FACULTY OF TECHNOLOGY

Comparison of Solar Output of Vertical and Inclined Solar Panels in the High North

Vivek Manjunatha Swamy

Energy systems engineering

Master’s thesis

June 2023

ABSTRACT

This thesis presents a comprehensive literature review on the endurance of solar photovoltaic (PV) systems in high north conditions and the optimized setup parameters for maximizing their output. To simulate data, PV panels were considered in the high north region of Oulu, Finland, and their output was measured under various setup parameters. The data was then analyzed using SketchUp simulation with the Skelion plug-in to determine the optimized setup parameters that yield maximum output.

The findings of the study highlight the importance of tilt angles and orientation for maximizing energy production. The evaluation of different tilt angles, including vertical panels, roof-mounted panels with varying tilt angles, and inclined panels on a carousel, revealed that tilt angles closer to 45 to 47 degrees contribute to improved solar PV performance. Inclined panels exhibited peak outputs during the summer months, while vertically mounted panels performed better during spring. The optimal tilt angle was determined to be 45 - 47 degrees, enabling effective energy generation throughout the year.

The study also emphasized the significance of south-facing panel orientation, which consistently yielded higher energy production compared to other orientations. Furthermore, the thesis suggests future research directions, including the incorporation of complex weather variables, analysis of regional variation and temperature patterns, and the integration of advanced technologies into solar PV system simulations.

Overall, this research contributes valuable insights for the design, installation, and optimization of solar PV systems in high north conditions, promoting the adoption of efficient and sustainable solar energy solutions.

FOREWORD

First and foremost, I would like to express my deepest appreciation to my supervisor and professor, Eva Pongracz. I am grateful for the countless hours she invested in providing invaluable guidance, mentorship, and support through every stage of my degree and thesis.

During my studies in Oulu, I have been incredibly fortunate to have a brotherly friend, Athith Sagar, by my side. Athith has been a constant voice of support, encouragement, and inspiration. His unwavering presence during the mentally challenging times and his ability to keep me grounded and motivated have been a source of immense strength. I am truly grateful for his friendship and belief in my abilities.

I would also like to extend my heartfelt appreciation to my dear friends Bhushan Gowda, Praneeth Susarla, Megha Mohan, Yashaswini Gowda, Ritesh and Seema Tripathy. They have been my pillars of strength and a reliable support system throughout my journey. Their friendship, encouragement, and belief in my capabilities have made this journey all the more meaningful and memorable.

Lastly, but certainly not least, I must express my deepest gratitude to my parents. Their boundless love, support, and sacrifices have been the bedrock upon which my academic pursuits have flourished. Without their constant encouragement and belief in my dreams, none of this would have been possible.

With deepest appreciation,
Vivek Manjunatha Swamy

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

CdTe: Cadmium telluride

CIGS: Copper Indium gallium selenide

DSC: Dye-sensitized Solar Cells

EEA: European Economic Area

EPW: Energy-Plus Weather

ETL: Electron Transport Layer

EU: European union

EW: East-West

HIT: Heterojunction with intrinsic thin layer

I-V: Current – Voltage

MPP: Maximum power point

MPPT: Maximum power point tracking

NS: North-South

OPV: Organic photo voltaic

OSC: Organic Solar Cell

PCE: Power Conversion Efficiency

PSC: Perovskite Solar Cell

PV: Photo Voltaic

PV/T: Photo voltaic/Tracking

RES: Renewable Energy system

SoA: State-of-the-art

1 INTRODUCTION

1.1 Background and motivation

Renewable energy has become increasingly important in the global energy mix due to its advantages for energy security and the environment (Inglesi-Lotz 2016). The use of renewable energy is seen as an important engine of growth for sustainable development (Tee *et al.* 2021). The Arctic region also experiences extreme temperature changes, and snow which can affect the performance of solar cells (Frimannslund et al. 2021). Therefore, it is important to select the most appropriate PV technology for a specific location to improve the system performance and increase the useful lifetime. The renewable energy sector is becoming increasingly important in the global energy balance due to the depletion of fossil resources and global environmental concerns. The development of renewable energy and access to low-cost, reliable, sustainable, and modern energy services is critical for achieving sustainable development goals (Drobotiuk et al. 2020). However, among these renewable energy sources, the solar energy is an important clean and abundant energy source that has gained increasing attention in recent years. The global energy system is transforming towards renewable energy, and solar energy will gradually replace traditional fossil energy to occupy the dominant position in the energy field (Hayat *et al.* 2019).

Solar energy is a component of the renewable energy mix in Finland, which is necessary to achieve the country's renewable energy targets. Nevertheless, changes in Finnish legislation could enable new economic possibilities in the use of solar power (Korpijarvi & Tanskanen 2019). Further statistics show that, Sweden, Finland and Latvia were the Member States with the highest RES share in 2021 (EEA 2023). However, the EU is committed to increasing the share of renewable energy in its energy mix to reduce dependence on foreign energy imports and to tackle climate change (Cucchiella *et al.* 2018, REPower EU 2022). The EU has set policy recommendations to enhance the utilization of renewable energy in its member states (EU Green deal 2020; Simionescu *et al.* 2018).

In terms of high north conditions, there are several challenges in the high north conditions in the utilization of solar energy. Hence in this thesis, studying the solar output of vertical and inclined solar panels in the high north (Arctic conditions) is significant due to the unique environmental conditions in the Arctic region. Solar panels located on high (Arctic and Antarctic) latitudes combine the harshness of the climate with that of the solar exposure. The performance of solar panels can be affected by temperature changes, and monocrystalline solar panels are less affected by temperature changes than polycrystalline solar panels (Olorunfemi *et al.* 2022). A study compared thin-film photovoltaic technologies' productivity for different installation sites and surface positions, and it was found that the appropriate inclination and orientation of the panels can increase the energy yield during the design of buildings with integrated photovoltaic panels (Stoyanov *et al.* 2016). In conclusion, studying the solar output of vertical and inclined solar panels in the high north (Arctic conditions) is significant due to the unique environmental conditions in the Arctic region, and selecting the most appropriate PV technology for a specific location can improve the system performance and increase the useful lifetime (Olorunfemi *et al.* 2022). The significance of studying the solar output of vertical and inclined solar panels in the high north faces several challenges, including the low altitude angle of the sun during winter months, and the arrangement of solar panels impacts the efficiency of solar panels. Solar PV installation in high north arctic cold conditions can be challenging due to the extreme weather conditions, including low temperatures, snow, and ice. However, there is limited research that proves that solar PV technology can be used in these conditions with the right design and installation.

Considering the above background and motivation, this thesis recognizes a gap and will focus on answering how to maximize the output of a solar PV under the challenging high north conditions.

1.2 Research methodology and Objectives

RQ1: What is the endurance of Solar PV in high north conditions?

RQ2: What are the optimized setup parameters to obtain maximum output from solar PVs?

RQ3: How to maximize the output of Solar PV under the challenging high north conditions?

This thesis includes the literature review of previous studies on the endurance of solar PVs in high north conditions and the optimized setup parameters to obtain maximum output from a PV. The literature review conducted in a way to collect data on the endurance of monocrystalline PV in high north conditions and the optimized setup parameters to obtain maximum output from a monocrystalline PV. This includes the installation of monocrystalline PV panels in the high north and the collection of data on the output of the panels under different setup parameters. The data collected is analysed in Sketch up simulation (with Skelion plug in) to determine the optimized setup parameters to obtain maximum output from a monocrystalline PV under the challenging high north conditions.

2 LITERATURE REVIEW

2.1 Solar energy in the high north

2.1.1 Solar radiation in high north

Solar radiation is the electromagnetic radiation emitted by the sun and can be converted directly or indirectly into renewable energy using various technologies such as photovoltaic, wind turbines, heat engines etc. Earth receives about 170000 terawatts (TW) of incoming radiation in the upper atmosphere, but the amount of renewable energy that can be generated is very small due to factors such as costs, number of heat-generating technology uses, varying radiation amounts at different times of the year etc. (Rhodes *et al*., 2010)

Untapped potential of solar energy is already being explored and estimated by different regions in the world. However, in a transition to mitigate the ongoing alarming levels of climate change, the high northern regions of the world with countries such as Finland, Norway, Sweden etc. are considering any direct subsidies for the usage of solar energy. For example, Finland's irradiation is almost the same as that of Germany, a country that is one of the top markets for photovoltaics in the world, also due to its successful support policy. The amount of solar energy is about the same in Finland as in Central Europe, with most of the radiation generated only by the Southern part of Finland from May to August (VTT, 43, 2015). Pihlakivi investigated the radiation amounts in different cities of Finland from Finnish Meteorological Institute radiation reports from 2014. The reports show the irradiation levels in Helsinki at around 980 kWh/m2 and in Sodankylä at around 790 kWh/m2 (Pihlakivi, 2015). Sodankylä is one of the high northern regions of Finland. This shows that the high northern regions have comparable solar radiation levels to generate valuable solar energy.

2.1.2 Climate conditions in high north regions

The Arctic region is experiencing amplified warming due to climate change, which has resulted in a decrease in the Arctic Sea ice cover and an increase in solar radiation absorption by the upper ocean (Pithan and Mauritsen 2014) (Pistone *et al.* 2014). In the High Arctic region, it is essential to make accurate estimations of the available solar radiation in order to incorporate solar energy as a significant component of the energy mix. (Garreau *et al.*2023). The Arctic region also experiences extreme temperature changes, which can affect the performance of solar cells (Pithan and Mauritsen 2014). Therefore, it is important to select the most appropriate PV technology for a specific location to improve the system performance and increase the useful lifetime (Pistone *et al.* 2019), it is important to note that the Arctic region is experiencing rapid declines in summer Arctic sea ice extent, and regional Arctic climate engineering has been suggested as an emergency strategy to save the sea ice (Tilmes *et al.* 2014).

2.1.3 Challenges of operating PV systems in high north conditions

Adverse environmental conditions associated with cold climates, such as recurrent hoarfrost and substantial snowfall, can give rise to elevated rates of degradation in photovoltaic (PV) systems. These factors have the potential to detrimentally impact the dependability, longevity, and efficiency of PV modules (Dhimish 2020). Furthermore, the electrical behavior of photovoltaic (PV) arrays can be affected by the uneven snow cover on their surface (Hosseini et al. 2020).

In cold weather, solar panels may experience lower temperatures, which can enhance their efficiency. However, snow cover and reduced sunlight intensity can pose challenges to the operation of PV systems. To address these issues, adjusting the tilt angle of the panels and implementing snow removal measures are recommended. Proper system maintenance is also vital for optimal performance. Further research specifically investigating the impact of cold conditions on PV systems would provide valuable insights in this area (Yamaguchi et al.2021). The performance of photovoltaic (PV) systems in cold weather is influenced by the operating temperature, which plays a crucial role in the photovoltaic conversion process. As indicated by the review conducted by Dubey et al. (2012), solar cell performance decreases with increasing temperature due to increased carrier concentrations and internal carrier recombination rates. However, the electrical efficiency and power output of PV modules exhibit a linear relationship with the operating temperature. This highlights the importance of selecting PV modules with appropriate temperature sensitivity based on the geographical location. While regions with high altitudes, such as the southern Andes, Himalayas, and Antarctica, demonstrate higher performance ratios due to lower temperatures, PV modules with reduced temperature sensitivity are preferred for high-temperature regions. Overall, understanding the insights of PV systems in cold weather is crucial for optimizing their electrical performance and power output (Dubey et al. 2012).

2.1.4 Sun path diagram

The sun-path diagram is a useful tool for designing and optimizing solar photovoltaic (PV) installations. By providing information about the angle and intensity of sunlight at different times of the day and year, the diagram can help identify the best location and orientation for solar panels. The Sunpath diagram is useful when installing solar PV because it helps determine the optimum tilt angle and orientation of the solar panels (Ogundimu *et al.* 2022), (Memon *et al.* 2021), (Kamanga *et al.* 2014). In addition, the Sunpath diagram can be used to design and fabricate an installation PV solar module tilting platform (Ogundimu *et al.* 2022). The diagram can also be used to evaluate the performance of PV models in simulating vector fields.

Considering all the above mentions, the Sunpath diagram is an important tool in determining the optimum tilt angle and orientation of solar panels during installation.

In this work, we consider Oulu as the example of a geographical location in the high north region and study the impact of sun during June, September equinox and December time of the year using the sun path diagram as shown in Figure 1.

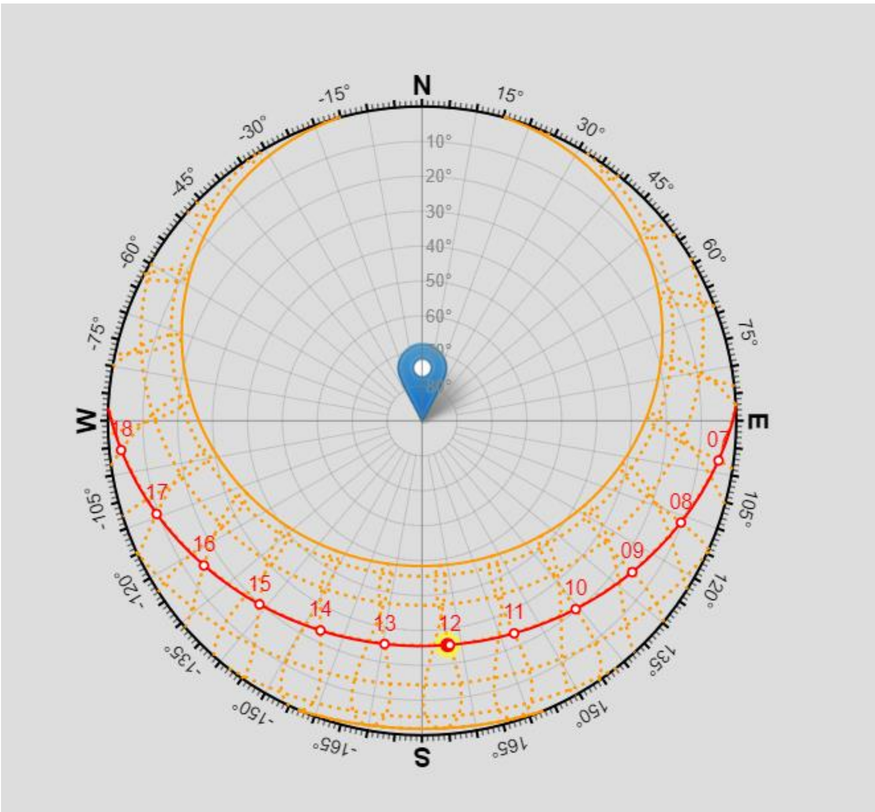

Figure 1: Sun path diagram of Oulu region (Source: PD – Sun Path)

2.2 Solar Photovoltaic Technology

2.2.1 Brief history of Solar PV

Solar photovoltaic (PV) technology has been around since the 19th century, when French physicist Alexandre Edmond Becquerel discovered the photovoltaic effect in 1839 (Lamont 2022). This discovery led to the development of solar cells that could convert sunlight into electricity. The first practical application of this technology was developed by Charles Fritts in 1883, who created a primitive version of what we now know as a modern-day solar panel. In 1954, Bell Laboratories developed the first silicon-based PV cell with an efficiency rate of 6% (Lawrence et al. 2022). This marked a major breakthrough for solar energy and paved the way for further advancements in PV technology over the next few decades. In 1958, Hoffman Electronics introduced their own version of a silicon-based PV cell with an efficiency rate of 11%, which was more than double that achieved by Bell Labs just four years earlier.

The 1970s saw significant progress in terms of both cost reduction and efficiency improvement for solar panels. During this decade, researchers at Exxon Corporation developed amorphous silicon cells with efficiencies up to 14%. By 1977, these cells had become commercially available and were being used to power calculators and other small electronic devices.

In 1982, Sharp Corporation released its HIT (Heterojunction with Intrinsic Thin layer) series modules which featured higher conversion efficiencies than any previous module on the market at that time – up to 17% (Jäger 2012). These modules quickly became popular among residential customers due to their improved performance compared to traditional crystalline silicon modules.

Since then, there have been numerous advances in Solar PV technology including thin film technologies such as CIGS (Copper Indium Gallium Selenide), CdTe (Cadmium Telluride), OPV (Organic Photovoltaics) and Perovskite Solar Cells; improvements in manufacturing processes; increased use of renewable energy sources; new financing models; better storage solutions; etc., all leading towards making Solar PV one of today's most promising clean energy sources.

PV energy is one of the largest growing industries in the world, with new developments coming in device design, production technologies, material use, and efficiency enhancement (Sampaio & Gonzalez, 2017).

2.2.2 Types of Solar PV technology from a State-of-the-Art point of view

Solar photovoltaic (PV) technology has been rapidly evolving in recent years, with new developments and improvements being made to increase efficiency and reduce costs. One of the most promising developments in solar PV technology is the use of halide perovskite materials, which have shown rapid improvements in solar cell performance, surpassing the top efficiency of semiconductor compounds such as CdTe and CIGS used in solar cells in just about a decade (Jena *et al.* 2019). Another promising development is the use of 2D materials, such as graphene, which have high transparency and conductivity and demonstrate immense potential for next-generation solar cells and other optoelectronic devices (Das *et al.* 2019). The development of third-generation photovoltaic technologies, such as dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), and perovskite solar cells (PSCs), is also being explored as alternatives to silicon solar cells (Giannouli *et al.* 2021). Perovskite cells emerge as a new era of solar panels due to their incredible improvement on the power conversion efficiency (PCE), which can exceed 20% within seven years of tremendous research with economic production costs (Park, et al., 2016, Ahmed, et al., 2015). The earliest application of perovskite materials was $MAPbBr_3$ nanocrystals that were applied as semiconductor sensitizers in liquid electrolyte dye sensitized solar cells (DSC's). These DSC's holds future potential to expand the PV industry to larger volumes, because the materials used in these cells are cheap and fully recyclable and the DSC's can produce electricity also in low-light conditions (Toivola, 2010). In 2009, the initial fabricated DSc device showed an efficiency of 3.1% (Kojima, Akihiro, et al., 2009). To date, the certified efficiency of Perovskite cells has skyrocketed to 22.1% PCE. Different device architecture of perovskite solar cells enhancing PCE are shown in Figure 2.

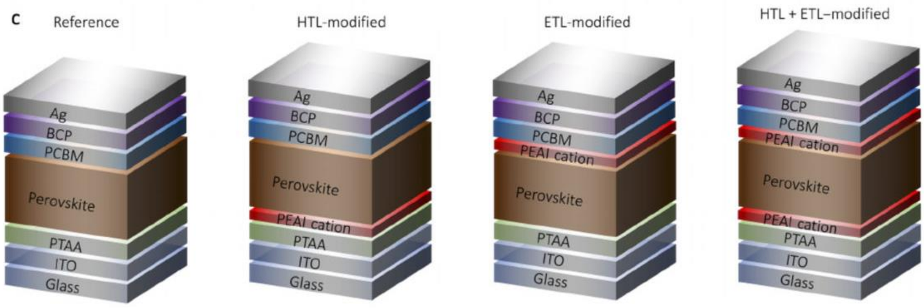

Figure 2: The device architecture of different perovskite solar cells with and without electron transport layer (ETL) (Bellini, 2022).

However, it is wise to note that these PV technologies are still not reached its maturity stage and is still not cost effective. Single or Monocrystalline silicon are manufactured from pure semiconducting materials with no defects or impurities in the silicon crystalline structure. Multi or Polycrystalline silicon manufacturing process is simpler than the monocrystalline ones. The performance of this technology is similar to Monocrystalline silicon, but there are more defects in the crystalline structures and the efficiency is slightly less than Monocrystalline cells. Monocrystalline cells convert sunlight into electricity more efficiently than polycrystalline cells, but polycrystalline cells are cheaper to manufacture. Both cells are about as cost-efficient, but the cheaper price of polycrystalline cells has made them slightly more common on the market.

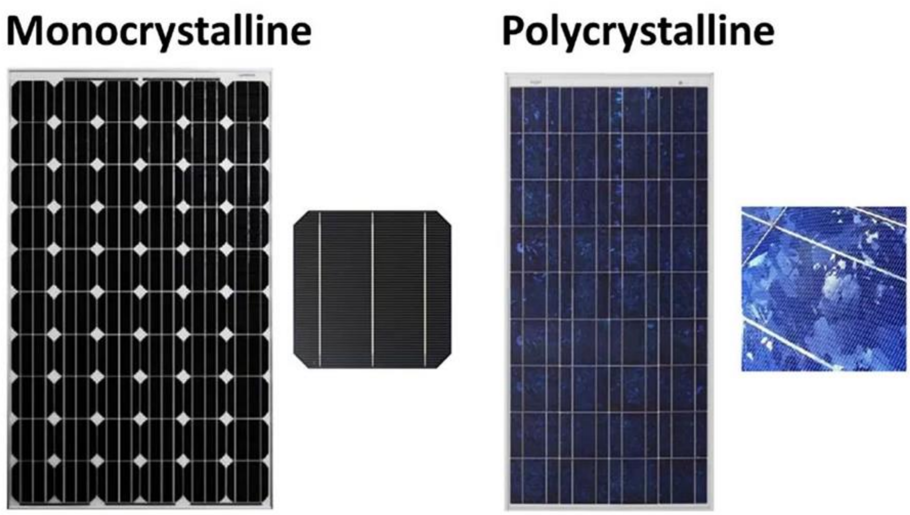

Figure 3: Monocrystalline and Polycrystalline device structure for solar cells (Greenlight Energy, 2021).

Following are certain research results on the PV modules and their efficiencies based on various characteristics.

- Single-crystal, thin-film GaAs PV modules - achieved higher efficiencies than their polycrystalline and amorphous counterparts (Silverman et al. 2013); (Meitzner *et al.* 2020).
- Perovskite PV modules - provide comparable performances with efficiencies of roughly 25% power conversion efficiency (PCE) for very small devices in the lab (Meitzner *et al.* 2020) and 16% PCE for small modules (Pehlivan *et al.* 2019)
- Thin film PV materials - can provide STH efficiencies beyond 13% even with PV modules with modest efficiency (Pehlivan *et al.* 2019)
- N-Type crystalline-silicon (c-Si) PV modules - have the potential for achieving high efficiencies (Yamaguchi et al. 2021)
- PV/T modules with nano-enhanced fluids and latent heat storage material - show average and peak overall PV/T efficiencies of 61.6% and 77.8%, respectively (Hussein *et al.* 2021)
- CIGS-based PV modules - have the highest demonstrated efficiency of any single-junction thin film PV device, with record efficiencies of 22.3% for cells and 17.5% for large area modules (Lovelett *et al.* 2016)
- PV modules can be manufactured using different materials by different fabrication technologies (Vítězslav *et al*. 2020)

The following table 1 shows the efficiencies of difference PV modules as per its materials.

Table 1: Efficiency of different PV modules

Material	Technology	Module Efficiency	Area needed per kW (approx)
Monocrystalline silicon	Crystalline	13-19%	7m^2
Multicrystalline silicon	Crystalline	11-15%	8 m^2
Amorphous silicon (a-Si)	Thin film	4-8%	15 m^2
Copper Indium Gallium DiSelenide (CIGS)	Thin film	7-11%	10 m^2
Dye-sensitized PV cells	Thin film	2-4%	
Cadmium Telluride (CdTe)	Thin film	10-11%	9 m^2

2.2.3 Overview of solar photovoltaic generation in the north

The generation of solar photovoltaic (PV) power in northern regions, especially in Arctic conditions, poses significant challenges attributed to the harsh weather elements such as extremely low temperatures, heavy snowfall, and icy conditions. These adverse weather conditions can significantly impact the performance and efficiency of PV systems, necessitating specific considerations and adaptations for successful operation in such environments. However, recent research has shown that solar PV technology can be used in these conditions with the right design and installation. Panchenko (2021) discussed the prospects of using frost-resistant solar modules with extended service life for energy supply of infrastructure facilities in the Arctic zone of Russia (Panchenko 2021). The study proposed the use of frost-resistant planar photovoltaic modules and solar roofing panels with an extended service life for power supply in the Arctic region.

In addition, the use of maximum power point tracking (MPPT) where the system is a crucial component in solar PV installations that optimizes the energy production of photovoltaic panels by dynamically adjusting the operating point to extract the maximum power available from the solar array. By continuously tracking and adjusting the voltage and current output of the panels, the MPPT system ensures efficient utilization of solar energy, maximizing the system's overall performance and enhancing its ability to adapt to changing environmental conditions can also improve the efficiency of solar PV systems. Taherbaneh *et al.* (2010) developed a method based on simultaneous use of two fuzzy controllers to maximize the generated output power of a solar panel in a photovoltaic system (Taherbaneh *et al.* 2010).

2.2.4 Factors affecting the performance and efficiency of PV modules.

Monocrystalline photovoltaic (PV) modules are widely used in solar energy applications due to their high efficiency and long-term reliability. However, the performance and efficiency of PV modules can be affected by various factors. One of the factors affecting the performance and efficiency of PV modules is the type of silicon used. Akhmad et al. (1997) investigated the outdoor performance of polycrystalline and amorphous silicon modules and found that amorphous silicon modules have better efficiency and output power in summer (Akhmad *et al.* 1997) Another study by Bashir et al. (2014) reported experimental data for different PV modules for January and found that monocrystalline modules were more efficient (Bashir *et al.* 2014).

The orientation and tilt angle of the PV modules also affect their performance and efficiency. Pavlovic et al. (2011) compared and assessed the electricity generation capacity for different types of PV solar plants of 1 MW in Serbia and found that PV solar plant with flat PV panels made of monocrystalline silicon had the highest electricity generation capacity (Pavlovic *et al.* 2011)

In conclusion, the performance and efficiency of monocrystalline PV modules can be affected by various factors, including the type of silicon used, temperature, and orientation and tilt angle. The dual-axis tracking PV solar plant with flat PV panels made of monocrystalline silicon has been found to have the highest electricity generation capacity.

2.3 Installations of Solar PV

2.3.1 Vertical and Traditional installations

According to Quing *et al.* (2022), there are two main types of installations for solar PV in rooftops: vertical installations and traditional installations. Vertical installations involve mounting solar panels vertically on the side of a building, while traditional installations involve mounting solar panels horizontally on the rooftop.

- **Vertical installations** are a relatively new approach to solar PV installations and have gained popularity due to their ability to maximize the use of available space on buildings. They are particularly useful in urban areas where space is limited and rooftops are often small. Vertical installations can also be used on the sides of buildings that receive direct sunlight, which can increase the overall energy output of the system (Quing *et al*. 2022).

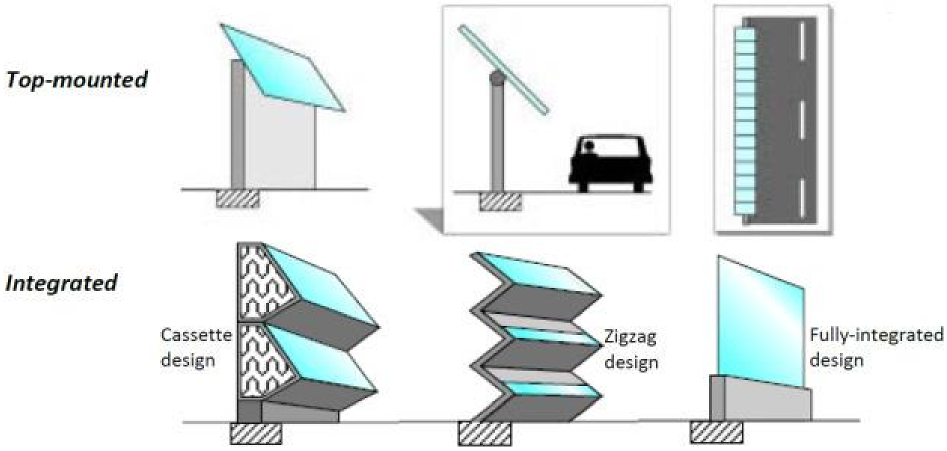

Fig 4: Different mounting/installation designs of solar PV (Poe et al. 2017)

- **Traditional installations**, On the other hand, are the most common type of solar PV installation on rooftops. They involve mounting solar panels horizontally on the rooftop, which allows for easy installation and maintenance. Traditional installations are arguably more efficient than vertical installations, as they are able to capture more sunlight due to their orientation (Quing *et al.* 2022).

2.3.2 Azimuth and inclination angle configurations of PV installations

Since the thesis focusses on the high north, in high north (Arctic conditions), the panel angle configurations of solar PV installations are crucial in determining the maximum energy output of the system. However, there is limited research on the optimum tilt angle and orientation of solar panels in these conditions.

One study investigated the optimum tilt angle of solar panels in extreme higher latitude cold climates and found that the optimum tilt angle for solar panels in cold climates is between 30° and 40° (Hailu and Fung 2019). The study also found that the optimum orientation of solar panels in cold climates is south-facing (180degrees), which maximizes the amount of solar radiation received by the panels.

Following are the systems that incorporate tilts in the angels.

Fixed Solar systems

Under the peak laboratory conditions, the PCE achieved is 32%, compared to the average efficiency of 15-20% in the real environment conditions (Partain and Fraas 2010 & Green, et al., 2017). Thus, to witness higher PCE under practical conditions, it is necessary to recover as much energy drawn from solar power system as possible by reducing inverter losses, storage losses, and light gathering losses. Of these, light gathering is dependent on the angle of incidence of the light source providing power to the solar panel's surface, and the closer to perpendicular, the greater the power (Partain and Fraas, 2010). If a flat solar panel is mounted on the level ground, the angle of incidence is 90 degrees only in the morning and evening. At such an angle, the light gathering ability of the cell is essentially zero, resulting in no output. Thus, to maintain the maximum power output from the panel, it needs to be tilted each time to continuously face the sun by tracking its position. Thus, tracked solar panels can be very efficient in reducing light-gathering losses compared to that fixed solar panels. Also, the amount of radiation incident on the photovoltaic surface is dependent on the geographic latitude, and hence a tracking system for solar panels is essential for the high northern region (Bahrami, et al., 2016).

Tracked Solar Panels

Different types of tracked solar panels available and are categorized mainly into single-axis and full/dual-axis tracking. The single-axis tracking design is relatively simple due to the fact that it is pivoted to rotate about a particular axis, this is more suited at the equatorial regions where the sun movement is only from east to west throughout the year and not shift in north or south axis. They are further classified according into vertical (azimuth trackers), horizontal and inclined or polar axis trackers. There are many single tracking strategies such as dual-axis, East-West (EW), North-South (NS), vertical-axis and inclined EW trackers that has been demonstrated to significantly increase the annual energy productivity relative to fixed solar panels (Lave and Kleissl, et al., 2011 & Quesada, et al., 2015).

Conversely, the dual axis tracking incorporates the second axis of rotation hence allowing the panel to follow the sun's path at all times. The dual-axis trackers are designed based on either serial mechanism or parallel mechanism (Wu, et al., 2015 & Wu, et al., 2016). A dual-axis tracking system would result in greater irradiance than a single-axis, due to its ability to minimize the cosine effect losses. In other words, panels are always normal to the sun's beam radiation, thus maximizing the amount of energy intercepted by the surface of a panel. Studies have shown that the increase in the energy gain of dual-axis trackers compared to the optimal fixed panel varies from 17.72% to 31.23% (Bahrami et al. 2016). The performance comparison among fixed, single and dual-axial solar panels has been well investigated in recent works (Ghalem et al., 2022). An example of fixed solar panel, single and dual-axis solar panel are shown in Figure 5.

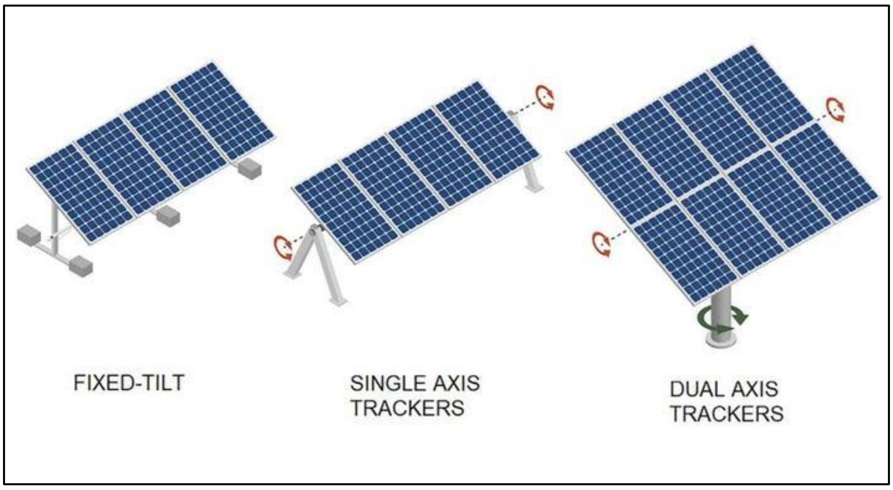

Figure 5: An example of fixed, single-axis and dual-axis solar panels (Sreenath et al, 2021).

2.3.3 Studies on endurance of PV modules in arctic weather conditions

Numerous investigations (Kim et at. 2021) have been conducted to examine the endurance of photovoltaic (PV) modules when subjected to severe cold weather conditions. As indicated by Kurtz et al. (2011), PV modules are exposed to extreme climatic factors such as radiation, humidity, and significant temperature fluctuations, both hot and cold (Kurtz et al. 2011). Another study highlights the concerns of PV module manufacturers regarding the reliability of their products when operating under various weather conditions. It was discovered that degradation rates can exceed 0.8% per year for silicon-based technology and reach as high as 2.76% per year in harsh climates (Hasan et al.2021). Dhimish (2020) conducted research indicating that PV systems subjected to cold climate conditions experience the highest rates of degradation due to frequent occurrences of hoarfrost and heavy snow, which have detrimental effects on the reliability, durability, and overall performance of PV modules (Dhimish, 2020). In their investigation, Emetere et al. (2020) explored the potential benefits of utilizing a biodegradable optical filter on PV modules to mitigate the impact of harsh weather conditions (Emetere et al. 2020). In other cases, Khenar et al. (2019) proposed a modeling approach for snow-covered PV modules, which was successfully validated through outdoor tests involving three distinct PV module technologies commonly employed in PV farms across North America, operating under various cold weather conditions (Khenar et al. 2019).

Moreover, the reliability of PV modules operating under various weather conditions is a concern for manufacturers, as several studies reveal a degradation rate higher than 0.8% per year for silicon-based technology. Electromigration and delamination are two failure modes that play a significant role in PV modules' output power losses. To assess the performance of PV modules, it is necessary to measure their current-voltage (I-V) output characteristics. However, the I-V curves measured at laboratory conditions may be rather different from the actual conditions that the panels may undergo, so affecting the I-V characteristic (Vega *et al.* 2019).

2.3.4 Degradation and lifetime of PV modules

Solar photovoltaic (PV) modules can undergo deterioration and experience a decrease in operational lifespan when exposed to cold climatic conditions. The temperature is a significant determinant of the decline in cell efficiency and the overall longevity of a PV cell (Rui at al. 2014). Mono-, poly-, and amorphous-silicon (Si) PV technologies are acknowledged for exhibiting differential rates of degradation and immediate power losses, contingent upon operational temperature, humidity, thermal cycling, and panel contamination (Flowers et al. 2016). Nevertheless, the substantial surge in the production and installation of PV modules will pose a formidable challenge in the future due to the limited lifespan of PV modules, typically ranging around 30 years (Chen et al.2020). Another important factor to consider is the temperature of the PV modules.

The reliability of PV modules operating under various weather conditions attracts the manufacturer's concern since several studies reveal a degradation rate higher than 0.8% per year for the silicon-based technology and reached up to 2.76% per year in a harsh climate. The lifetime of the PV modules is decreased because of numerous degradation modes, including delamination and electromigration. The presence of localized shading on PV modules leads to an overheating of the shaded PV cells despite the activation of bypass diodes, which reduces considerably PV module performances and its lifetime (Bressan *et al.* 2016). The degradation of PV performance is influenced by weather conditions such as variation in solar irradiance, change in the angle of incidence, high/low temperature, and humidity (Dhimish *et al.* 2020). The efficiency of modules decreases with an increase in module temperature (Bashir *et al.* 2018). Therefore, it is important to consider the actual conditions that the panels may undergo, such as irradiance, temperature, and series-parallel solar cells combinations, to evaluate the performance of PV modules (Vega *et al.* 2019).

2.3.5 Optimization of setup parameters for PV modules

Optimizing the setup parameters for monocrystalline PV modules from an installation perspective involves considering various factors that can affect their performance. As per the study conducted by Park et al. (2019), replacing conventional monofacial silicon PV modules with bifacial silicon PV modules can reduce the number of modules required for power production systems and the overall installation cost, including ground area, materials, labor costs, and construction period. The study also found that bifacial PV modules can generate a maximum of 30% additional electricity simply by optimizing the installation conditions, such as height and angle (Park *et al.* 2019). Therefore, it is important to control the temperature of the modules during installation to ensure optimal performance.

Additionally, the inclination angle, PV module number, module type, and module construction structure can also affect the performance of PV systems. The optimization of these parameters can be achieved using different user-friendly software that estimates energy production using climate data and provides economic data accordingly (Limem and Sezen 2021).

In conclusion, optimizing the setup parameters for monocrystalline PV modules from an installation perspective involves considering various factors such as the use of bifacial PV modules, controlling the temperature of the modules, and optimizing the inclination angle, PV module number, module type, and module construction structure.

3 SIMULATION: EMPIRICAL STUDY

3.1 Simulation tool

The solar panel simulation tool developed using SketchUp and the Skelion plugin offers a powerful solution for optimizing solar energy generation. Its ability to accurately model solar panels, vary tilt angles, and analyse energy output provides valuable insights for architectural design, energy efficiency assessments, and renewable energy planning. By leveraging this tool, stakeholders can make informed decisions to maximize the potential of solar energy installations in Oulu, Finland, and beyond. The simulation tool generates comprehensive output data for each panel and tilt angle combination. The primary output is the total power output of each panel in relation to different tilt angles throughout the year. This data can be visualized and analysed using graphs or charts, providing valuable insights into the performance of various tilt angles and their impact on energy generation.

3.1.1 Overview of SketchUp and Skelion Plugin

SketchUp

SketchUp is a versatile 3D modeling software that provides a powerful platform for modeling buildings, integrating weather data, and simulating solar panels. With its user-friendly interface and extensive range of tools, SketchUp allows users to create detailed and accurate representations of buildings. The software enables precise modeling of architectural elements, including roofs, facades, and other surfaces where solar panels can be installed.

SketchUp also supports the import and integration of weather data, which is essential for simulating solar panel performance in specific locations. By incorporating weather data such as solar radiation levels, temperature variations, and wind speeds, users can analyze the impact of environmental factors on the energy output of solar panels. This combination of building modeling and weather data integration makes SketchUp an ideal platform for simulating and optimizing solar panel installations in diverse environments, including high north latitudes.

Skelion Plugin

Skelion is a plugin specifically designed for SketchUp, it is designed for solar energy analysis and simulation. By integrating Skelion into SketchUp, we gain access to a range of features and functionalities that enable precise analysis of solar PV simulations. With Skelion, one can automate the placement, sizing, and orientation of solar panels on various surfaces within the SketchUp environment, such as roofs or facades. The plugin provides tools for adjusting the tilt angles of the panels, allowing for the evaluation of different configurations and their impact on energy output.

Skelion incorporates solar radiation data specific to the location, considering factors such as the sun's position, shading, and local weather conditions. It utilizes accurate solar position algorithms to calculate the incident solar radiation on each panel for different tilt angles and times of the year. Skelion generates comprehensive output data, including the total power output of each panel in relation to different tilt angles throughout the year. This data can be visualized and analysed, providing valuable insights into the performance of various tilt angles, and aiding in the optimization of solar panel installations. The Skelion plugin enhances the capabilities of SketchUp, making it an invaluable tool for precise and efficient solar PV simulation and analysis.

3.1.2 Simulation Process and Methodology

The simulation process involved in Skelion's SketchUp simulation of solar PV involves several key steps:

Building Modeling

The first step is to create a 3D model of the building or structure in SketchUp. This includes specifying the dimensions, orientation, and location of the building. Skelion provides tools to facilitate the modeling process and ensure the precise placement of solar panels on different surfaces, such as roofs or facades. Here, the building is modeled roughly in reference to one of the buildings in the university of Oulu campus. The building is geo-located in the simulation setup with the help of the Geo-location tool in Sketchup which uses the geographical data from the google maps/earth. The tool works by taking creating a fabric of map where the building can be placed on the desired location.

Fig 6: Simulation building model.

Solar Panel Placement

Once the building model is complete, Skelion enables the automatic placement of solar panels on the specified surfaces, in this case the Solar panel placement is based on the actual experimental setup on one of the buildings of University of Oulu. The panel layout, including the number of panels and their arrangement has been influenced based on the Experimental setup. Skelion ensures that the panels are accurately positioned on the surfaces, taking into account factors such as spacing, alignment, and available area.

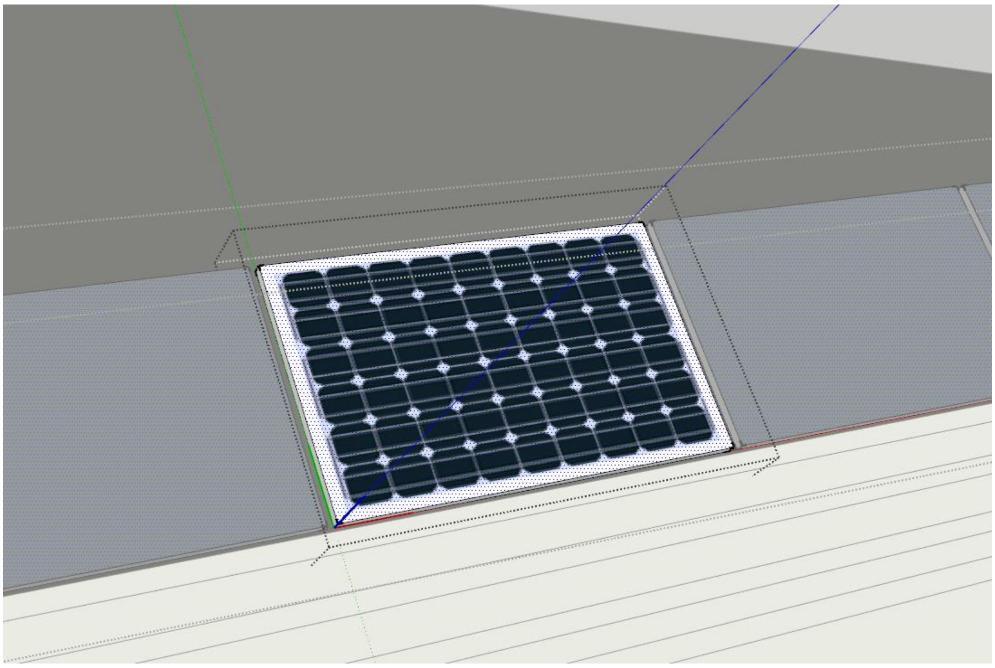

Fig 7: Solar panel placement in sketchup

Tilt Angle Adjustment

Skelion allows users to adjust the tilt angle of the solar panels. This parameter is crucial as it affects the amount of solar radiation captured by the panels. Users have the option to vary the tilt angles throughout the year to assess the impact on energy output. Skelion provides tools to set specific tilt angles for different months or seasons, allowing for comprehensive analysis.

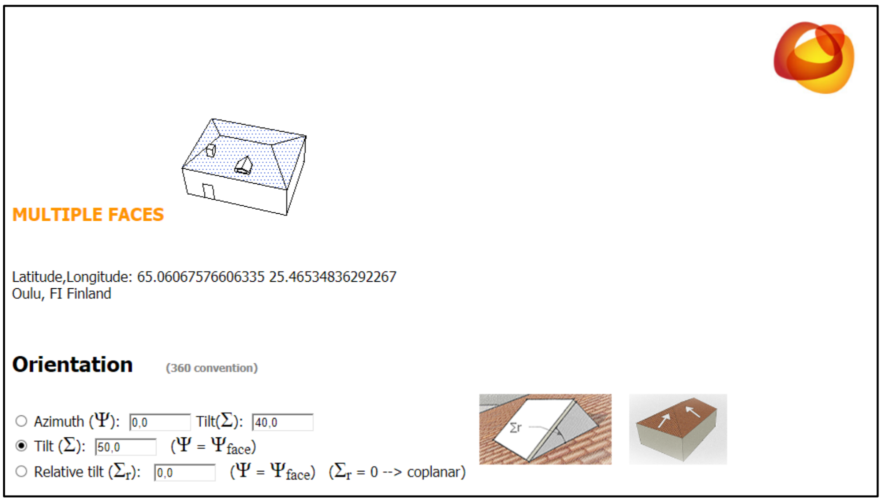

Fig 8: Solar PV tilt angle setup in sketchup/skelion

Solar Radiation Analysis

Skelion incorporates solar radiation data specific to the location of the building. This data includes information about solar radiation levels, sun path, and shading. Skelion's algorithms calculate the incident solar radiation on each panel based on the sun's position and other relevant factors. The software takes into account shading from nearby objects or structures, providing a realistic assessment of energy generation.

Energy Output Analysis

Once the solar radiation analysis is complete, Skelion generates output data related to the energy output of the solar PV system. This data includes the total power output of each panel for different tilt angles and time periods, such as monthly or seasonal variations. Skelion provides visualization tools, such as graphs or charts, to present the data in a clear and comprehensible manner.

Optimization and Iteration

Based on the simulation results, users can evaluate the performance of different panel configurations, tilt angles, or shading scenarios. Skelion allows for iterative optimization, enabling users to fine-tune the solar PV system design to maximize energy output. By adjusting parameters and analysing the resulting data, users can identify the most efficient and effective configuration for their specific requirements.

The Skelion simulation in SketchUp offers a comprehensive and efficient approach to designing and analysing the performance of solar PV systems on buildings. By accurately modelling the building in 3D and incorporating real-world data, such as solar radiation levels and shading, Skelion provides valuable insights into the energy output of the PV system.

3.2 Simulation parameters

While studying the solar panels in high north latitudes, it is essential to discuss the simulation parameters used for Solar PV simulation in SketchUp. The simulation parameters define the conditions and variables that are considered during the simulation process, affecting the accuracy and reliability of the results. In this chapter, the key simulation parameters are described.

Geographic Location

The location is Oulu, the latitude, longitude, and elevation of the site are summarized below in table 2:

Latitude, longitude	65°03’34’’N, 25°28’01’’E
Elevation above Sealevel	21meters

Table 2: Latitude, longitude and elevation of Oulu region.

Climate Data

Climate data typically include solar radiation levels, temperature variations, wind speeds, and other relevant meteorological factors. The climate data, obtained from meteorological station in the city of Oulu was incorporated to the simulation software in the form of an EPW file.

To expand more on the EPW weather file, an EPW (EnergyPlus Weather) file is a standardized weather data file format. The EPW file contains a comprehensive set of weather data for a specific location, typically spanning multiple years. The data includes information such as temperature, humidity, solar radiation, wind speed and direction, precipitation, and atmospheric conditions. EPW files are created by collecting and processing weather data from various sources, such as weather stations, meteorological databases, or weather modeling. The data is typically recorded at regular intervals, typically hourly or sub-hourly, to provide a detailed representation of the weather conditions throughout the year.

Solar Position

The solar position algorithms or models are used to determine the sun's position at different times of the year. These algorithms take into account factors such as the date, time of day, latitude, and longitude to calculate the sun's azimuth (horizontal angle) and elevation (vertical angle) relative to the solar panels.

Panel Orientation and Tilt

The panel orientation and tilt angles are considered in the simulation based on the setup. The varied options are available for evaluating fixed tilt angles, adjustable tilt systems, or tracking systems. This specifically helps in considering the impact of panel orientation on energy production throughout the year, especially in high north latitudes where the sun's path and tilt angles vary significantly between seasons.

Panel Characteristics

The panel characteristics provide details about the solar panel models and specifications used in the simulation. This includes parameters such as panel efficiency, nominal power rating, dimensions, and temperature coefficients. The simulation can account for different panel technologies, such as monocrystalline, polycrystalline, or thin-film panels, as they can exhibit different performance characteristics.

Shading Analysis

Shading analysis is incorporated into the simulation. Shading from nearby objects or structures can significantly affect solar panel performance. The Skelion plugin adopts algorithms to assess shading, such as shade analysis tools in SketchUp or shadow-casting algorithms.

Simulation Timeframe

The timeframe for which the simulation is conducted is an important factor, here in the simulation an entire year is being considered for the time frame. However, the EPW file does have the data for multiple years and the weather for the simulation of an entire year time frame is being estimated based on the computational average of the values of climate factors over many years.

By considering the simulation parameters, the rigor and accuracy of the Solar PV simulation in high north latitudes are fairly demonstratable.

3.3 Experimental setup

The experimental simulation setup of solar PV panels encompasses a diverse range of configurations to assess solar output in various directions. The PV setup is divided into 4 parts in the simulation.

- Carousel
- Horizontal panels on roof
- South wall panels
- East wall panels

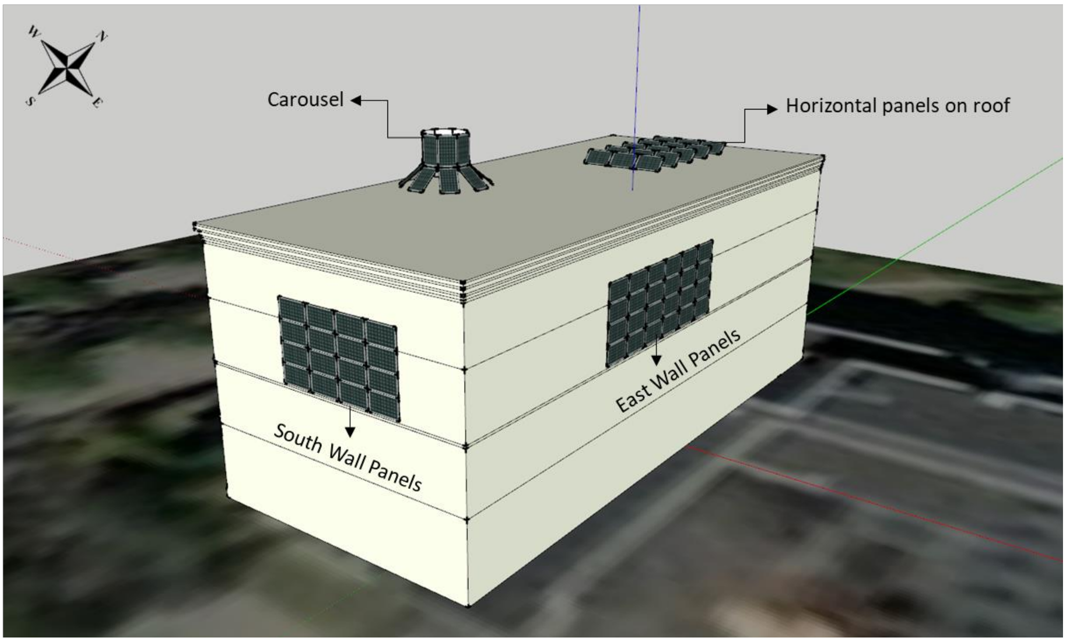

Fig 9: Building setup with all the PV setup.

The centrepiece of the setup is a rooftop carousel, which consists of eight panels that are mounted at an inclination of 40 degrees, while another eight panels are positioned at 90 degrees in a circular pattern. This circular arrangement allows for the evaluation of solar output in all 360 degrees, enabling a comprehensive analysis of the system's performance across different orientations.

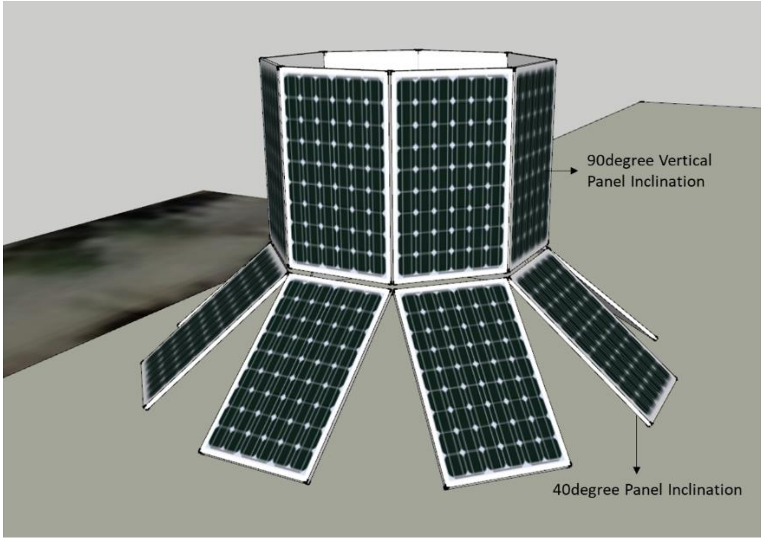

Fig10: Carousel simulation setup

In addition to the carousel panels, the simulation setup incorporates five rows of horizontal panels on the rooftop. These panels are inclined at increasing angles from 40 degrees to 50 degrees, with a gradual increment of 2.5 degrees for each successive row. This inclination range ensures that the panels are positioned optimally to capture solar radiation throughout the day, accounting for the changing angle of the sun.

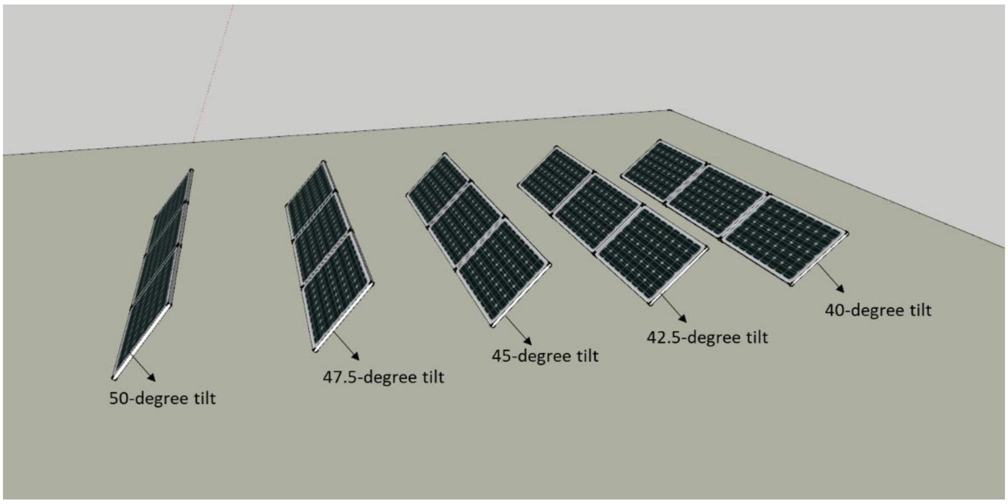

Fig11: Roof top horizontal panel setup

To further enhance the evaluation of solar output, vertical panels are mounted on both the south-facing and east-facing walls of the building. The south-facing wall panels are strategically positioned to directly receive sunlight for a significant portion of the day, maximizing energy generation. Similarly, the east-facing wall panels are designed to capture and study early morning sunlight, contributing to the overall energy output throughout the day.

This experimental simulation setup aims to comprehensively assess the performance and efficiency of the solar PV system across different orientations and angles. By incorporating a carousel of panels, rooftop panels with varying inclinations, and vertical panels on different building walls, the simulation provides valuable insights into the impact of panel positioning on solar output. The data collected from this setup enables a comprehensive analysis of solar radiation levels, shading effects, and energy generation across the entire system.

The specification of the PV module with its Polycrystalline metrics can be seen in table 3 below.

Type of PV	Polycrystaline
Nominal Capacity	270 Wp
MPP current	8.65 A
MPP Voltage	31.2 V
Short Circuit Current	9.29 A
Open Circuit Voltage	38.3 V
Max. Voltage	1000 V
Length	1640 mm
Width	992 mm
Depth	40 mm
Weight	18.1 Kg

Table 3: Type of PV Vs its polycrystalline metrics

The PV module used in the simulation setup is a Polycrystalline panel with the above-mentioned specifications. This module represents a typical photovoltaic panel commonly used in solar energy systems. This module, being the exact make used in the simulation setup, serves as a representative component for analysing the performance and energy generation of the solar PV system.

Figure 12: SolarWatts 270WP, product picture of the solar PV used for simulation.

3.4 Simulation location

Location: The setup in located in the campus of University of Oulu, Oulu, Finland. The co-ordinate for the building is 65º05` N, 25º.46` E.

The location is surrounded by trees and plants however these have no shading effect on the setup as the PV setup in located on the roof top clear of any shading trees. The building block chosen for the experimental setup is on the south-western side of the campus.

Fig13: Uni Oulu birds eye view (University of Oulu, 2023)

Fig14: Uni Oulu birds eye view (University of Oulu, 2023)

The above picture shows the bird's eye view of the university of Oulu campus. The highlighted area in red is the location where the experimental setup is placed, and experiments are carried out.

Following are some of the photos from the carousel, roof and wall installations at University of Oulu:

Fig 15: Experimental carousel setup on the roof of University of Oulu

Figure 16: Roof panels with varying tilt angle setup

Figure 17: South wall vertical panels

3.5 Assessment of the results

3.5.1 Performance Evaluation and results of the Carousel PV Setup

A comprehensive face analysis of the 16 panels in the carousel (8 panels on the 90 degree tilt and 8 panels on the 40 degree tilt) configuration has been conducted. The analysis focuses on evaluating the solar PV output in terms of key performance metrics such as yield and energy. The study encompasses both annual and monthly assessments to capture the variations in solar radiation and panel performance throughout the year.

By considering the azimuth and tilt angles of the panels, the thesis aims to understand how the orientation and inclination impact the energy generation of the solar PV system. The azimuth angle represents the direction the panels face, while the tilt angle determines the inclination of the panels relative to the horizontal plane. These factors play a crucial role in capturing optimal sunlight and maximizing energy production.

The annual study provides an overview of the system's performance over the course of a full year. It takes into account the changing position of the sun, varying solar radiation levels, and seasonal fluctuations in weather conditions. By assessing the yield and energy output on an annual basis, the thesis aims to determine the overall effectiveness and efficiency of the carousel configuration.

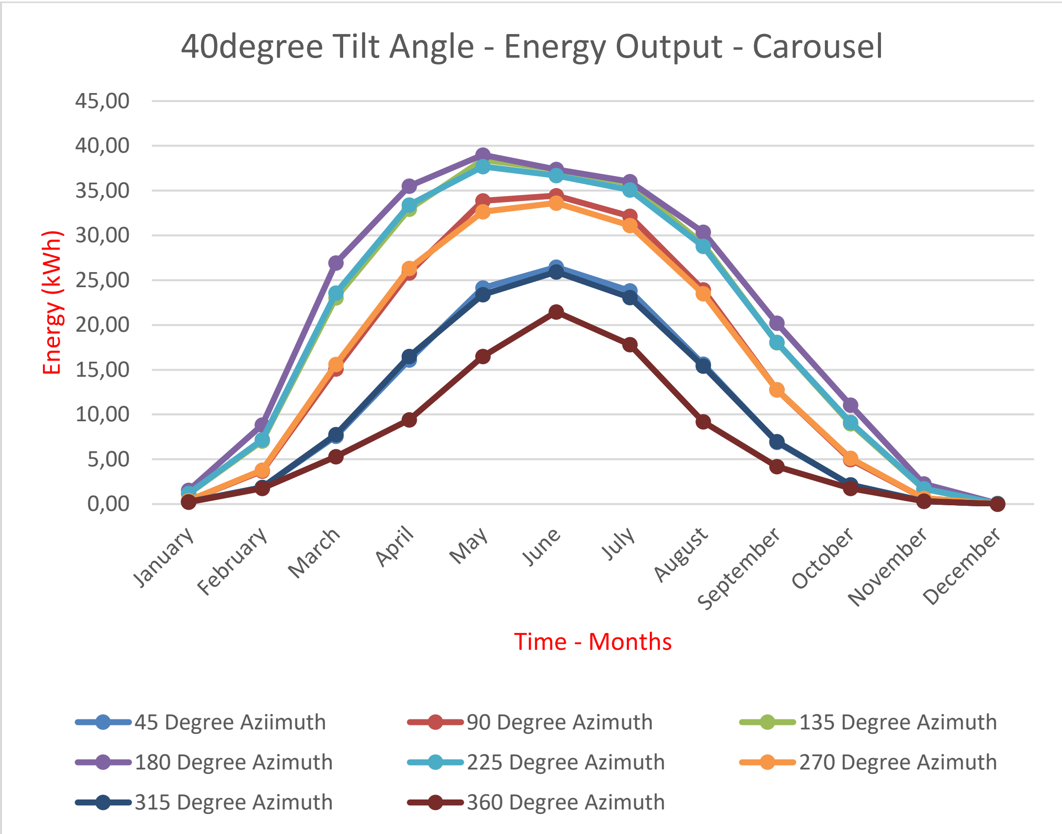

Figure 18: Graph of energy production throughout the year for 40degree tilt part of carousel.

Month	Energy Yield (kWh) with respect to Azimuth							
	45 Degree	90 Degree	135 Degree	180 Degree	225 Degree	270 Degree	315 Degree	360 Degree
January	0,24	0,39	1,16	1,55	1,18	0,4	0,24	0,23
February	1,87	3,68	7,04	8,82	7,19	3,81	1,88	1,74
March	7,59	15,1	23,04	26,93	23,57	15,58	7,77	5,3
April	16,08	25,8	32,92	35,51	33,41	26,32	16,48	9,41
May	24,13	33,87	38,43	38,99	37,69	32,65	23,37	16,48
June	26,46	34,44	37,38	37,37	36,7	33,62	25,92	21,46
July	23,81	32,16	35,74	36,01	35,09	31,11	23,06	17,81
August	15,64	23,93	29,04	30,36	28,8	23,48	15,43	9,19
September	6,9	12,76	18,01	20,2	18,05	12,78	6,96	4,18
October	2,14	4,98	8,97	11,05	9,12	5,1	2,16	1,76
November	0,32	0,64	1,7	2,26	1,72	0,65	0,33	0,31
December	0,01	0,02	0,06	0,08	0,06	0,02	0,01	0,01

Table 4: Annual energy yield with respect to Azimuth with a constant 40 degree tilt angle

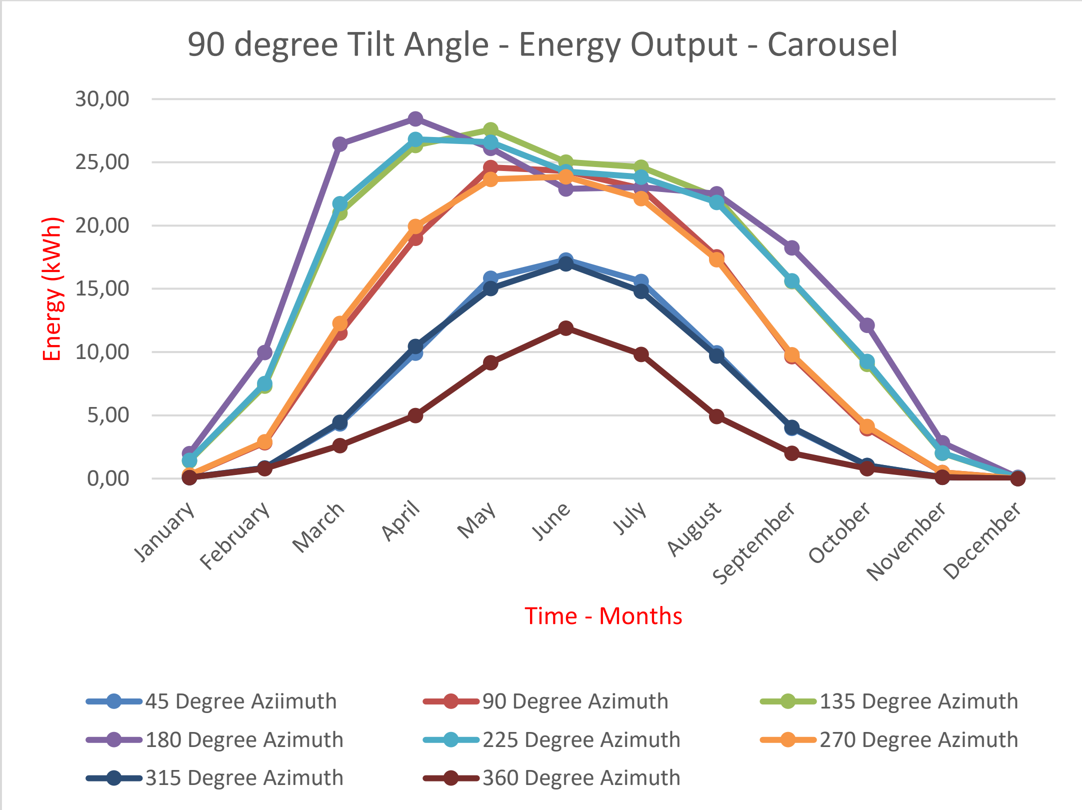

Figure 19: Graph of energy production throughout the year for 90degree tilt part of carousel.

Month	Energy Yield (kWh) with respect to Azimuth							
	45 Degree	90 Degree	135 Degree	180 Degree	225 Degree	270 Degree	315 Degree	360 Degree
January	0,08	0,26	1,4	1,99	1,44	0,28	0,08	0,08
February	0,85	2,84	7,32	9,99	7,52	2,91	0,85	0,79
March	4,33	11,51	21,01	26,45	21,74	12,27	4,46	2,61
April	9,93	19	26,34	28,45	26,82	19,95	10,45	5
May	15,85	24,6	27,58	26,12	26,6	23,66	15,04	9,16
June	17,3	24,32	25,03	22,91	24,27	23,87	16,99	11,91
July	15,6	22,93	24,62	23,03	23,84	22,14	14,82	9,83
August	9,95	17,53	22,25	22,52	21,85	17,32	9,7	4,92
September	3,99	9,64	15,6	18,24	15,65	9,8	4,06	2,01
October	1,04	3,96	9,05	12,13	9,27	4,13	1,05	0,79

November	0,11	0,48	2	2,84	2,03	0,49	0,11	0,11
December	0	0,01	0,07	0,1	0,07	0	0	0

Table 5: Annual energy yield with respect to Azimuth with a constant 90 degree tilt angle

Furthermore, the monthly study delves into the specific variations in solar PV output throughout different months of the year. This analysis helps identify any patterns or trends in energy generation and allows for a more detailed understanding of the system's performance. Factors such as the length of daylight hours, solar angles, and weather conditions specific to each month are considered in this assessment.

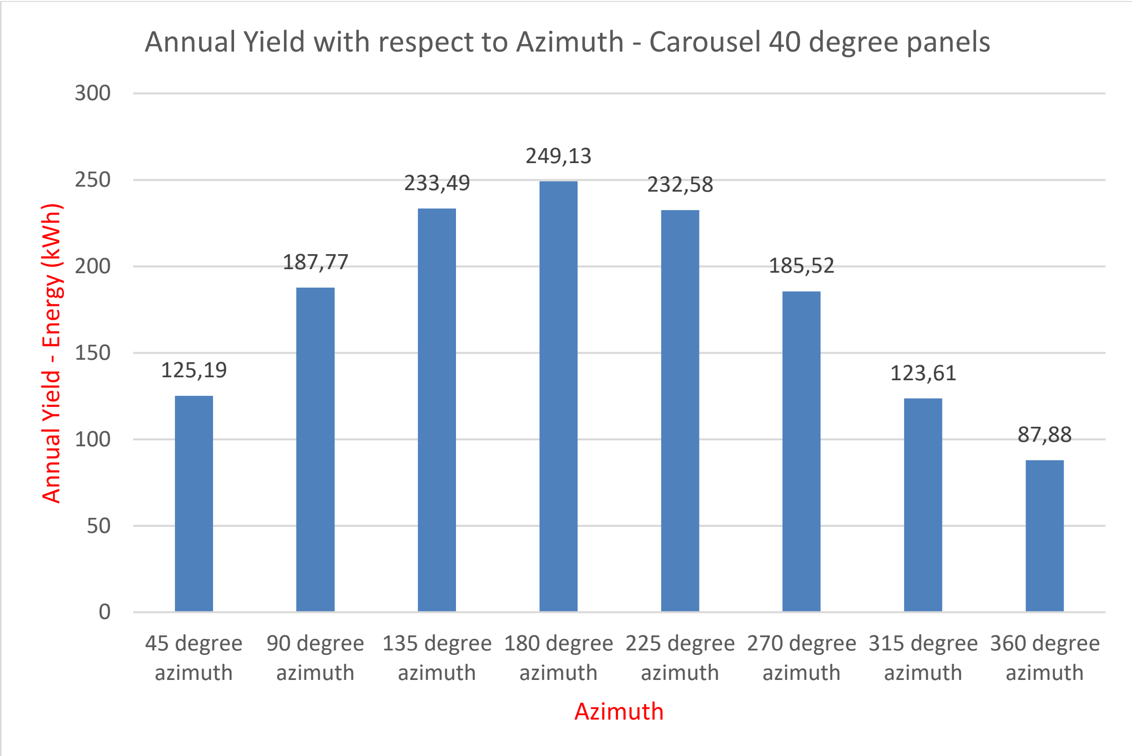

Figure 20: Graph of annual yield- 40degree tilt part of carousel.

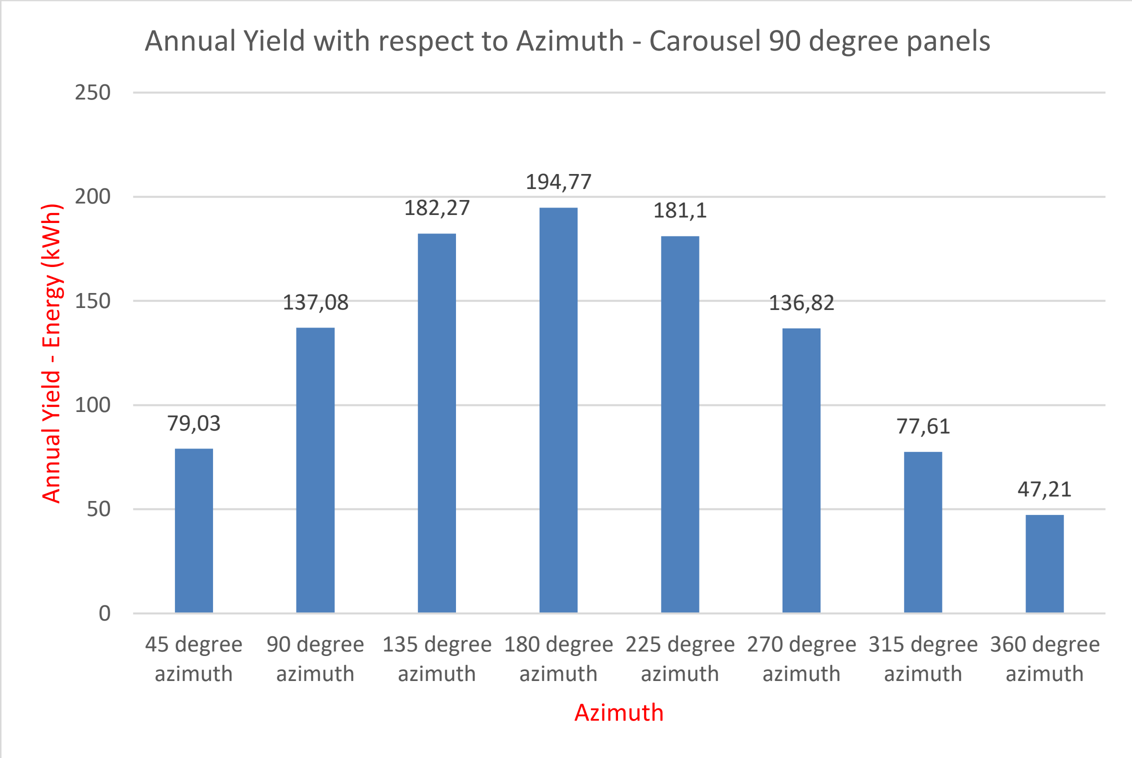

Figure 21: Graph of annual yield -90-degree tilt part of carousel.

The results obtained from the annual and monthly studies provide valuable insights into the performance of the solar PV system in the carousel configuration. By analysing the yield and energy output in relation to the azimuth and tilt angles of the panels, the study aims to optimize the system design and identify the most favourable orientations and inclinations for maximum energy production.

3.5.2 Performance Evaluation and results of Horizontal Panels on Roof

In this chapter, a comprehensive performance evaluation of the rooftop solar PV system is presented, focusing specifically on the horizontal panels with varying tilt angles. The study considers the geographical location of the panels in Oulu, Finland, and analyses the annual and monthly energy yield with respect to the tilt angle. The results provide valuable insights into the system's performance and help optimize its design for maximum energy output.

Annual Energy Yield with Respect to Tilt Angle

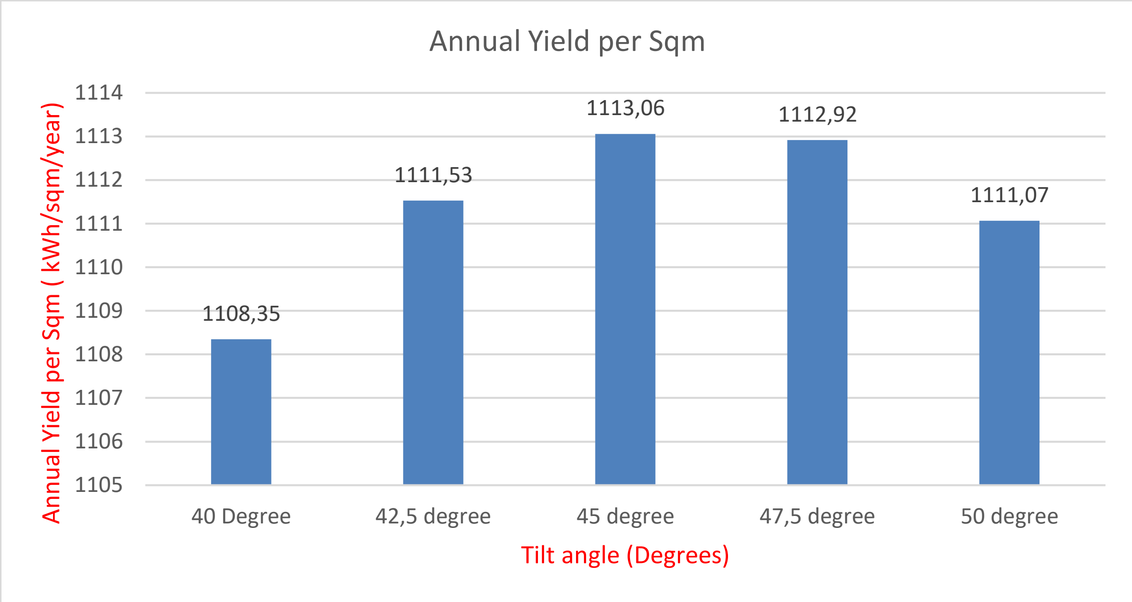

Figure 22: Annual yield per Sqm with respect to tilt angle

Figure 22 depicts the annual energy yield of the solar PV system as a function of the tilt angle. The tilt angle represents the inclination of the panels with respect to the horizontal plane. Upon analyzing the data, it is evident that the panels set at a tilt angle of 45 degrees to 47.5 degrees consistently generate the highest energy output throughout the year. This finding aligns with the geographical location of Oulu, Finland, where the optimal tilt angle for solar panels is often recommended to be around 45 degrees. The 45-degree panels exhibit an optimal balance between capturing sunlight during the summer months when the sun is higher in the sky and minimizing shading and snow accumulation during the winter months.

Furthermore, the results also indicate that the panels set at a tilt angle of 47.5 degrees closely follow the performance of the 45-degree panels, yielding slightly lower but still significant energy output. This observation highlights the robustness of the chosen tilt angle range and reinforces the effectiveness of the design for maximizing solar PV generation in Oulu's climate.

Monthly Energy Output for Different Tilt Angles

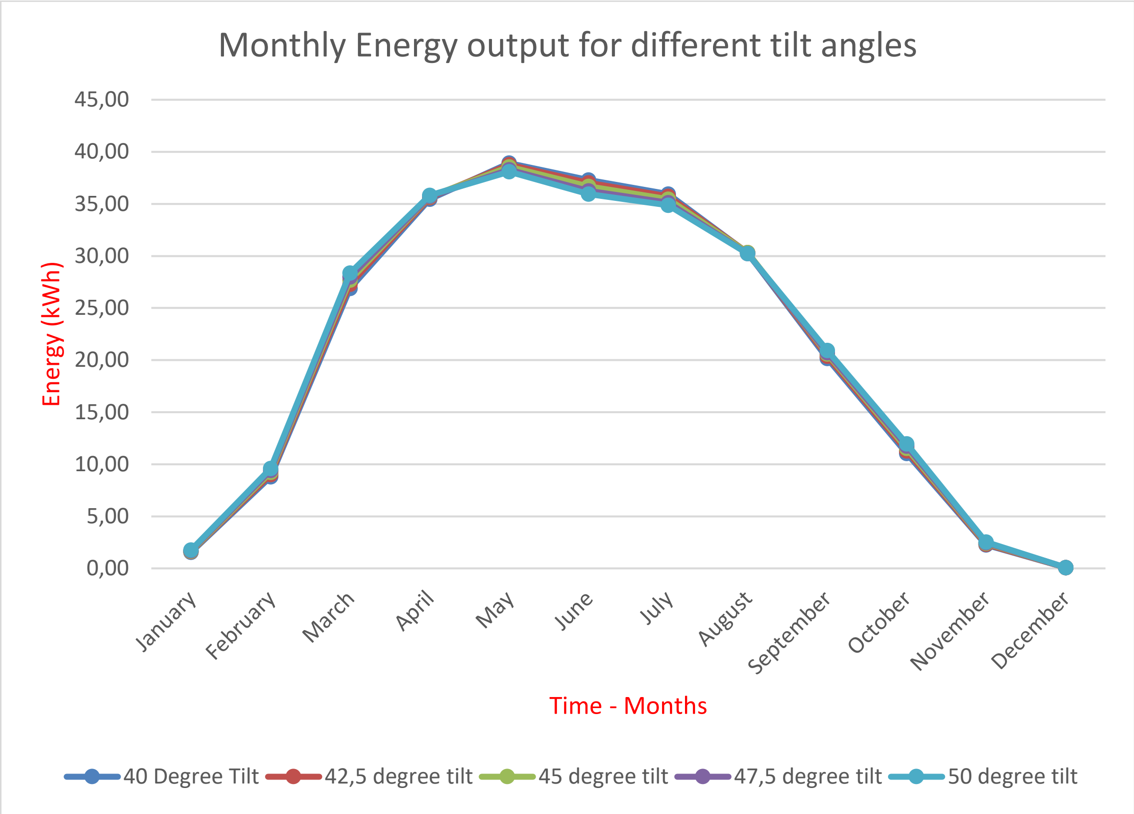

Figure 23: Monthly energy output for different tilt angles throughout the year

The graph presents the monthly energy output of the solar PV system for different tilt angles. While the lines representing the various tilt angles appear close to each other, a closer examination of the annual energy yield graph provides a clearer understanding of the optimal tilt angle. Although the monthly energy output for different tilt angles may exhibit minimal variations, the cumulative effect over the entire year clearly favours the 45-degree panels. The 45-degree tilt angle consistently captures the maximum amount of solar radiation over the year, leading to the highest overall energy yield.

These findings emphasize the importance of considering the geographical location and optimizing the tilt angle for solar PV systems. By aligning the tilt angle with the specific solar resource availability in Oulu, Finland, the 45-degree tilt angle proves to be the most effective in maximizing energy production.

3.5.3 Performance Evaluation and results of South Wall Vertical Panels

In this chapter, the focus is on the analysis of the south-facing vertical panels mounted on the wall of the building simulation. The purpose of this simulation is to investigate the energy production in the south direction and understand the impact of panel orientation on overall performance. The results obtained from the simulation are examined in detail, particularly through the representation of a graph depicting energy production for different months.

The findings reveal that the maximum energy production occurs during the months of March, April, and May, with April exhibiting the highest production. This observation contrasts with the conventional expectation of peak solar output during the summer months of June and July. However, upon closer examination, the reason for this deviation becomes clear: the vertical panels are aligned at a tilt angle of 90 degrees, which restricts their ability to fully exploit the higher solar angles prevalent during the summer months.

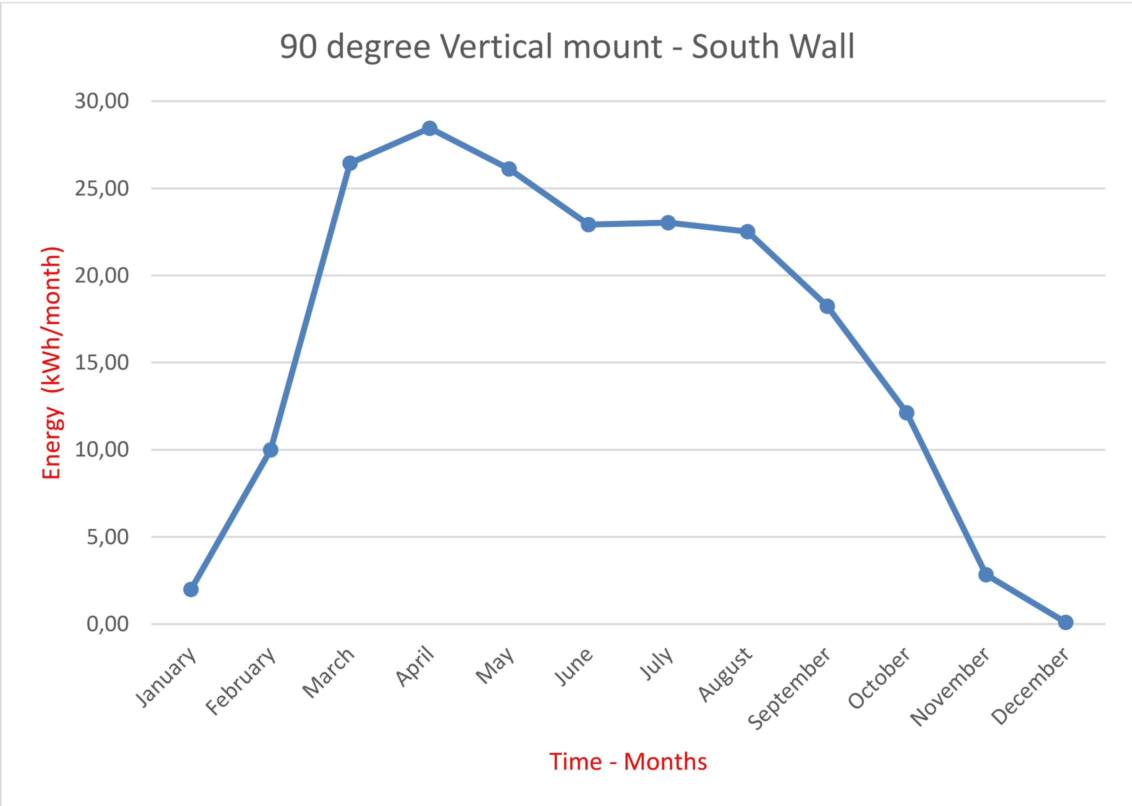

Figure 24: Energy production for 90 degree vertical mount-South wall throughout the year

The results of Figure 24 analysis highlight an interesting trend in the energy production of the south-facing vertical panels. During the spring months, from March to May, the sun's position in the sky is comparatively lower, resulting in a longer duration of optimal sunlight for these vertically oriented panels. Additionally, as spring progresses, the days become increasingly longer, providing more daylight hours for solar energy generation. These two factors, combined with the vertical orientation of the panels, contribute to the observed maximum energy production during this period.

Conversely, during the summer months of June and July, when the sun is at its peak in terms of intensity and higher angles, the vertical panels at a 90-degree tilt angle cannot fully capitalize on the available solar radiation. Since the panels are mounted vertically, they are unable to capture the sunlight effectively when it is incident at a higher angle. This limitation leads to a decrease in energy production during the summer months for the vertical panels, which explains the unexpected dip in energy output compared to the spring season.

It is important to note that the configuration and tilt angle of the vertical panels were specifically chosen for this study, aiming to assess their performance under these conditions. While the vertical orientation may not maximize energy production during the summer months, it is crucial to consider other factors such as space constraints or aesthetic requirements that might influence the choice of panel orientation.

3.5.4 Performance Evaluation and results of East Wall Vertical Panels

This chapter analyses the east-facing vertical panels mounted on the walls of the solar PV system. The obtained results are compared with those obtained from the carousel setup to establish any similarities or differences. The energy production graph, depicting the output of the panels across different months of the year, plays a crucial role in the analysis. The findings align with the expectations and closely mirror the results obtained from the carousel.

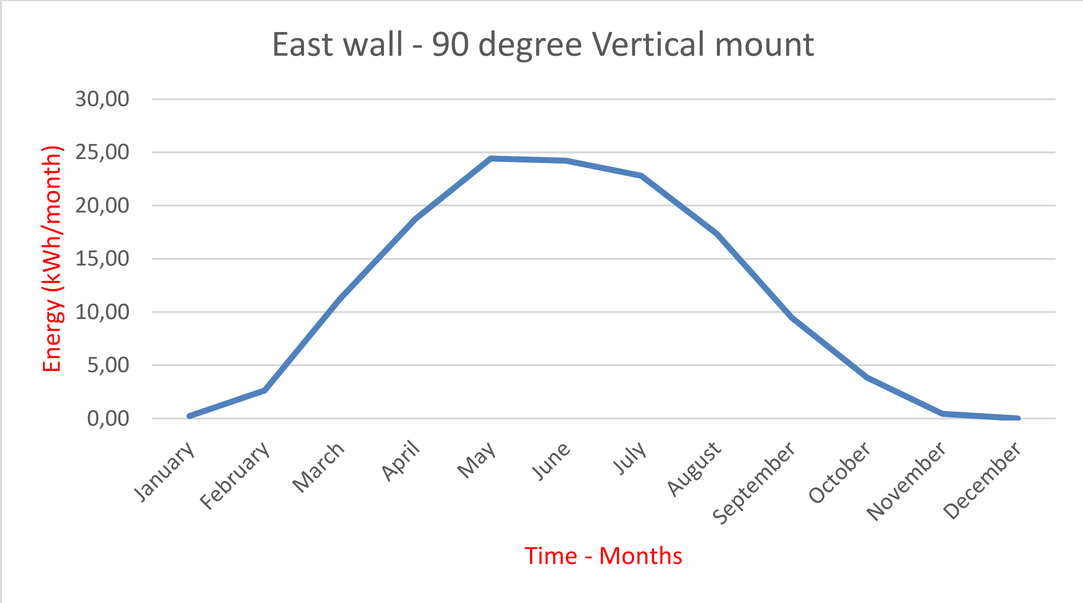

Figure 25: Energy production for 90 degree Vertical mount-East wall throughout the year

The data obtained from the simulation demonstrates a trend in the energy production of the east-facing vertical panels. The maximum output is consistently achieved during the months of May, June, and July, coinciding with the period of maximum solar radiation. This outcome aligns with the initial expectations, as these summer months typically receive the highest solar irradiance. The panels' east-facing orientation allows them to capture the early morning sunlight, which gradually increases in intensity as the day progresses, leading to a peak in energy production during midday.

The observed alignment between the results of the east-facing vertical panels and the carousel setup further validates the accuracy and reliability of the simulations. It highlights the consistency in energy production patterns, with respect to the panel orientation or configuration. This finding contributes to the overall understanding of solar PV system performance and aids in predicting energy generation capabilities in different scenarios.

Month	Energy Yield (kWh) per month
January	0,23
February	2,65
March	11,23

April	18,75
May	24,42
June	24,21
July	22,80
August	17,35
September	9,46
October	3,83
November	0,45
December	0,00

Table 6: Energy yield per month for the east vertical panels

It is worth noting that the east-facing vertical panels are specifically oriented to capture the morning sunlight, maximizing their energy production during this period. However, this orientation also means that the panels receive less direct sunlight during the later part of the day when the sun shifts towards the west. Consequently, the energy output gradually decreases as the day progresses, leading to lower production levels in the afternoon and evening.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Evaluation of Tilt Angles and Orientation

In this study of the solar PV setup, a thorough evaluation of various tilt angles was conducted to assess their impact on energy production. The evaluated configurations included the carousel setup with vertical panels and 40-degree tilt panels, as well as the roof-mounted horizontal panels with tilt angles ranging from 40 to 50 degrees in 2.5-degree increments, the south wall vertical panels and the east wall vertical panels. The findings shed light on the optimal tilt angle for maximizing energy output and provide valuable insights for solar PV system design and installation.

Inclined Panels and Vertical Panels

One of the key observations from the study was that the inclined panels on the carousel exhibited peak outputs during the summer months, with maximum values achieved in May and June. This finding indicates that the tilt angles, closer to the 45-degree position, result in increased energy production during periods of higher solar irradiance when compared to the vertical (90-degree) panels. The inclination allows the panels to capture sunlight more effectively, maximizing their exposure to the sun's rays and thus generating higher energy yields. Therefore, the results suggest that panels with tilt angles within a reasonable range close to 45-degrees can significantly contribute to improved solar PV performance.

At the same time, the assessment from the performance of vertically mounted panels on the south-facing wall and the vertical panels of the carousel with a 90-degree tilt angle. The obtained results indicated that the peak production of these panels occurred during the spring months of March and April. This outcome can be attributed to the lower sun angles during spring, which align more favorably with the vertical orientation of the panels. The panels were able to capture sunlight at lower angles for longer durations, resulting in higher energy production during this period. However, during the summer months when the sun is at higher angles, the vertical panels were unable to take full advantage of the increased solar radiation, leading to a decrease in their overall output.

Optimal Tilt Angle

Considering the results obtained from the configurations, the more optimum tilt angle is 45 degrees. The 45-degree tilt angle allows for a more effective energy generation during both the summer and winter months, optimizing the overall performance of the solar PV system.

Azimuth Considerations

Furthermore, the study emphasized the importance of panel orientation in maximizing energy output. The results indicated that the south-facing direction consistently yielded higher energy production compared to other orientations. The south-facing panels benefitted from the sun's path throughout the day, ensuring prolonged exposure to direct sunlight.

The evaluation of tilt angles in the solar PV setup revealed important insights regarding their impact on energy production. The findings provide valuable guidance for the design and installation of efficient and productive solar PV systems, contributing to the advancement of renewable energy utilization.

4.2 Future research

Future research in the field of solar PV systems should focus on incorporating complex weather variables, such as shade, snow cover, high winds, rain, and dust accumulation. By considering these factors, researchers can gain a better understanding of how different weather conditions impact energy production and develop strategies to mitigate their negative effects. Additionally, investigating the effects of equipment failure rates, periodic maintenance, and upgrades is crucial to enhance the practicality and reliability of solar PV installations. By incorporating these variables into simulations, researchers can optimize system designs and develop maintenance strategies that minimize downtime and maximize long-term performance.

Another area for future research is the analysis of regional variation and temperature patterns in solar PV systems. Simulating different regions in the upper north latitudes and considering temperature variations will enable researchers to optimize system designs specific to local climates, ultimately enhancing the overall efficiency and effectiveness of solar PV installations. Moreover, future research should explore the integration of advanced technologies, such as novel panel materials, advanced tracking mechanisms, energy storage systems, and smart grid integration, into system simulations. By evaluating the performance of these technologies, researchers can assess their benefits, identify optimal configurations, and guide the development of innovative solar PV systems, promoting the adoption of more efficient and sustainable solar energy solutions in the future.

5 APPENDIX

Simulation result tables for the Carousel Setup.

Results for solar modules in each face												
Face	Model	N°P.	P. power (Wp)	Power (kWp)	Weight (kg)	Azimuth	Tilt	Relative tilt	Energy (kWh)	Yield (kWh/kWp)	$\sum H_m$ (kWh/m²/year)	Shading L. (%)
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	180,00	40,00	40,00	249,13	922,70	1108,35	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	360,00	40,00	40,00	87,88	325,48	484,18	5,99
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	270,00	40,00	40,00	185,52	687,11	850,07	0,52
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	225,00	40,00	40,00	232,58	861,41	1040,33	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	315,00	40,00	40,00	123,61	457,81	603,99	2,17
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	45,00	40,00	40,00	125,19	463,67	607,51	2,27
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	90,00	40,00	40,00	187,77	695,44	851,66	0,09
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	135,00	40,00	40,00	233,49	864,78	1041,68	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	180,00	90,00	90,00	194,77	721,37	872,23	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	225,00	90,00	90,00	181,10	670,74	817,08	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	270,00	90,00	90,00	136,82	506,74	634,01	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	135,00	90,00	90,00	182,27	675,07	818,04	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	90,00	90,00	90,00	137,08	507,70	628,62	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	45,00	90,00	90,00	79,03	292,70	388,97	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	360,00	90,00	90,00	47,21	174,85	260,29	0,00
3	Test Panel OAMK:TPO	1	270,00	0,27	1,00	315,00	90,00	90,00	77,61	287,44	386,08	0,00

E_m (kWh/month)												
Face	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3	1,55	8,82	26,93	35,51	38,99	37,37	36,01	30,36	20,20	11,05	2,26	0,08
3	0,23	1,74	5,30	9,41	16,48	21,46	17,81	9,19	4,18	1,76	0,31	0,01
3	0,40	3,81	15,58	26,32	32,65	33,62	31,11	23,48	12,78	5,10	0,65	0,02
3	1,18	7,19	23,57	33,41	37,69	36,70	35,09	28,80	18,05	9,12	1,72	0,06
3	0,24	1,88	7,77	16,48	23,37	25,92	23,06	15,43	6,96	2,16	0,33	0,01
3	0,24	1,87	7,59	16,08	24,13	26,46	23,81	15,64	6,90	2,14	0,32	0,01
3	0,39	3,68	15,10	25,80	33,87	34,44	32,16	23,93	12,76	4,98	0,64	0,02
3	1,16	7,04	23,04	32,92	38,43	37,38	35,74	29,04	18,01	8,97	1,70	0,06
3	1,99	9,99	26,45	28,45	26,12	22,91	23,03	22,52	18,24	12,13	2,84	0,10
3	1,44	7,52	21,74	26,82	26,60	24,27	23,84	21,85	15,65	9,27	2,03	0,07
3	0,28	2,91	12,27	19,95	23,66	23,87	22,14	17,32	9,80	4,13	0,49	0,00
3	1,40	7,32	21,01	26,34	27,58	25,03	24,62	22,25	15,60	9,05	2,00	0,07
3	0,26	2,84	11,51	19,00	24,60	24,32	22,93	17,53	9,64	3,96	0,48	0,01
3	0,08	0,85	4,33	9,93	15,85	17,30	15,60	9,95	3,99	1,04	0,11	0,00
3	0,08	0,79	2,61	5,00	9,16	11,91	9,83	4,92	2,01	0,79	0,11	0,00
3	0,08	0,85	4,46	10,45	15,04	16,99	14,82	9,70	4,06	1,05	0,11	0,00
∑	11,00	69,10	229,26	341,87	414,22	419,95	391,60	301,91	178,83	86,70	16,10	0,52

Simulation result tables for the Horizontal roof top panels.

Results for solar modules in each face													
Face	**Model**	**N°P.**	**P. power (Wp)**	**Power (kWp)**	**Weight (kg)**	**Azimuth**	**Tilt**	**Relative tilt**	**Energy (kWh)**	**Yield (kWh/kWp)**	**$\sum H_m$ (kWh/m^2/year)**	**Shading L. (%)**
3	Test Panel OAMK:TPO	3	270,00	0,81	3,00	180,00	42,50	42,50	748,23	923,74	1111,53	0,22
3	Test Panel OAMK:TPO	3	270,00	0,81	3,00	180,00	45,00	45,00	749,48	925,28	1113,06	0,24
3	Test Panel OAMK:TPO	3	270,00	0,81	3,00	180,00	47,50	47,50	749,06	924,77	1112,92	0,32
3	Test Panel OAMK:TPO	3	270,00	0,81	3,00	180,00	50,00	50,00	750,49	926,53	1111,07	0,00
3	Test Panel OAMK:TPO	3	270,00	0,81	3,00	180,00	40,00	40,00	745,84	920,79	1108,35	0,21

Each row contains 3 panels. The results are for the sum of 3 panels on each row.

E_m (kWh/month)												
Face	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
3	4,81	27,06	81,89	106,78	116,28	111,02	107,16	90,98	61,15	33,87	6,99	0,24
3	4,96	27,67	83,01	107,09	115,67	110,00	106,38	90,93	61,73	34,58	7,21	0,25
3	5,11	28,22	83,93	107,16	114,82	108,75	105,37	90,68	62,16	35,21	7,40	0,25
3	5,26	28,82	85,04	107,49	114,26	107,79	104,64	90,66	62,74	35,91	7,62	0,26
3	4,64	26,39	80,63	106,32	116,73	111,88	107,80	90,90	60,47	33,09	6,76	0,23
$\sum$	24,78	138,16	414,50	534,84	577,76	549,44	531,35	454,15	308,25	172,66	35,98	1,23

Simulation results table for the South facing wall panels.

E_m (kWh/month)												
Group	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	31,89	159,79	423,21	455,26	417,95	366,58	368,40	360,37	291,79	194,01	45,43	1,53
$\sum$	31,89	159,79	423,21	455,26	417,95	366,58	368,40	360,37	291,79	194,01	45,43	1,53

(The results are for the entire wall panels, which contains a sum of 16 panels)

Simulation results table for the east facing wall panels.

E_m (kWh/month)												
Group	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	5,63	63,59	269,50	449,95	586,05	581,11	547,22	416,45	227,05	91,83	10,70	0,11
$\sum$	5,63	63,59	269,50	449,95	586,05	581,11	547,22	416,45	227,05	91,83	10,70	0,11

(The results are for the entire wall panels, which contains a sum of 24 panels)

6 REFERENCES

Ahmed, Muhammad Imran, Amir Habib, and Syed Saad Javaid. "Perovskite solar cells: potentials, challenges, and opportunities." International Journal of Photoenergy 2015 (2015).

Bahrami, Arian, Chiemeka Onyeka Okoye, and Ugur Atikol. "The effect of latitude on the performance of different solar trackers in Europe and Africa." *Applied energy* 177 (2016): 896-906.

Bashir, M.A., Ali, H.M., Amber, K.P., Bashir, M.W., Ali, H., Imran, S. and Kamran, M.S., 2018. Performance investigation of photovoltaic modules by back surface water cooling. Thermal Science, 22(6 Part A), pp.2401-2411.

Bashir, M.A., Ali, H.M., Khalil, S., Ali, M. and Siddiqui, A.M., 2014. Comparison of performance measurements of photovoltaic modules during winter months in Taxila, Pakistan. International Journal of Photoenergy, 2014.

Bellini, E., 2022. Inverted perovskite solar cell with 23.7% efficiency. [online] pv magazine International. https://www.pvmagazine.com/2021/12/03/inverted-perovskite-solar-cell-with-23-7-efficiency

Bressan, M, Y. El Basri, A.G. Galeano, C. Alonso, A shadow fault detection method based on the standard error analysis of I-V curves, Renewable Energy, Volume 99, 2016, Pages 1181-1190, ISSN 0960-1481.

Chen, W.S., Chen, Y.J. and Yueh, K.C., 2020. Separation of valuable metal from waste photovoltaic ribbon through extraction and precipitation. Resources Recycling, 29(2), pp.69-77.

Cucchiella, F., D'Adamo, I., Gastaldi, M. and Miliacca, M., 2018. Efficiency and allocation of emission allowances and energy consumption over more sustainable European economies. Journal of Cleaner Production, 182, pp.805-817.

Das, S., Pandey, D., Thomas, J. and Roy, T., 2019. The role of graphene and other 2D materials in solar photovoltaics. *Advanced Materials*, *31*(1), p.1802722.

Dhimish, M., 2020. Performance ratio and degradation rate analysis of 10-year field exposed residential photovoltaic installations in the UK and Ireland. Clean Technologies, 2(2), p.12.

Dhimish, M., 2020. Performance ratio and degradation rate analysis of 10-year field exposed residential photovoltaic installations in the UK and Ireland. Clean Technologies, 2(2), p.12.

Drobotiuk, O., Osadchuk, V. and Shaidetska, V., 2020. Energy Transformation in China: Towards Global Leadership in Renewable Energy. Kitaêznavčì doslìdžennâ, 1, pp.17-26.

Dubey, S., Sarvaiya, J.N. and Seshadri, B., 2013. Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world–a review. Energy Procedia, 33, pp.311-321

EEA 2023. Share of energy consumption from renewable sources in Europe (8^{th} EAP). Link: https://www.eea.europa.eu/ims/share-of-energy-consumption-from

Emetere, M.E. and Rokosu, A.K., 2020, September. Investigation of biodegradable optical filter in a turbulent solar irradiation. In IOP Conference Series: Earth and Environmental Science (Vol. 566, No. 1, p. 012006). IOP Publishing.

Energy plus weather file, EPW file archive, https://climate.onebuilding.org/WMO_Region_6_Europe/FIN_Finland/index.html , 2023

EU Green deal 2020. 2050 long term strategy. Link: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en European photovoltaic industry association (EPIA), “PV technologies: Cells and modules,” 2010

Flowers, M.E., Smith, M.K., Parsekian, A.W., Boyuk, D.S., McGrath, J.K. and Yates, L., 2016. Climate impacts on the cost of solar energy. Energy Policy, 94, pp.264-273.

Frimannslund Iver, Thomas Thiis, Arne Aalberg, Bjørn Thorud, Polar solar power plants – Investigating the potential and the design challenges, Solar Energy, Volume 224, 2021.

Garreau, A., Skjerve, T., Sjöblom, A. and Shestov, A., 2023. From solar radiation estimation to solar energy potential in the High Arctic (No. EGU23-8140). Copernicus Meetings.

Ghalem, Kamel & Ziane, Mohamed & Hamoul, A & Gheni, R. (2022). Maxi dual axis solar tracker system.

Giannouli, M., 2021. Current status of emerging PV technologies: a comparative study of dye-sensitized, organic, and perovskite solar cells. International Journal of Photoenergy, 2021, pp.1-19.

Green, MA, Dunlop, ED, Hohl-Ebinger, J, et al. Solar cell efficiency tables (Version 60). Prog Photovolt Res Appl. 2022; 30(7): 687- 701. doi:10.1002/pip.3595

Grunow, Paul & Lust, Sandra & Sauter, D. & Hoffmann, Volker & Beneking, C. & Litzenburger, B. & Podlowski, L. (2004). Weak light performance and annual yields of PV modules and systems as a result of the basic parameter set of industrial solar cells. Proc. 19th European Photovoltaic Solar Energy Conference.

Hailu, G. and Fung, A.S., 2019. Optimum tilt angle and orientation of photovoltaic thermal system for application in greater Toronto area, Canada. Sustainability, 11(22), p.6443.

Hasan, A.A., Ahmed Alkahtani, A., Shahahmadi, S.A., Nur E. Alam, M., Islam, M.A. and Amin, N., 2021. Delamination-and electromigration-related failures in solar panels—A review. Sustainability, 13(12), p.6882.

Hassan, Y., Orabi, M., Alshreef, A., M. Al-Rabghi, O., Habeebullah, B.A., El Aroudi, A. and A. Ismeil, M., 2020. Improvement of Extracted Power of Pole Mounted Solar Panels by Effective Cooling Using Aluminum Heat Sink under Hot Weather and Variable Wind Speed Conditions. Energies, 13(12), p.3159.

Hayat, M.B., Ali, D., Monyake, K.C., Alagha, L. and Ahmed, N., 2019. Solar energy—A look into power generation, challenges, and a solar-powered future. International Journal of Energy Research, 43(3), pp.1049-1067.

Hossain, R., Ahmed, A.J., Islam, S.M.K.N., Saha, N., Debnath, P., Kouzani, A.Z. and Mahmud, M.P., 2020. New Design of solar photovoltaic and thermal hybrid system for performance improvement of solar photovoltaic. International Journal of Photoenergy, 2020, pp.1-6.

Hosseini, S., Taheri, S., Pouresmaeil, E. and Taheri, H., 2020. Analysis of electrical behaviour of PV arrays covered with non-uniform snow. Electronics Letters, 56(4), pp.192-194.

Hosseini, S., Taheri, S., Pouresmaeil, E. and Taheri, H., 2020. Analysis of electrical behaviour of PV arrays covered with non-uniform snow. Electronics Letters, 56(4), pp.192-194.

Huang, C.Y., Sung, H. and Yen, K.L., 2013. Experimental study of photovoltaic/thermal (PV/T) hybrid system. Int. J. Smart Grid Clean Energy, 2(2), pp.147-151.

Hussein A. Kazem, Miqdam T Chaichan, Ali H.A. Al-Waeli, K Sopian, Comparison and evaluation of solar photovoltaic thermal system with hybrid collector: An experimental study, Thermal Science and Engineering Progress, Volume 22, 2021, 100845, ISSN 2451-9049

Ineson, S., Maycock, A.C., Gray, L.J., Scaife, A.A., Dunstone, N.J., Harder, J.W., Knight, J.R., Lockwood, M., Manners, J.C. and Wood, R.A., 2015. Regional climate impacts of a possible future grand solar minimum. Nature Communications, 6(1), p.7535.

Inglesi-Lotz, R., 2016. The impact of renewable energy consumption to economic growth: A panel data application. Energy economics, 53, pp.58-63.

ISSN 0306-2619 Taherbaneh, M., Rezaie, A.H., Ghafoorifard, H., Rahimi, K. and Menhaj, M.B., 2010. Maximizing output power of a solar panel via combination of sun tracking and maximum power point tracking by fuzzy controllers. International Journal of Photoenergy, 2010.

Jäger-Waldau, 1.09 - Overview of the Global PV Industry, Editor(s): Ali Sayigh, Comprehensive Renewable Energy, Elsevier, 2012, Pages 161-177, ISBN 9780080878737

Jena, A.K., Kulkarni, A. and Miyasaka, T., 2019. Halide perovskite photovoltaics: background, status, and future prospects. Chemical reviews, 119(5), pp.3036-3103.

Joon, C.J. and Jin, K.C.W., 2021. Design of Augmented Cooling System for Urban Solar PV System. In MATEC Web of Conferences (Vol. 335, p. 03002). EDP Sciences.

K. Akhmad, A. Kitamura, F. Yamamoto, H. Okamoto, H. Takakura, and Y. Hamakawa, "Outdoor performance of amorphous silicon and polycrystalline silicon PV modules," Solar Energy Materials and Solar Cells, vol. 46, no. 3, pp. 209–218, 1997.

Kamanga, B., Kamunda, C., Mlatho, J.S.P. and Mikeka, C., 2014. Optimum tilt angle for photovoltaic solar panels in Zomba district, Malawi.

Khenar, M., Hosseini, S., Taheri, S., Cretu, A.M., Pouresmaeil, E. and Taheri, H., 2019. Particle swarm optimisation-based model and analysis of photovoltaic module characteristics in snowy conditions. IET Renewable Power Generation, 13(11), pp.1950-1957.

Kim, J.; Rabelo, M.; Padi, S.P.; Yousuf, H.; Cho, E.-C.; Yi, J. A Review of the Degradation of Photovoltaic Modules for Life Expectancy. Energies 2021, 14, 4278. https://doi.org/10.3390/en14144278

Kojima A, Kenjiro Teshima, Yasuo Shirai, and Tsutomu Miyasaka"Organometal halide perovskites as visible-light sensitizers for photovoltaic cells." Journal of the american chemical society 131.17 (2009): 6050-6051.

Korpijärvi, J, & Tanskanen, R. (2019/09). The Economy and Possibility of Energy Community in Finnish Solar Energy Production. Proceedings of the International Conference on Digital Technologies in Logistics and Infrastructure (ICDTLI 2019), 180-184. https://doi.org/10.2991/icdtli-19.2019.34

Korpijärvi, J. and Tanskanen, R., 2019, September. The Economy and Possibility of Energy Community in Finnish Solar Energy Production. In International Conference on Digital Technologies in Logistics and Infrastructure (ICDTLI 2019) (pp. 180-184). Atlantis Press.

Kurtz, S., Whitfield, K., TamizhMani, G., Koehl, M., Miller, D., Joyce, J., Wohlgemuth, J., Bosco, N., Kempe, M. and Zgonena, T., 2011. Evaluation of high-temperature exposure of photovoltaic modules. Progress in photovoltaics: Research and applications, 19(8), pp.954-965.

L.A. Lamont, 1.03 - History of Photovoltaics, Editor(s): Trevor M. Letcher, Comprehensive Renewable Energy (Second Edition), Elsevier, 2022, Pages 34-49, ISBN 9780128197349

Laeng, B., Brennen, T., Elden, Å., Paulsen, H.G., Banerjee, A. and Lipton, R., 2007. Latitude-of-birth and season-of-birth effects on human color vision in the Arctic. Vision Research, 47(12), pp.1595-1607.

Lave, Matthew, and Jan Kleissl. "Optimum fixed orientations and benefits of tracking for capturing solar radiation in the continental United States." *Renewable Energy* 36.3 (2011): 1145-1152.

Lawrence L. Kazmerski, 1.02 - Solar Photovoltaics: Living a Technology From Research Curiosity to Reality, Editor(s): Trevor M. Letcher, Comprehensive Renewable Energy (Second Edition), Elsevier, 2022, Pages 8-33, ISBN 9780128197349

Limem, F. and Sezen, S., 2021. Comparative Analysis of Different Photovoltaic Simulation Software: Case Study on Analyzing the Performance of a 5,1 kWp Grid Connected Photovoltaic System. Avrupa Bilim ve Teknoloji Dergisi, (32), pp.816-826.

Lovelett R, Gregory M. Hanket, William N. Shafarman, Robert W. Birkmire, Babatunde A. Ogunnaike, Design and experimental implementation of an effective control system for thin film Cu(InGa)Se2 production via rapid thermal processing, Journal of Process Control, Volume 46, 2016, Pages 24-33, ISSN 0959-1524

Meitzner K.V., Katz, E.A., Abate, A. et al. Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures. Nat Energy 5, 35–49 (2020). https://doi.org/10.1038/s41560-019-0529-5

Memon, Q.A., Rahimoon, A.Q., Ali, K., Shaikh, M.F. and Shaikh, S.A., 2021. Determining Optimum Tilt Angle for 1 MW Photovoltaic System at Sukkur, Pakistan. International Journal of Photoenergy, 2021, pp.1-8.

Ogundimu, E.O., Akinlabi, E., Mgbemene, C. and Jacobs, I., 2022. Designing and fabrication of an installation PV solar modules tilting platform. Sustainable Engineering and Innovation, 4(1), p.46.

Olorunfemi, B.O., Ogbolumani, O.A. and Nwulu, N., 2022. Solar panels dirt monitoring and cleaning for performance improvement: a systematic review on smart systems. Sustainability, 14(17), p.10920.

Panchenko, V., 2021. Prospects for Energy Supply of the Arctic Zone Objects of Russia Using Frost-Resistant Solar Modules. In Research Anthology on Clean Energy Management and Solutions (pp. 944-964). IGI Global.

Park, H., Chang, S., Park, S. and Kim, W.K., 2019. Outdoor performance test of bifacial n-type silicon photovoltaic modules. Sustainability, 11(22), p.6234.

Partain, Larry D., and Lewis M. Fraas. Solar cells and their applications. John Wiley & Sons, 2010.

Pehlivan B, Ilknur & Edoff, & Stolt, & Edvinsson, Tomas. (2019). Optimum Band Gap Energy of ((Ag),Cu)(InGa)Se2 Materials for Combination with NiMo–NiO Catalysts for Thermally Integrated Solar-Driven Water Splitting Applications. Energies. 12. 4064. 10.3390/en12214064.

Pihlakivi, Emma. "Potential of solar energy in Finland: research for solar leap." (2015).

Pistone, K., Eisenman, I. and Ramanathan, V., 2014. Observational determination of albedo decrease caused by vanishing Arctic sea ice. Proceedings of the National Academy of Sciences, 111(9), pp.3322-3326.

Pithan, F. and Mauritsen, T., 2014. Arctic amplification dominated by temperature feedbacks in contemporary climate models. Nature geoscience, 7(3), pp.181-184.

Poe, C.D., Plovnick, A., Hodges, T., Hastings, A.L., & Dresley, S. (2017). Highway renewable energy : photovoltaic noise barriers.

Qing Zhong, Jake R. Nelson, Daoqin Tong, Tony H. Grubesic, A spatial optimization approach to increase the accuracy of rooftop solar energy assessments, Applied Energy, Volume 316, 2022, 119128,

Quesada, Guillermo & Guillon, Laura & Rousse, Daniel & Mehrtash, Mostafa & Dutil, Yvan & Paradis, Pierre-Luc. (2015). Tracking strategy for photovoltaic solar systems in high latitudes. Energy Conversion and Management. 103.

RePowerEU 2019. RePower EU at a glance. Link:https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

Rhodes, Christopher J. "Solar Energy: Principles and Possibilities." Science Progress (1933-), vol. 93, no. 1, 2010, pp. 37–112.

Rui Q. Yang, Hossein Lotfi, Lu Li, Robert T. Hinkey, Hao Ye, John F. Klem, L. Lei, T. D. Mishima, J. C. Keay, M. B. Santos, M. B. Johnson, "Quantum-engineered interband cascade photovoltaic devices," Proc. SPIE 8993, Quantum Sensing and Nanophotonic Devices XI, 899310, 2014.

Sampaio, Priscila Gonçalves Vasconcelos, and Mario Orestes Aguirre González. "Photovoltaic solar energy: Conceptual framework." Renewable and Sustainable Energy Reviews 74 (2017): 590-601.

Sreenath, S., Sudhakar, K. and Yusop, A. (2021) "Suitability Analysis of Solar Tracking PV System in the Airport Based on Glare Assessment", International Journal of Automotive and Mechanical Engineering, 18(3), pp. 9061–9070. doi: 10.15282/ijame.18.3.2021.18.0695

Stoyanov, L., Zarkov, Z., Notton, G. and Lazarov, V., 2016. Comparison of thin film modules productivity for building integration. In Materials Science Forum (Vol. 856, pp. 309-314). Trans Tech Publications Ltd.

Tilmes, S., Jahn, A., Kay, J.E., Holland, M. and Lamarque, J.F., 2014. Can regional climate engineering save the summer Arctic sea ice?. Geophysical Research Letters, 41(3), pp.880-885.

Toivola, Minna. "Dye-Sensitized solar cells on alternative substrates." (2010).

University of oulu, Birds eye view of Uni Oulu 2023, https://www.oulu.fi/en/civ-contact-information.

Vega, A., Valiño, V., Conde, E., Ramos, A. and Reina, P., 2019. Double sweep tracer for IV curves characterization and continuous monitoring of photovoltaic facilities. Solar Energy, 190, pp.622-629.

Vítězslav Benda, Ladislava Černá, PV cells and modules – State of the art, limits and trends, Heliyon, Volume 6, Issue 12, 2020, e05666, ISSN 2405-8440

Wu, Jun, Binbin Zhang, and Liping Wang. "Optimum design and performance comparison of a redundantly actuated solar tracker and its nonredundant counterpart." *Solar Energy* 127 (2016): 36-47.

Wu, Jun, Xiaolei Chen, and Liping Wang. "Design and dynamics of a novel solar tracker with parallel mechanism." *IEEE/ASME Transactions on Mechatronics* 21.1 (2015): 88-97.

Xie, Y., Huang, J., Wu, G. and Liu, Y., 2023. Potential Vorticity Dynamics Explain How Extratropical Oceans and the Arctic Modulate Wintertime Land-Temperature Variations. Earth's Future, 11(2), e2022EF003275.

Yamaguchi S, Bas B. Van Aken, Maciej K. Stodolny, Jochen Löffler, Atsushi Masuda, Keisuke Ohdaira, Effects of passivation configuration and emitter surface doping concentration on polarization-type potential-induced degradation in n-type crystalline-silicon photovoltaic modules, Solar Energy Materials and Solar Cells, Volume 226, 2021, 111074, ISSN 0927-0248

Yamaguchi, M., Masuda, T., Araki, K., Ota, Y., Nishioka, K., Takamoto, T., Thiel, C., Tsakalidis, A., Jaeger-Waldau, A., Okumura, K. and Satou, A., 2021. Analysis of temperature coefficients and their effect on efficiency of solar cell modules for photovoltaics-powered vehicles. Journal of Physics D: Applied Physics, 54(50), p.504002.