peak solar radiation period, typically between 12:00 and 13:30, CWs with the 1-s on/180-s off pump cycle were more effective than the other EC setups, followed by the HRs with 1-s on/180-s off pump cycle, CWs with 1-s on/300-s off pump cycle, and manual spraying on CWs. The manual spraying on CWs and the 1-s on/300-s off pump cycle with HRs showed comparable results, while the manual spraying on HRs demonstrated lower performance. The performance order for all setups used in this study is illustrated in **Figure 8.86**.

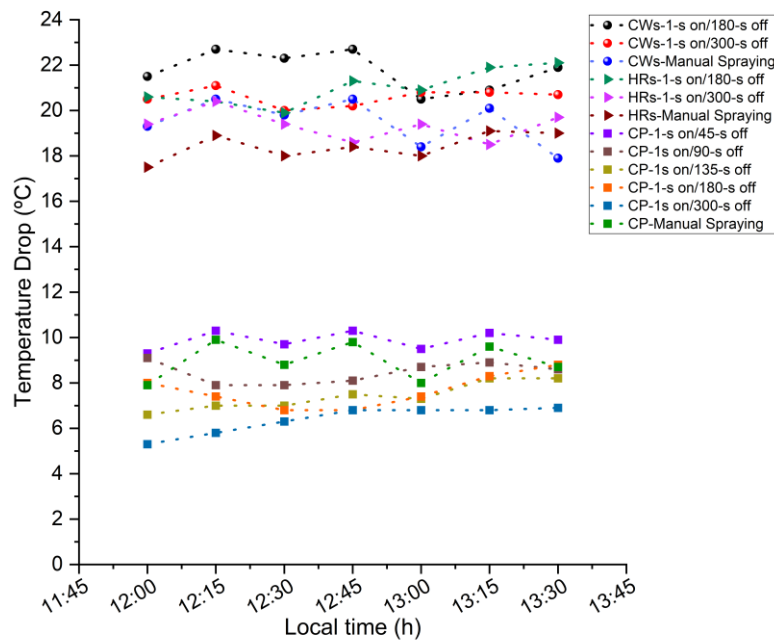


Figure 8.86. Temperature reduction performance of the EC setups

Furthermore, as can be determined from **Figure 8.86**, the EC configurations using the CP had substantially lower temperature reduction performance compared to both CWs and HRs-based cooling setups. The CP with 1-s on/45-s off pump cycle was the most effective configurations relative to the other CP setups, followed by the manual spraying, and 1-s on/90-s off pump cycle. The 1-s on/135-s off pump cycle and 1-s on/180-s off pump cycle exhibited similar results, whereas the 1-s on/300-s off pump cycle demonstrated lower performance.

The EC approach employing CWs in combination with the liquid distribution system and 1-s on/180-s off pump cycle achieved the greatest improvement in panel and overall cell efficiency, followed by CWs operating on the 1-s on/300-s off cycle and HRs using the 1-s on/180-s off cycle, as illustrated in **Figure 8.87**. In addition, the rise in average efficiency was significantly smaller for the EC using the CP compared to the cooling setups based on both CWs and HRs. Furthermore, among the manual spraying configurations, spraying on CWs resulted in the highest average efficiency increase relative to the reference panel.

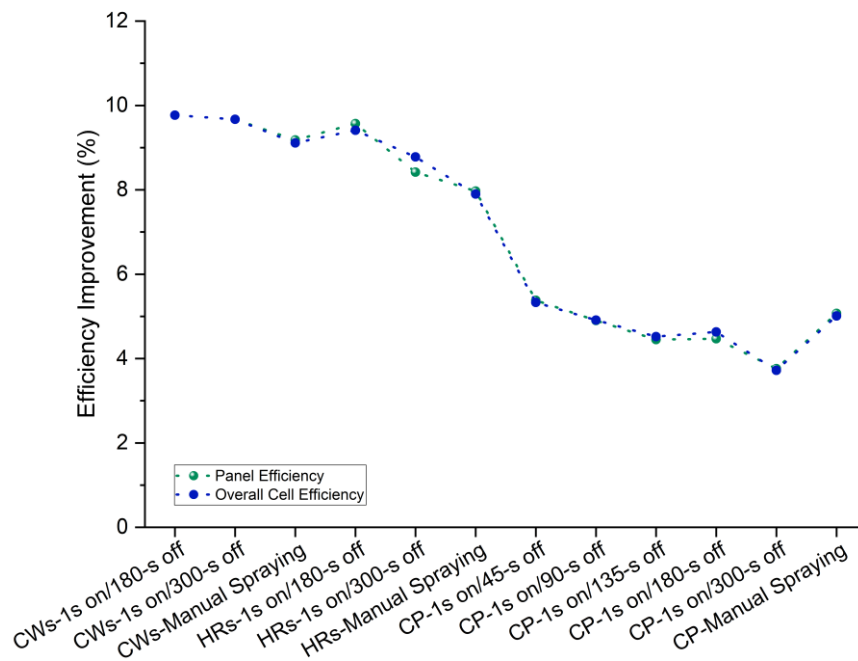


Figure 8.87. Efficiency enhancements of the EC setups

In line with the efficiency trend, the EC method using CWs, combined with the liquid distribution system and the 1-s on/180-s off pump cycle achieved the highest

percentage enhancement in cumulative energy output, followed by CWs with the 1-s on/300-s off pump cycle, and HRs with the 1-s on/180-s off pump cycle, as presented in **Figure 8.88**.

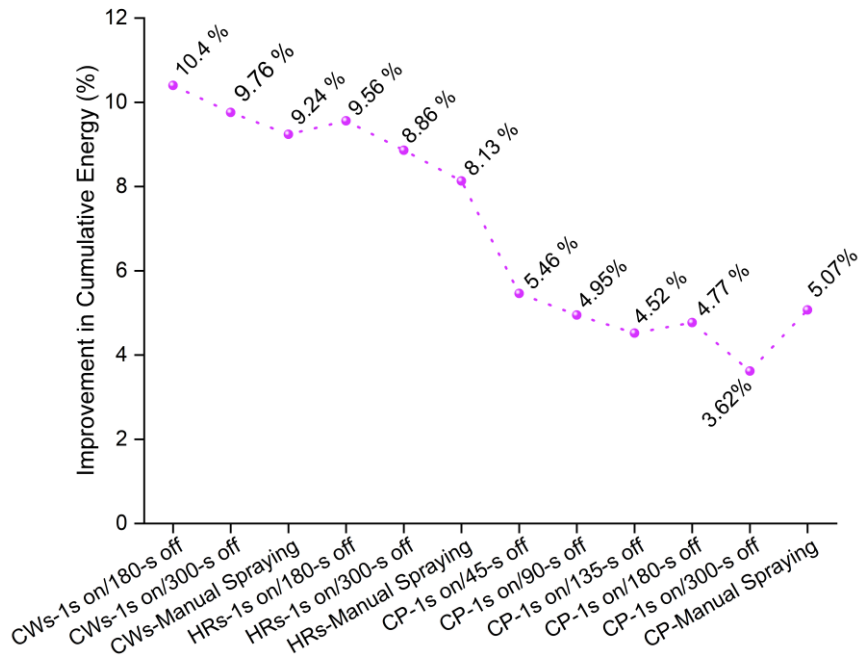


Figure 8.88. Improvement in cumulative energy output of the EC Setups

In agreement with the efficiency pattern, the percentage increase in cumulative energy was distinctly lower for the EC employing the CP relative to both CWs and HRs-based cooling configurations, as shown in **Figure 8.88**.

The manual spraying on CWs and HRs was more promising than manual spraying on the CP in terms of temperature reduction and performance improvement of the panel. The improvements in cumulative energy percentage were 9.24%, 8.13%, and 5.07% for the manual spraying on CWs, HRs and CP, respectively, under comparable weather conditions, relative to the cumulative energy output of the reference panel. The optimum temperature drops achieved by the manual spraying on CWs, HRs, and CP were 20.5 °C, 19.2 °C, and 10.1 °C, respectively.

The manual spraying on HRs sustained the temperature difference more effectively over the period of 30 min when compared to the manual spraying on CWs. This is possibly due to the higher density, and superior water retention capacity of HRs.

Parameters such as a higher improvement ratio in cumulative energy and a greater temperature drop were achieved with the manual spraying on CWs, compared to manual

spraying on HRs, while using less average water per spray. The higher water consumption observed during the HRs tests can be attributed to variations in meteorological conditions, as the mean air temperature on the testing day was higher for the manual spraying on HRs.

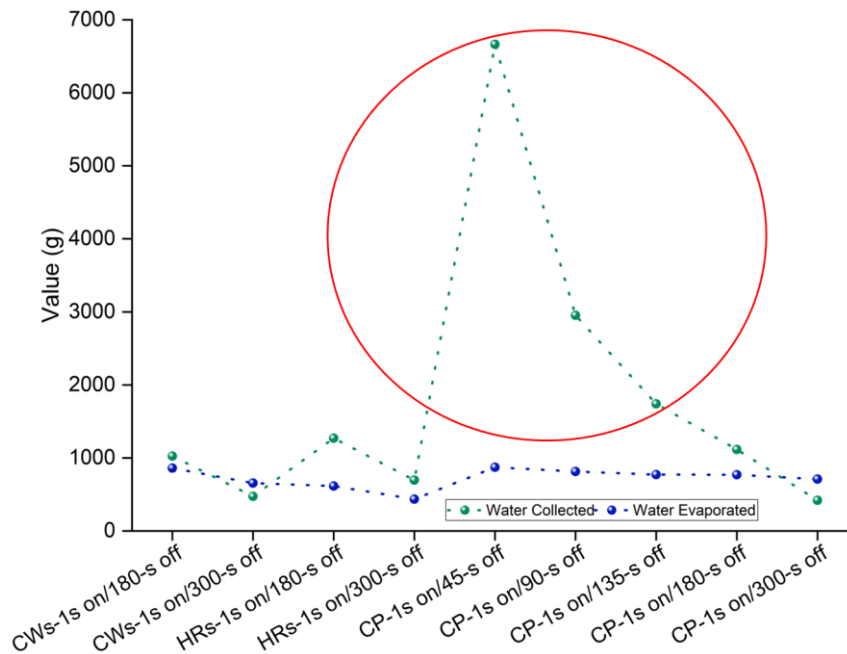


Figure 8.89. Water collected and evaporated during the operation of EC configurations

The red circle in **Figure 8.89** indicates that significantly higher amount of water were collected during the CP with the 1-s on/45-s off, 1-s on/90-s off, and 1-s on/135-s off compared to other EC configurations. However, the water evaporated in these cases remained relatively stable and did not display a dramatic peak, so they did not enhance evaporation. Therefore, the 1-s on/45-s off, 1-s on/90-s off, and 1-s on/135-s off test conditions were not applied to CWs and HPs setups to avoid surplus water consumption.

As revealed in **Figure 8.89**, a greater amount of water evaporated during the CP with 1-s on/180-s off pump cycle compared to the CP with 1-s on/300-s off cycle, which is expected since the 1-s on/180-s off cycle resulted in greater temperature reductions at all measurement points, requiring more water evaporation to achieve the larger cooling effect. In addition, the volume of water evaporated during the CP using the 1-s on/135-s off and 1-s on/180-s off pump cycles was similar, since both produced comparable temperature reductions under alike meteorological conditions. Furthermore, during the CP with 1-s on/90-s off pump cycle, more water evaporated relative to the CP with 1-s on/135-s off and 1-s on/180-s off cycles, as it generally produced greater temperature

reductions at each monitoring point. Moreover, when the CP with 1-s on/45-s off pump cycle was employed, water evaporation exceeded that of the CP using 1-s on/90-s off cycle, due to the usually larger temperature reductions observed throughout the measurement periods.

Additionally, as evident from **Figure 8.89**, a larger volume of water evaporated during the CWs with the 1-s on/180-s off pump cycle used to remove excess heat from the panel than throughout the CWs with 1-s on/300-s off cycle. On the day the 1-s on/180-s off cycle was operated, solar radiation was higher, relative humidity was lower, and average air temperature and wind speed were greater, specifically around midday, than on the day the 1-s on/300-s off cycle was performed. Consequently, more water evaporation was required to remove the additional heat.

Moreover, as shown in **Figure 8.89**, a greater amount of water evaporated during the HRs with the 1-s on/180-s off pump pattern in comparison to the HRs with the 1-s on/300-s off cycle. This can be partially attributable to higher mean air temperatures on the day the 1-s on/180-s off cycle was applied, which stimulated higher evaporation.

A comparison of the SEG for the EC setups is shown in **Figure 8.90**. The manual spraying configurations were more effective based on energy gain per gram of evaporated water, especially with CWs, because the manual spraying distributed the coolant more uniformly over the surface of the panel, which ensured a greater effective evaporation area and enhanced heat removal. Furthermore, the sprayed water was easier to control, so reducing absorption and storage losses. Moreover, accumulated liquid water in the porous material may obstruct the natural convection of air in configurations operating with pump cycles.

In terms of SEG, HRs outperformed CWs and CP under both operation cycles of 1-s on/ 180-s off and 1-s on/ 300-s off owing to their superior absorption and retention capacity, as demonstrated in **Figure 8.90**. Overall, the EC configurations using CP exhibited the lowest SEG, which is due to its lower water absorption and heat removal properties.

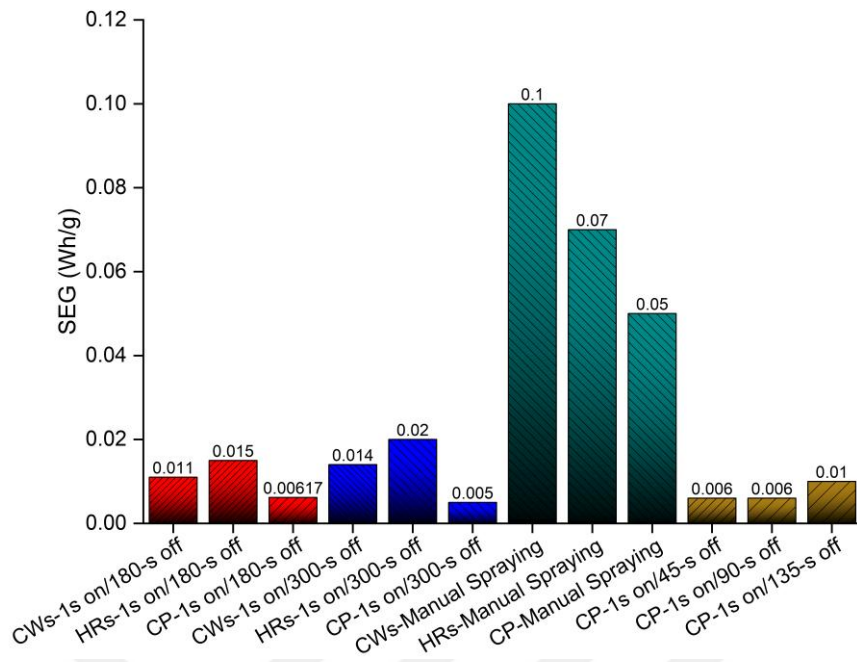


Figure 8.90. SEG comparison for the EC configurations

9. CONCLUSION

The following conclusion can be drawn from the EC techniques employed in this thesis:

- The thermal state of the PV panels and the intensity of solar radiation substantially influenced their energy output.
- Meteorological factors, including mean air temperature, wind speed and relative humidity, significantly influenced temperature drop and energy output of the panels. In particular, the difference in energy output between the reference and cooled panels increased when there was a sudden rise in average wind speed at the measurement points. In contrast, wind direction had less influence on panel temperature and energy production than average air temperature, relative humidity, and solar radiation levels.
- Average air temperature, wind speed and relative humidity, markedly affected the amount of water evaporated. A greater amount of water evaporated under higher mean air temperatures, stronger wind speeds, and lower relative humidity.
- The efficiency of the panels gradually declined over the experimental period due to increase in cell operating temperature, possibly caused by the elevated air temperature.
- The V_{mpp} and V_{oc} of the PV panels were primarily influenced by temperature and solar radiation, while the I_{mpp} and I_{sc} were mainly determined by solar radiation. The I_{mpp} and I_{sc} readings of the reference and cooled PV panels were mostly equivalent, and their curves aligned with the curve of solar radiation. Hence, the enhancement in the electrical performance of the cooled panel was chiefly driven by improved voltage production brought about by the EC.
- The EC systems designed in this thesis are environmentally friendly, sustainable, easy to manufacture, and can be simply integrated with PV panels to enhance their electrical energy production and efficiency. Furthermore, they are cost-effective and extend the panels' operational lifetime.
- The EC approaches evaluated in this thesis proved effective in arid and intensely hot climates.

- The EC methods investigated in this thesis consistently reduced the surface temperature of the PV panels, thereby enhancing energy output and improving panel and total cell efficiency. This overall improvement in electrical performance, primarily as a result of increased voltage, was observed in all cases.
- The porous EC materials used in this thesis absorbed water quickly. The CWs and HRs retained water for a longer time and were able to reduce the panel temperature over longer intervals compared to the CP.
- Compared to the CP, the CWs and HRs provided more contact area with the rear side of the cooled panel due to not having large airflow porous, allowing for greater water absorption and heat removal. Therefore, a CP with smaller airflow pores could be considered as an alternative to the one used in this thesis. Alternatively, the pore orientation in the pad can be adjusted and specifically designed for PV panel applications.
- The CP was comparably effective in the late afternoon period as in the midday period, despite significantly lower solar radiation. This reveals that the pad remained effective as long as it was adequately wet, since increased air temperatures, higher wind speeds, and lower relative humidity during the late afternoon could sustain the cooling process.
- The EC approaches examined in this thesis provided homogeneous cooling across the entire panel surface, thereby effectively mitigating the occurrence of hotspots, current mismatch and long-term structure damage.
- CWs with the 1-s on/180-s off pump cycle were more effective than the other EC configurations in terms of temperature reduction, efficiency improvements, and energy production.
- CWs with the 1-s on and 300-s off pump cycle was a more water-saving configuration, as it provided similar temperature reduction, efficiency improvement, and energy generation compared to CWs with the 1-s on/180-s off pump cycle.
- The manual spraying on CWs proved more promising than the manual spraying on HRs and CP regarding temperature reduction, efficiency improvements, and energy output.
- The manual spraying on HRs maintained the temperature difference more consistently over the 30-min period compared to manual spraying on CWs and CP. This suggests that the cooling technique could remain effective over extended durations.

- The EC configurations using CP were less effective at reducing temperature, enhancing efficiency, and increasing energy production compared to the EC setups employing CWs and HRs.
- According to SEG calculations, the manual spraying configurations of the EC systems proved more efficient because they ensured more even water distribution, enhanced evaporation thus heat dissipation, and decreased absorption losses.
- Based on SEG analysis, the EC configurations employing the CP had the lowest values due to its limited water absorption and heat extraction ability.
- The cycle trigger timer delay used in the EC systems in this thesis delivered water according to the time period programmed via the pump. The timer delay was not adaptive to the solar radiation received by the cooled panel or its temperature. Therefore, an adaptive timer delay can be designed to adjust water spraying according to the solar radiation or temperature of PV panels. Thus, maximum cooling can be achieved using the least amount of water in shorter intervals. Moreover, the dripping water from the porous evaporative materials will be minimized, eliminating the need for the collection tray beneath the panel. As a result, maximum enhancement in power and efficiency of PV panels can be achieved using a minimal amount of water.
- A device integrated with an adaptive timer delay can be designed in future studies to automate spraying onto the porous EC materials attached to the rear side of PV panels, operating based on environmental conditions and eliminating the need for manual spraying.
- A CP can be specifically designed for cooling the rear side of PV panels, featuring well-oriented and suitably sized airflow pores.
- The experiments can be carried out over longer periods of time than in this thesis if a tracking system is integrated into the PV panel setup.
- As an alternative, a passive EC system using porous evaporative material, such as HRs, and CWs, can be designed to increase overall system efficiency.

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APPENDIXS

Appx. 1. NRG 40C anemometer technical specifications

General Information	
Sensor Type	3-cup sensor
Applications	Wind source determination Meteorological studies Environmental monitoring
Measurement Range	1 m/s ~ 96 m/s (recorded highest value)
Compatibility	All NRG data loggers
Output Signal	
Signal Type	AC sine wave (frequency varies linearly with wind speed)
Transfer Function	$m/s = (Hz \times 0,765) + 0,35$
Accuracy	0.1 m/s (between 5 m/s and 25 m/s)
Calibration	Each anemometer is calibrated individually
Output Signal Range	Between 0 and Hz 125 Hz (recorded highest value)
Response Characteristics	
Threshold Value	0,78 m/s
Distance Constant	3.0 m
Moment of Inertia	68×10^{-6} S-ft ²
Rotor Sweep Diameter	190 mm
Installation	
Mounting	13 mm diameter threaded pin
Required Tools	13 mm wrench, lubricant, insulation tape
Environmental	
Operating Temperature Range	-55°C ~ 60°C
Operating Humidity Range	0 ~ %100 RH
Physical	
Connection	4-40 brass hex nut
Weight	0,14 kg
Dimensions	81 mm
Material	
Cups	Single-piece injection-molded black polycarbonate
Body	Black ABS plastic
Shaft	Hardened beryllium copper
Bearing	Modified Teflon
Magnet	Index 1, 25 mm diameter, 13 mm length, 4-pole
Winding	4100 turns single coil

Appx. 2. NRG 200P wind direction sensor technical specifications

General Information	
Sensor Type	Potentiometric continuous rotation
Applications	Wind source determination, Meteorological studies, Environmental monitoring
Measurement Range	360° mechanical angle
Compatibility	All NRG data loggers
Output Signal	
Signal Type	DC voltage provided by potentiometer, 10 K Ω
Transfer Function	Proportional voltage
Accuracy	Potentiometer linearity, %1
Dead Zone	Maximum 8°, typical 4°
Output Signal Range	0 V ~ Excitation voltage
Response Characteristics	
Threshold Value	1 m/s
Power Requirements	
Voltage Supply	1 V to 15 V DC
Installation	
Mounting	13 mm diameter threaded pin
Required Tools	13 mm socket wrench, oil, insulation tape
Environmental	
Operating Temperature Range	-55°C ~ 60°C
Operating Humidity Range	0 ~ %100 RH
Operating Life	50 million cycles (2 ~6 year)
Physical	
Connection	4-40 brass hex nut
Weight	0,14 kg
Dimensions	21x12 cm, 27 cm scanning diameter
Material	
Cups	UV stabilized injection plastic
Body	UV stabilized anti-static plastic
Shaft	Stainless steel
Bearing	Stainless steel

Appx. 3. CMP6 pyranometer technical specifications

Specifications	CMP6
Applications	Meteorological Stations, Field tests
ISO 9060:1990 classification	Class 1
Sensitivity	5 ~ 20 $\mu\text{V}/\text{W}/\text{m}^2$
Impedance	20 ~ 200 Ω
Output Voltage	0 to 30 mV (0 ~ 1500 W/m^2 range)
Maximum Operating Irradiance	2000 W/m^2
Response Time (%63)	< 6 s
Response Time (%95)	< 18 s
Spectral Range (%20)	285 ~ 3000 nm
Spectral Range (%50)	300 ~ 2800 nm
Long-term Stability	< %1 ($\text{W}/\text{m}^2/\text{year}$)
Linearity	< %1,5 (100 ~ 1000 W/m^2)
Directional Response (up to 80° at 1000 W/m^2)	< 20 W/m^2
Spectral Selectivity	< %3 (350 ~ 1500 nm)
Tilt Response	< %1 (0° ~ 90°, 1000 W/m^2)
Temperature Response	< % 5 (-10°C ~ +40°C)
Field of View	180°
Bubble Level Sensitivity	< 0,2°
Sensor Type	Thermopile
Operating Temperature Range	-40°C ~ +80°C
Operating Relative Humidity Range	0 ~ %100 RH
Time Between Failures	> 10 years
Ingress Protection Class	67

Appx. 4. HC2S3 temperature and humidity sensor technical specifications

General Information	
Filter Description	Polyethylene (standard), Teflon (optional)
Current Consumption	< 4.3 mA (@ 5 Vdc) < 2.0 mA (@ 12 Vdc)
Voltage Supply	5 ~ 24 Vdc
Start-Up Time	1,5 s
Maximum Start-Up Current	< 50 mA
Analog Outputs	±3 mV
Dimensions	15x85 mm (Diameter, Length)
Weight	10 g
Air Temperature	
Sensor Type	PT100 RTD, IEC 751 1/3 Class B
Measurement Range	-40° ~ +60°C (default) -50° ~ +100°C (possible)
Output Signal Range	0 ~ 1 Volt
Accuracy	±0,1°C (standard configuration, 23°C)
Long-term Stability	< 0.1 °C/year
Sensor Time Constant Standard PE filter	≤ 22 s
Sensor Time Constant Optional Teflon filter	≤ 30 s
Relative Humidity	
Sensor Type	Rotronic® Hygrometer IN-1
Measurement Range	0 to %100 RH (non-condensing)
Output Signal Range	0 ~ 1 Volt
Accuracy	±%0,8 RH (standard configuration, 23°C)
Long-term Stability	< %1 RH (per year)
Sensor Time Constant Standard PE filter	≤ 22 s
Sensor Time Constant Optional Teflon filter	≤ 30 s

Appx. 5. CR1000 data logger technical specifications

Property	CR1000
Operating temperature range	-55°C to +85°C
Maximum scan rate	100 Hz
Memory	4 MB
Number of analog inputs	16
Communication/Data/Storage ports	1 CS I/O 1 RS-232 1 parallel
Switched 12 V	1
Digital ports	8 I/O or 4 RS-232 COM
Input voltage range	0 ~ ±5 Vdc
Analog voltage accuracy	± %0.06 (Measured value, 0°C - 40°C)
Output signal range	0 V ~ Excitation voltage
Analog resolution	0.33 µV
A/D Bits	13
Power supply	9.6 to 16 Vdc
Real-time clock accuracy	±3 min. (Per year)
Supported protocols	PakBus, Modbus, DNP3, FTP, HTTP, XML, POP3, SMTP, Telnet, NTCIP, NTP, SDI-12, SDM
Dimensions	23.8 x 10.1 x 5.4 cm
Weight	1 kg

Appx. 6. Data logger program commands

```
'CR1000
'Created by Short Cut (3.0)

'Declare Variables and Units
Public BattV
Public PTemp_C
Public Ruz_Yon
Public Ruz_Hiz
Public Hav_Sic
Public Hav_Nem
Public Glob_Rad
Public SolarkJ
Public NormalPOrta
Public SogutPUst
Public SogutPOrta
Public SogutPAlt
Public ToprakSicakligi

Units BattV=Volts
Units PTemp_C=Deg C
Units Ruz_Yon=degrees
Units Ruz_Hiz=meters/second
Units Hav_Sic=Deg C
Units Hav_Nem=%
Units Glob_Rad=kW/m^2
Units SolarkJ=kJ/m^2
Units NormalPOrta=Deg C
Units SogutPUst=Deg C
Units SogutPOrta=Deg C
Units SogutPAlt=Deg C
Units ToprakSicakligi=Deg C

'Define Data Tables
DataTable(Table1,True,-1)
    DataInterval(0,15,Min,10)
    WindVector (1,Ruz_Hiz,Ruz_Yon,FP2,False,0,0,0)
    FieldNames("Ruz_Hiz_S_WVT,Ruz_Yon_D1_WVT,Ruz_Yon_SD1_WVT")
    Average(1,Ruz_Hiz,FP2,False)
    Average(1,Hav_Sic,FP2,False)
    Sample(1,Hav_Nem,FP2)
    Average(1,Glob_Rad,FP2,False)
    Totalize(1,SolarkJ,IEEE4,False)
    Average(1,NormalPOrta,FP2,False)
    Average(1,SogutPUst,FP2,False)
    Average(1,SogutPOrta,FP2,False)
    Average(1,SogutPAlt,FP2,False)
    Average(1,ToprakSicakligi,FP2,False)
EndTable

DataTable(Table2,True,-1)
    DataInterval(0,1440,Min,10)
    Minimum(1,BattV,FP2,False,False)
```

EndTable

'Main Program

BeginProg

 'Main Scan

 Scan(5,Sec,1,0)

 'Default Datalogger Battery Voltage measurement 'BattV'

 Battery(BattV)

 'Default Wiring Panel Temperature measurement 'PTemp_C'

 PanelTemp(PTemp_C,_60Hz)

 'NRG #200P Wind Direction Sensor measurements 'Ruz_Yon'

 BrHalf(Ruz_Yon,1,mV2500,1,1,1,2500,True,0,_60Hz,360,0)

 If Ruz_Yon>=360 Or Ruz_Yon<0 Then Ruz_Yon=0

 'NRG #40 Wind Speed Sensor measurements 'Ruz_Hiz'

 PulseCount(Ruz_Hiz,1,1,1,1,0.752,0.38)

 If Ruz_Hiz<0.39 Then Ruz_Hiz=0

 'HC2S3 (constant power) Temperature & Relative Humidity Sensor measurements 'Hav_Sic' and 'Hav_Nem'

 VoltSE(Hav_Sic,1,mV2500,2,0,0,_60Hz,0.1,-40)

 VoltSE(Hav_Nem,1,mV2500,3,0,0,_60Hz,0.1,0)

 If Hav_Nem>100 And Hav_Nem<103 Then Hav_Nem=100

 'CMP3/CMP6/CMP11 Pyranometer measurements 'SolarkJ' and 'Glob_Rad'

 VoltDiff(Glob_Rad,1,mV250,3,True,0,_60Hz,1,0)

 If Glob_Rad<0 Then Glob_Rad=0

 SolarkJ=Glob_Rad*0.295858

 Glob_Rad=Glob_Rad*59.1716

 'Type K (chromel-alumel) Thermocouple measurements 'NormalPOrta'

 TCDiff(NormalPOrta,1,mV2_5C,5,TypeK,PTemp_C,True,0,_60Hz,1,0)

 'Type K (chromel-alumel) Thermocouple measurements 'SogutPUst'

 TCDiff(SogutPUst,1,mV2_5C,6,TypeK,PTemp_C,True,0,_60Hz,1,0)

 'Type K (chromel-alumel) Thermocouple measurements 'SogutPOrta'

 TCDiff(SogutPOrta,1,mV2_5C,7,TypeK,PTemp_C,True,0,_60Hz,1,0)

 'Type K (chromel-alumel) Thermocouple measurements 'SogutPAlt'

 TCDiff(SogutPAlt,1,mV2_5C,8,TypeK,PTemp_C,True,0,_60Hz,1,0)

 'Type K (chromel-alumel) Thermocouple measurements 'ToprakSicakligi'

 TCDiff(ToprakSicakligi,1,mV2_5C,4,TypeK,PTemp_C,True,0,_60Hz,1,0)

 'Call Data Tables and Store Data

 CallTable(Table1)

 CallTable(Table2)

 NextScan

EndProg

Appx. 7. Data logger connection diagram

NRG #200P - Ruz_Yon

Signal	1H
Shield	$\perp$ (Ground)
Ground	$\perp$ (Ground)
Power	VX1 or EX1

CR1000

NRG #40 - Ruz_Hiz

Shield	$\perp$ (Ground)
Ground	$\perp$ (Ground)
Signal	P1

CR1000

HC2S3 (CP) - Hav_Sic, Hav_Nem

Brown	1L
White	2H
Green	12V
Clear	$\perp$ (Ground)
Yellow	$\perp$ (Ground)
Gray	$\perp$ (Ground)

CR1000

CMP3/CMP6/CMP11 - Glob_Rad, SolarkJ

White	3H
Black	3L
Clear	$\perp$ (Ground)
	3L
Jumper	$\perp$ (Ground)

CR1000

Type K TC (1) - NormalPorta

Yellow	5H
Red	5L

CR1000

Type K TC (2) - SogutPUst

Yellow	6H
Red	6L

CR1000

Type K TC (3) - SogutPorta

Yellow	7H
Red	7L

CR1000

Type K TC (4) - SogutPAIt

Yellow	8H
Red	8L

CR1000

Type K TC (5) - ToprakSicakligi

Yellow	4H
Red	4L

CR1000

Appx. 8. Amprobe Solar-600 solar analyzer technical specifications

Parameters	Value
Power	0-720 W
DC Voltage	0.000 V - 0.999 V, 10.00 V - 60.00 V
DC Current	0.01 A - 9.99 A, 10.0 A -12.0 A
DC Current Simulation	0.01 A - 9.99 A, 10 A - 12 A
Scan Delay	0 mS - 3000 mS
Solar Panel Area	0.001 m ² - 99.99 m ²
Standard Light Source	10 W/m ² - 1000 W/m ²
Data Source Memory	99 Records
Battery Type	Rechargeable Lithium Battery, 11.1 V DC, 3400 mAh
Data Logging Memory Size	99 Records
AC Adaptor	AC 110 V or 220 V input, DC 15V / 1~3 A output

Appx. 9. UTI721M thermal camera technical specifications

Parameters	Value
Product Dimensions	33 mm × 28.2 mm × 11.3 mm
Infrared Resolution	256 × 192
Field of View	56.0° × 42.2°
Thermal Sensitivity	≤50mK at 25 °C
Spatial Resolution	3.8 mrad
Frame Rate	≤ 25 Hz
Spectral Range	8–14 μm
Focus	Fixed focus
Temperature Measurement Range	-20°C ~ 550 °C
Measurement Modes	Industry, EST (Elevated Skin Temperature)
Accuracy	Industry: ±2 °C or ±2%, whichever is greater (0°C ~ 550 °C) EST: ±0.5 °C (30 °C ~ 40 °C)
Emissivity	Adjustable from 0.01 to 1.00 (Default: 0.95)
Color Palettes	7 (White Hot, Lava, Iron Bow, Black Hot, Red Hot, Rainbow, Rainbow HC)
Image Modes	Thermal, Fusion, PIP (Picture in Picture)
Image/Video Storage Forma	JPEG, MP4

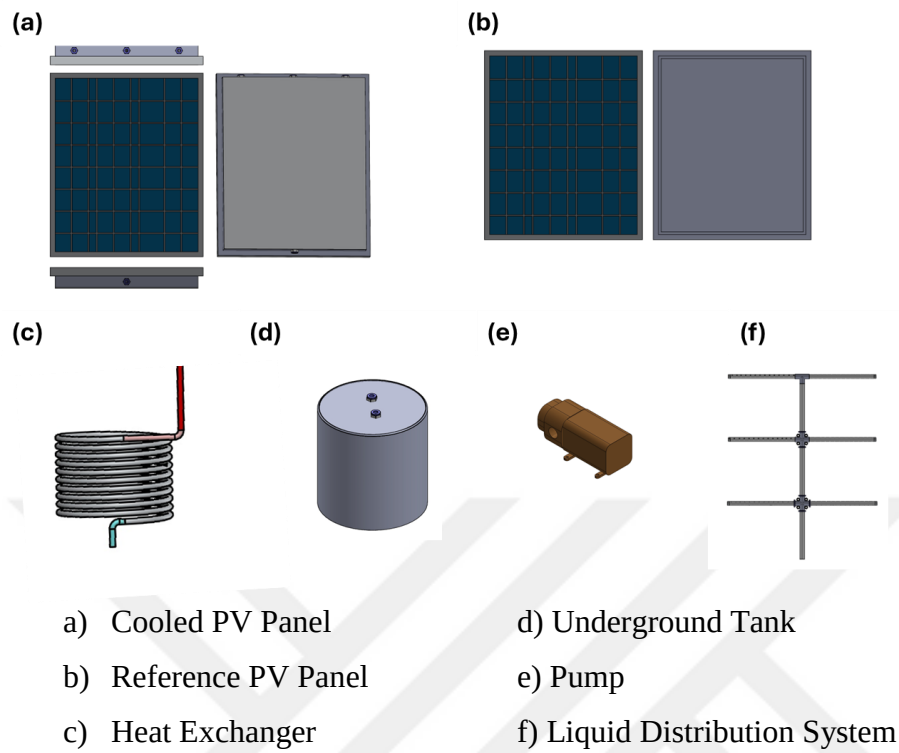
Appx. 10. CEM DT-1307 solarimeter technical specifications

Parameters	Value
Measurement Range	1999 W/m ² or 634 BTU (ft ² .h)
Accuracy	±10 W/m ² (±3 BTU) or ±5%
Resolution	1 W/m ² , 1 BTU (ft ² .h)
Measurement Units	W/m ² , BTU (ft ² .h)
Operating Temperature and Humidity	5 °C to +40 °C, below 80% humidity
Storage Temperature and Humidity	-10 °C to +60 °C, below 80% humidity
Display	LCD screen
Dimensions	162 x 63 x 28 mm (H x W x D)
Power Supply	3 x 1.5V AAA batteries
Response Time	Approximately 0.25 seconds
Weight	176 grams

Appx. 11. Radwag PS 1000.R2 precision balance technical specifications

Parameters	Value
Maximum capacity	1000 g
Minimum load	20 mg
Readability	0.001 g
Tare range	-1000 g
Verification scale interval	0.01 g
Repeatability	0.0015 g
Repeatability at low load	0.0005 g
Linearity	±0.003 g
Stabilization time	2s
Adjustment	internal (automatic)
OIML Class	II
Levelling system	manual
Display	LCD (backlit)
Weighing pan dimensions	128 x 128
Packaging dimensions	470 x 380 x 336 mm
Net weight	3.9 kg
Gross weight	5.5 kg
IP Rating	IP 43
Communication interfaces	2 x RS232 ¹ , USB-A, USB-B, Wi-Fi® (optional)
Power supply	100-240 V AC, 50/60 Hz
Operating temperature	+10 - +40 °C

Appx. 12. Main components of the experimental setup



Appx. 13. DC pump technical specifications

Property	Value
Voltage	12V DC
Current	2A
Power	24W
Pressure	0.9 MPa
Flow rate	3 L/min

