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DESIGN OF A MINIATURIZED BIFACIAL SINGLE-AXIS SOLAR TRACKER

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YKSIAKSELIAURINKOSEURAIMEN SUUNNITTELU BIFACIAL-PANEELEILLE

Ilmastonmuutos on uhka tulevaisuuden hyvinvoinnille. Energiantuotanto on suuri tekijä kasvihuonepäästöissä. Täten on tärkeää kehittää ja valjastaa käyttöön kestävän kehityksen mukaisia energianlähteitä korvaamaan fossiiliset energianlähteet.

Tämän projektin toimeksiantona oli tehdä pienikokoinen yksiakseliseuraaja mittaamaan kaksipuolisten paneeleiden suorituskykyä verrattuna yksipuolisiin paneeleihin. Suuntaa-antavina verrantoina annettiin pari olemassaolevaa vastaavaa laitetta. Lisäksi laitteen piti olla verrannollinen kaupallisiin suuriin järjestelmiin. Kaksipuolisten paneeleiden ominaisuuksista seurantalaitteissa ei ole paljoa mittausdataa saatavilla ja tämän laitteen kautta saadaan lisää tietoa kaksipuolisten paneeleiden potentiaalista.

Laitteen suunnittelussa kiinnitettiin huomio aiempiin tutkimuksiin kaksipuolisista paneeleista ja niiden toimintaolosuhteista, sekä seurantalaitteista, joissa käytettiin yksipuolisia paneeleita. Aiemman datan avulla tästä yritettiin tehdä validi ja mukautettava kokonaisuus, jolla voidaan tehdä monipuolisia mittauksia muokkaamalla mittausolosuhteita.

ASIASANAT:

aurinkoenergia, kaksipuolinen aurinkopaneeli, aurinkoseurain

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DESIGN OF A BIFACIAL SINGLE-AXIS SOLAR TRACKER

Climate change is a threat to the well being of life in the earth in the future. Energy industry is a major factor in greenhouse emissions. Therefore it is important to develop and harness sustainable energy sources into use to replace fossil fuels.

Goals of this project was to make a small single axis solar tracker to measure the output of bifacial solar panels in comparison to monofacial solar panels. Few similar systems were gives as guidelines for the design. Additionally the system needed to be comparable to commercial large scale systems. There is not a lot of measured data available for bifacial solar panels in tracking systems. This system will be another device to add data in the possibilities and potential of tracked bifacial panels.

In the considerations of the design of the system attention was given to data from bifacial solar panels and tracked monofacial solar panels. Previous data was used to make this system a valid addition in the field with adjustable parameters to increase the long term usefulness of the device.

KEYWORDS:

solar energy, bifacial solar panel, solar tracker

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USED ABBREVIATIONS OR VOCABULARY

Abbreviation	Explanation
AM	Air mass
PV	Photovoltaics
FiT	Feed in Tariff
ppm	Parts per million
CO_2	Carbon dioxide
C-Si	Crystalline Silicon
UTC	Coordinated universal time

1 INTRODUCTION

The assignment of the project was to build a 1 axis bifacial tracker that is small enough to be moved to another location with moderate effort by two persons. The goal is the aquire more data of bifacial solar tracking. Hypotethically the result should be further improvement of energy output and cost efficiency.

Given sources of inspiration for the system were bifiPV workshop of 2019 and Biforot and miniaturized test array in and built by Zurich University of Applied Sciences. Miniaturization of the system was a mandatory function of the design due to lack of space in the property and to reduce the external forces due to wind.

This thesis provides background information why this is a necessary field of research, some basics of solar energy, an outlook to bifacial solar and solar tracking technologies and a review of the case project this thesis is about.

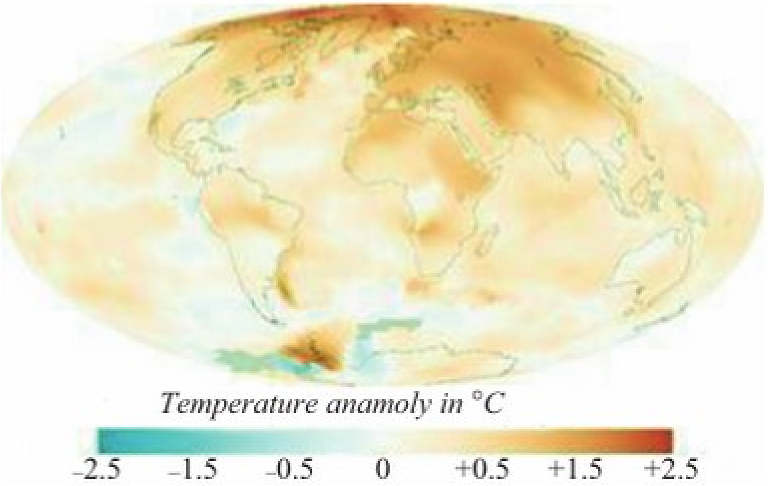
This project was launched by New Energy Research Center of Turku University of Applied Sciences. More information about the projects from New Energy Research Center can be found in www.nerc.turkuamk.fi.

2 PHOTOVOLTAICS

2.1 Drivers for solar energy

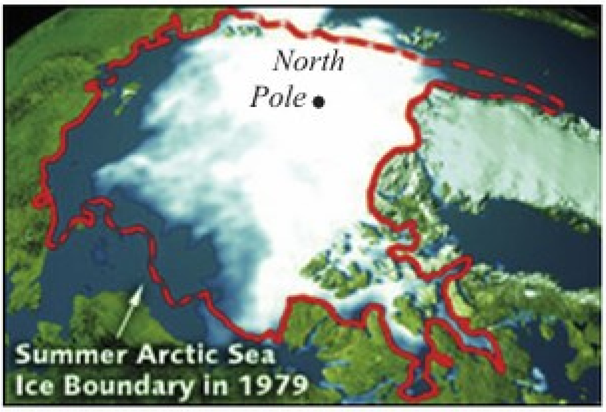
2.1.1 Climate Change

Average temperature has been rising constantly from the beginning of industrialization. This is due to rising CO_2 emissions that began to rise during that period. CO_2 acts as a greenhouse gas in the atmosphere. Greenhouse gases are gases that reflect radiation back towards the Earth, that was reflected from the surface of the Earth into space. Other greenhouse gases in the atmosphere are methane and water vapor. Although water vapor and methane are more potent, their lifespan in the atmosphere is much shorter than CO_2, which has a half-life of centuries in the atmosphere. CO_2 level was at 280ppm before industrial revolution and 393ppm in 2013, making a 40% increase in CO_2 levels. In picture 1 is represented how the northern hemisphere is more impacted by the rise of the global temperatures. (Wong, 2015.)



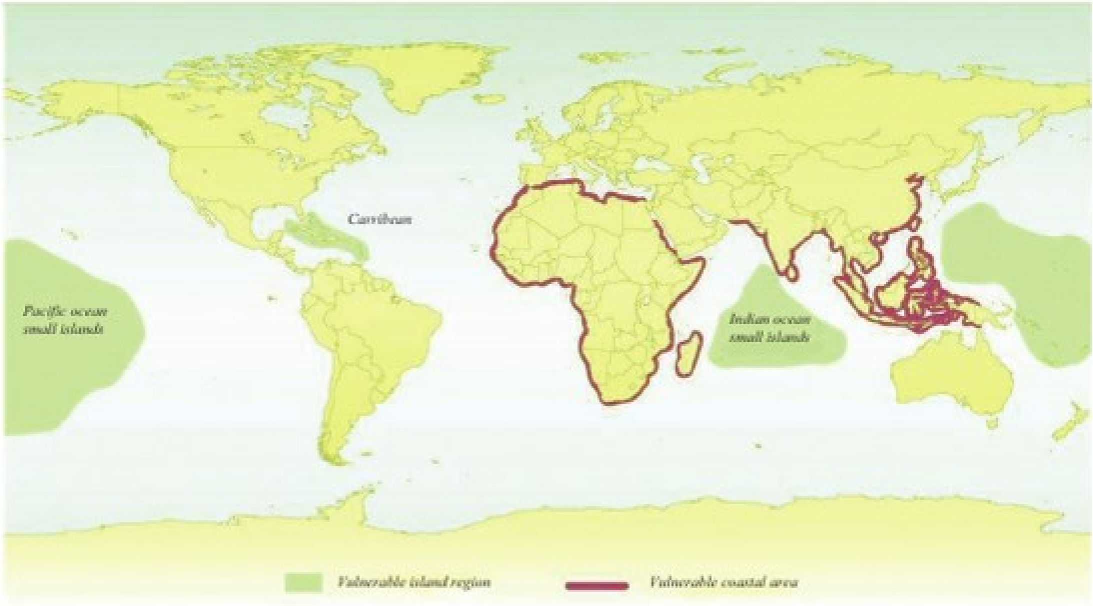
Picture 1 Global mean temperature 2000-2009 in comparison to 1951-1980 mean temperature. (Wong, 2015.)

The rise in temperature is causing the climatic conditions to be out of balance. This provides to the increase in extreme weather conditions, like more extreme storms, droughts, heat waves, hurricanes and tornadoes. As the temperature rises, the melting of arctic ice is accelerated. In current pace, it is possible that in the future there will be no permanent ice in North pole. (Wong, 2015.)



Picture 2 Comparison of arctic ice in 1979 and 2003. (Wong, 2015.)

The melting of the permanent arctic ice and thermal expansion form the warming of the oceans are contrubuting to the rise of sea levels. This puts many populated areas in danger. Including some smaller islands, which may be completely submerged due to the rise of sea levels. Differences in temperatures also threatens many species by reducing their numbers due to the lack of proper living conditions. Mass extinctions of species unable to find new hospitable areas that fill their needs, or lacking the time or skills to adapt to the changing conditions. As the increase in temperature is more impacted in the north, the arctic animals living in north pole are more impacted as their homes are melting in a rapid pace. (Wong, 2015.)

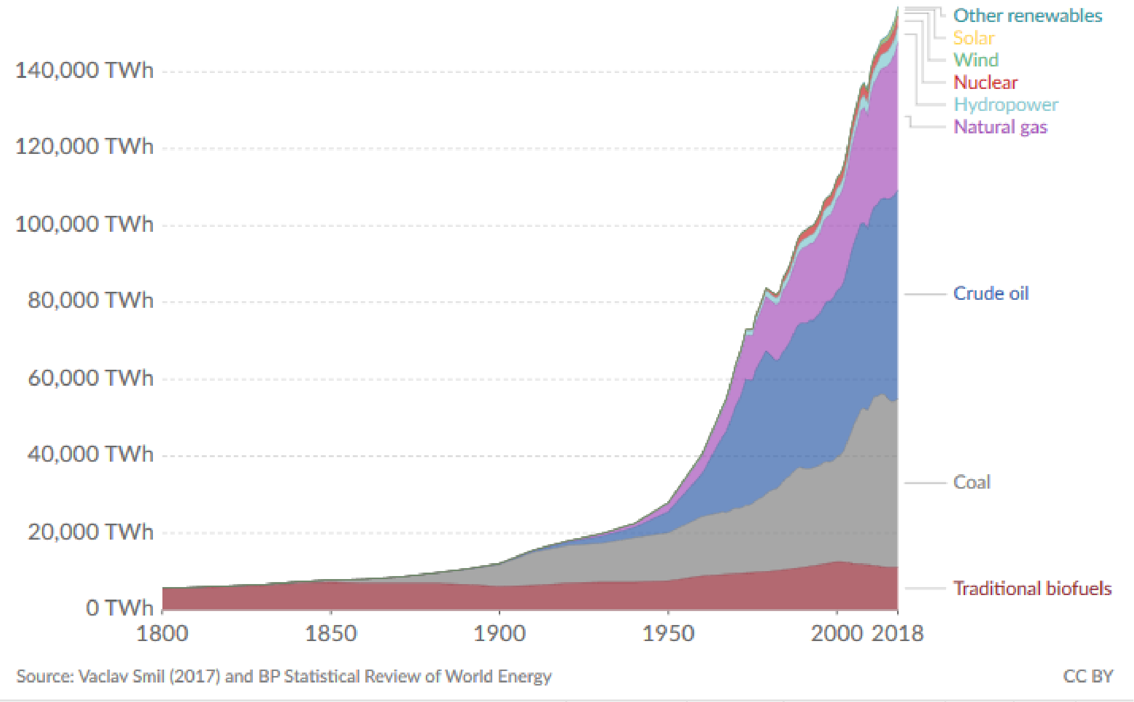


Picture 3 Regions vulnerable to rising sea level. (Wong, 2015.)

Largest impact in the increase of CO_2 levels is caused by the energy industry. Burning fossil fuels have severe environmental impact and it is still used as main source of energy. The energy sector needs to going through major transformation to be compatible with sustainable future. This is done by implementing renewable energies and nuclear energy. The change can be driven by individual people. Making smart decisions everyday, putting pressure on companies and pushing for politicies in the government level that would drive faster transition between the old technologies and the new sustainable technologies. (Wong, 2015.)

2.1.2 Global energy demand

Total energy consimption in 2018 was 160 TWh and the demand for energy is constantly growing. From 1950's the curve has been steep. Despite the high demand for energy and growing environmental concerns the share of consumed energy produced by renewable sources is just a fraction of the total. in 2018 fossil fuels was used to produce 87% of total consumed energy. (Ourworldindata.org, 2020.)



Source: Vaclav Smil (2017) and BP Statistical Review of World Energy

Figure 1 Energy consumption by produced source, 1800-2018. (ourworldindata.org, 2020.)

2.1.3 Fossil fuels in Europe

Fossil fuels are still the main source of electricity in European nations. Only two countries are lower than 40% and 5 under 60% or electricity production share of fossil fuels. Finland produces appproximately 50% of electricity with fossil fuels. (Martins, 2019.)

Burning fossil fuels reduce the quality of air by emitting particulate matter in the air, which can be deadly to humans in high enough concentrations. Additionally, fossil fuel usage increases the amount of greenhouse gases like SO_4 and CO_2, which contribute to climate change. (Martins, 2019.)

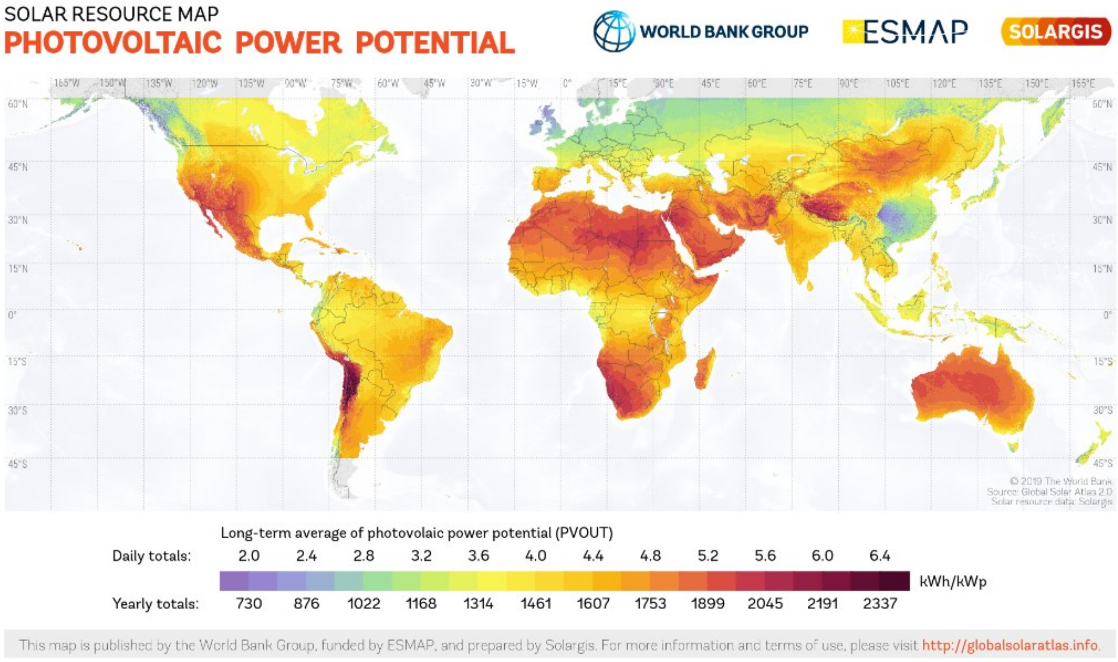
Fossil fuels are an unpredictable market. Fossil fuel reserves like gas, coal and oil, are not evenly distributed. This causes possible fluctuations on prices as availability and political climate can affect the import and export markets. Additionally fossil fuels reduce the quality of air. At the current state there is approximately 50 years before oil and gas reserves are depleted and 150 years before coal reserves are depleted. (Martins, 2019.)

2.2 Amount of available energy

Solar constant, the average theoretical direct radiation from Sun to Earth, is calculated to be 1367W/m^2. Actual solar radiance reaching Earth depends on multiple factors listed in part 2.2.1. (Mertens, 2019.) It is possible in theory to meet the world energy needs by using only 0,4% of the land area with solar energy with a system efficiency of 10%. (Mertens, 2019; Lugue & Al, 2012.)

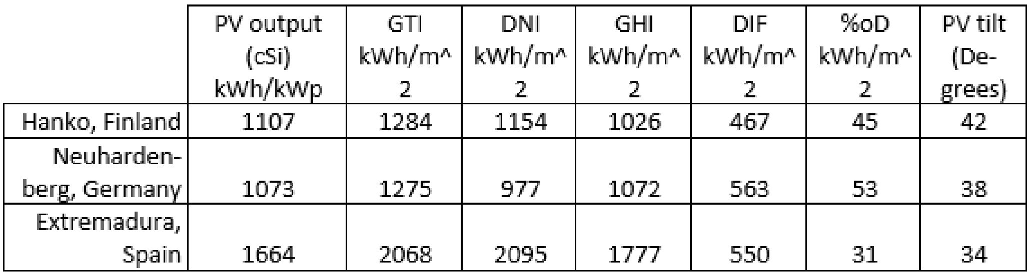
2.2.1 Factors affecting radiation levels

Factors that affect radiation levels are; Location, season, altitude, particles in the air (dust, vapour, pollution, etc) and clouds. Picture 4 presents the importance of location for PV output. (Vaisala Energy, 2020). In general guideline it could be concluded from the map that the most potential conditions for PV systems are when built between the Tropic of Cancer and the Tropic of Capricorn. (Solargis, 2020.)



Picture 4 Global map of PV potential (Solargis, 2020.)

Table 1 Comparison of PV possibilities between Hanko, Finland, Nauhardenberg, Germany and Extremadura, Spain. PV output kWh/cSi: Yearly output of average quality chrystallized silicon PV panels in unit kWh/kWp. GTI: Yearly solar irradiation with optimized angle. DNI: Yearly solar irradiation DNI: Direct normal irradiation per year. GHI: Global horizontal irradiation. DIF: Diffuse radiation. %oD: Percentage of diffuse radiation of direct radiation. PV tilt: optimal tilt angle of PV modules. (Solargis, 2020.)



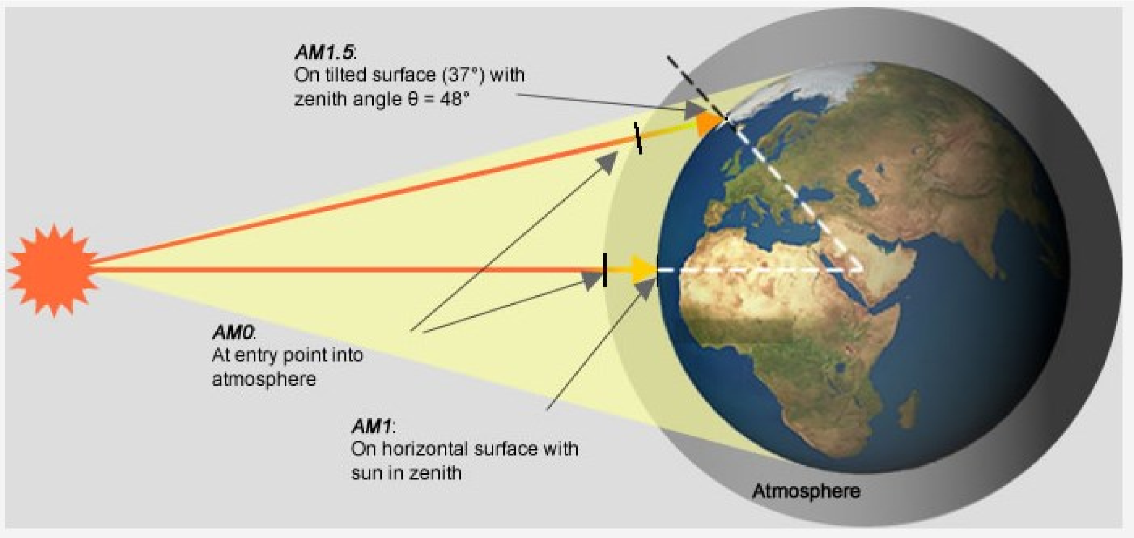
	PV output (cSi) kWh/kWp	GTI kWh/m^2	DNI kWh/m^2	GHI kWh/m^2	DIF kWh/m^2	%oD kWh/m^2	PV tilt (Degrees)
Hanko, Finland	1107	1284	1154	1026	467	45	42
Neuhardenberg, Germany	1073	1275	977	1072	563	53	38
Extremadura, Spain	1664	2068	2095	1777	550	31	34

Table 1 compares solar irradiance data of three different locations in Europe; Extramadura, Spain, Neuhardenberg, Germany and Hanko, Finland. Hanko was chosen as the represantative of Finland as Turku was not available in the dataset. Turku is the location where this project will be built. Neuhardenberg and Extramadura were chosen as there is a large scale PV power plant built in both locations. Fourth largest in Europe in Neuhardenberg and largest in Europe in Extramadura (Chakrabarti 2019). Table 1 is presenting the effect of location in PV output. Germany is a large contributor in PV technology despite the suboptimal geographical location. The results that Germany has accomplished with PV technology show that PV technology can be a major contributor to sustainable energy systems even when being used so far from the equator. Despite the latitude difference of approximately seven degrees latitude between Neuhardenberg and Hanko, the two locations have similiar PV energy outputs. Between Extramadura and Neuhardenberg the difference in output is clear. (Solargis, 2020)

2.2.2 Air mass

Air mass, AM, is an indicator of how much air must the solar radiation pass before hitting the surface of the Earth. AM 1 translates to the lenght of one atmosphere. This happens when solar radiation hits Earth at 90 degree angle. AM 1,5 is approximately the average AM value in a year. Therefore AM 1,5 is used as the value in standard test conditions.

The higher the AM value the more absorption and scattering occurs before the radiation reaches the surface. (Mertens, 2019.)



Picture 5 Visualization of AM (greenrhynoenergy, 2016.)

2.2.3 Radiation diffusion and diffuse radiation

As light passes through the atmosphere, some photons hits particles before reaching surface. This reduces the amount of direct sunlight reaching the Earth, but also increases the diffuse radiation reaching PV systems in couldy weather, where the majority of sunlight reaching the solar panel can be from diffuse radiation. (Mertens, 2019.)

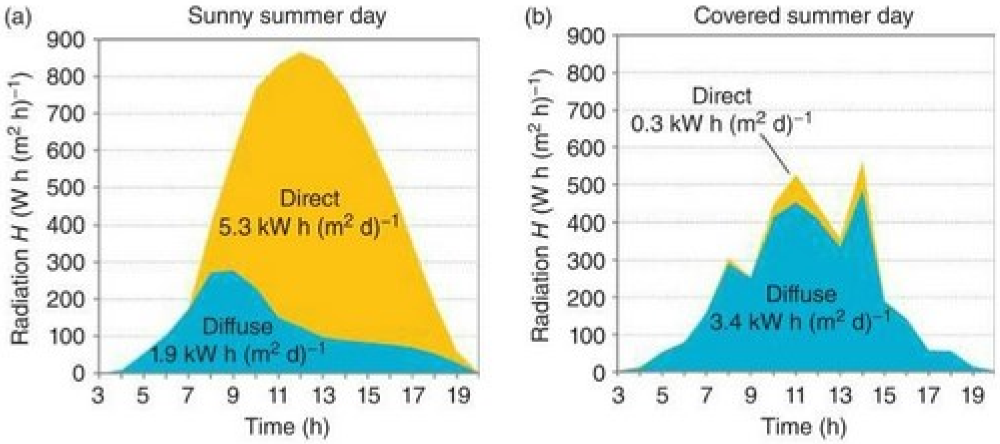


Figure 2 Comparison of the amounts of direct and diffuse radiation between sunny and covered days during summer. Measured in Braunschweig, germany. (Mertens, 2019.)

2.3 PV system

PV system consists of modules, inverter and electrical components, metering devices and frames of the build. It may include a battery as an mean to storage excess energy. (Luque & Al, 2012.)

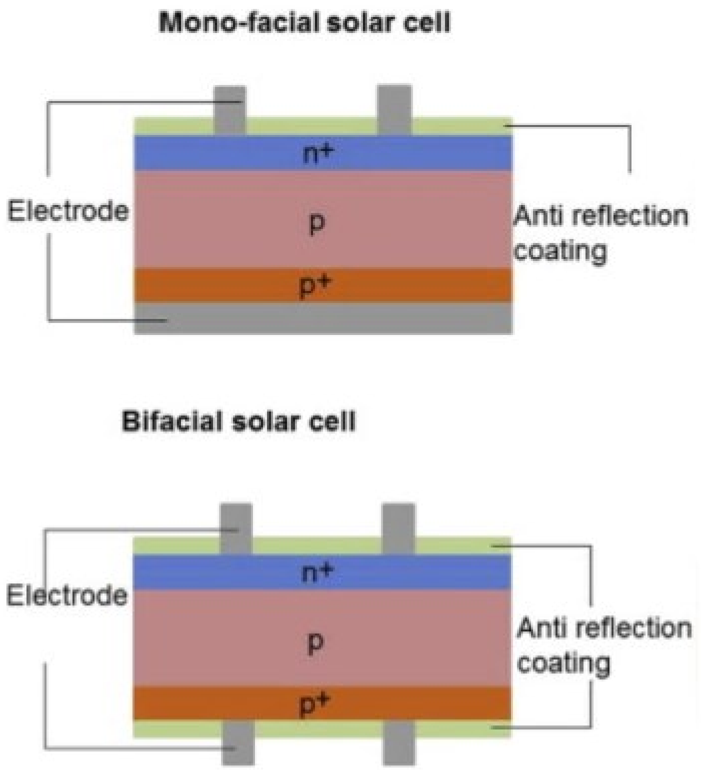
2.4 Bifacial PV

Bifacial technology was first proposed in 1960. The thought of the inventor was to improve the efficiency in long wavelength photons with the backside of the bifacial panel. The inventor of bifacial concept also thought about using mirrors underneath the PV system to improve the total output, by reflecting more irradiance to the backside of the panel. (Duran, 2012.)

Even though bifacial technology is decades old, only now has it began to claim a share of the PV market. This is due to cost efficiency. Despite the slow rise of bifacial PV technology it is estimated to shortly become the dominating PV technology in new investments. (Guerrero-Lemus & Al, 2016.)

2.4.1 Bifacial PV cell and module structure

Picture 6 represents the main difference between bifacial and monofacial cell structure. In bifacial cell the backside is left without cover, so it is possible to harvest solar radiation from both sides.



Picture 6 Standard structures of monofacial and bifacial PV cells. (Shishavan, 2019.)

C-Si technology is dominating the PV market (Cherradi, 2018). Al-BSF technology was the clear leader in C-Si cell technology, but PERC technologies are growing and expected to dominate the market in near future. PERC, PERT, PERL and PERF cell technologies are all labeled under the PERC general category. PERC is predicted to grow to be the most used PV technology in near future. (Aleo, 2020.)

Half cell PV technology could be a choice for certain conditions, as the technology has lower shading losses, but half cell technologies are not as efficient in low light conditions as standard full cut cells (Chiodetti & Al, 2019). In bifacial modules further advantage of half cut PV cells comes from increased benefit of the lower resistance of the half cut cells, as the currents are higher in bifacial PV cells (Cherradi, 2018).

Table 2 Efficiency % and bifaciality% of different bifacial technologies. (Liang & Al, 2019.)

	Efficiency %	Bifaciality %
PERC	20	80
PERL	20	89
PERT	21	85
IBC	23	75
HIT	25	95
DSBCSC	22	74

Bifacial PV modules are built with different structures; Glass/glass and glass/backsheet. Glass/glass modules are the common bifacial PV module structure. The advantage of glass/glass module is the additional collected radiation reflected from the surroundings due to transparent backside of the PV panel. (Singh & Al, 2015). The performance of bifacial module may be enhanced with a reflecting backsheet. (Mittag & Al, 2017.)

2.4.2 Parameters affecting the backside performance of a fixed bifacial PV panel

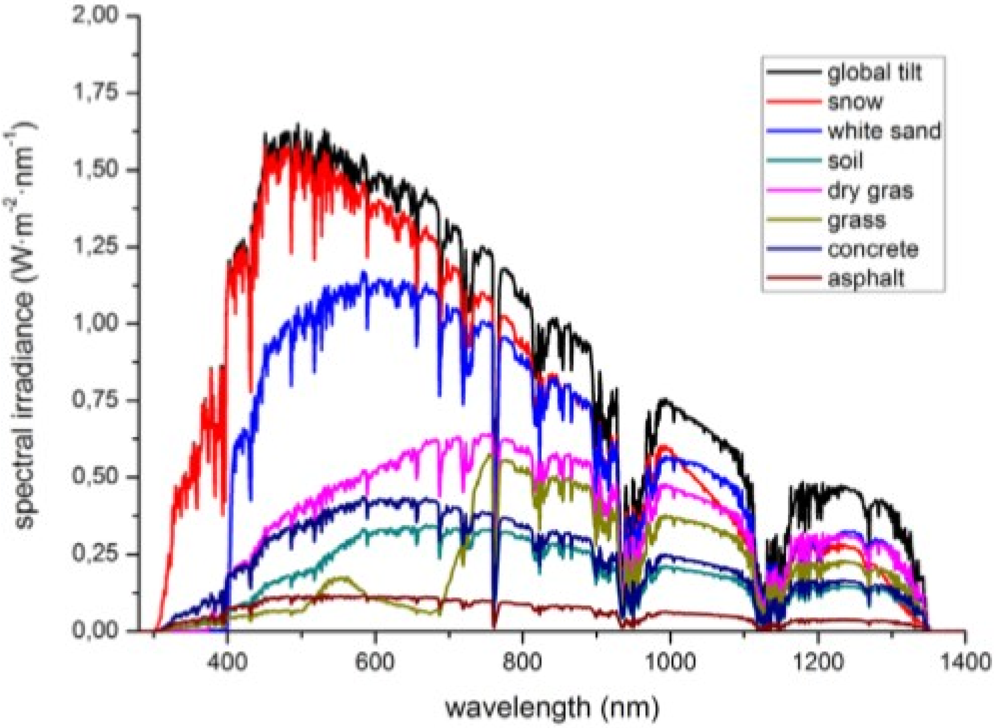


Figure 3 Reflected irradiance of different surfaces. (Guerrero-Lemus & Al, 2016.)

Figure 3 presents measured spectral irradiation of different materials and therefore presents their potential to be used as material under the bifacial PV system to boost the electricity output of the backside. Additional difference seen in figure 3 is the amount of differing wavelenghts each material irradiates. Different PV technologies excel in different wavelengts making this a considerable variable when selecting the optimal combination of surrounding material and PV technology. (Guerrero-Lemus & Al, 2016.)

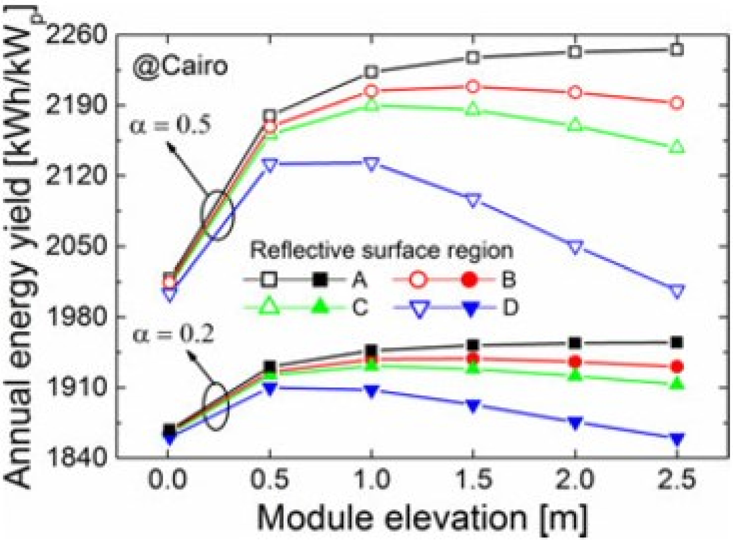


Figure 4 The effect of albedo, reflective surface area and elevation in annual energy yield at optimal angle in Cairo. (Yusufoglu & Al, 2015.)

The letters representing the reflective surface region in figures 4 and 5 are A=100m x 50m, B=15m x 7,5m, C=10m x 5m and D=5m x 2,5m. These figures represent two very different conditions and how the different factors affect the production. In both Cairo and Oslo it is clear that the larger the size of the relfecting surface, the better the production. Surface region C is the the closest representation of practical implementation possibilities. (Yusufoglu & Al, 2015.)

For both albedo coefficients, 0,2 and 0,5, the results show the same pattern. The difference is that with higher albedo coefficient the differences between the different conditions are magnified. (Yusufoglu & Al, 2015.)

The difference between the two locations is the effect in module elevation. In Oslo the highest energy output generally is with 0,5m elevation. Exception to that is with the surface region A, which shows slightly increased production in 1,0m elevation. In Cairo the measures show that the larger the reflecting surface area, the higher should be the elevation of the panel. If the panel is elevated too much in comparison to the reflecting surface area, the panel output drops significantly. (Yusufoglu & Al, 2015.)

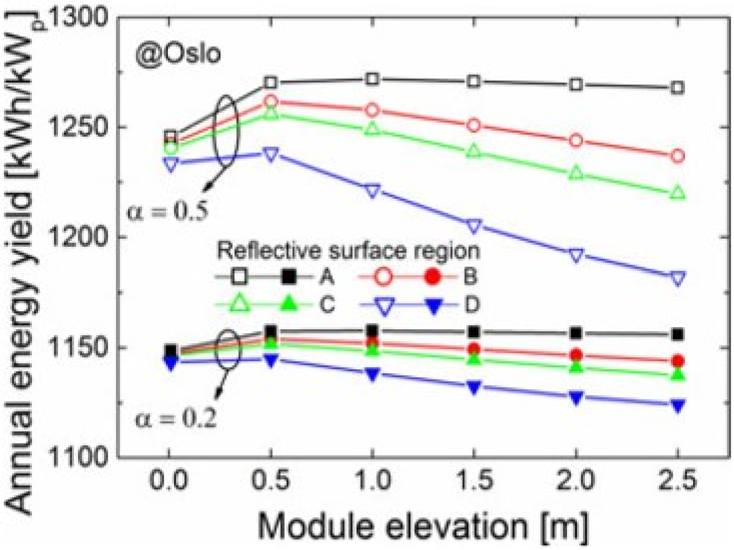


Figure 5 The effect of albedo, reflecting surface area and elevation in annual energy yield at optimal anglein Oslo. (Yusufoglu & Al, 2015.)

Similiar to installment height, PV system row spacing needs to be taken into account when optimizing the backside production of the bifacial PV panel. If the panels are too close to each other, panels will reduce the reflected irradiance reaching the backside due to row shading. (PI Berlin, 2019.)

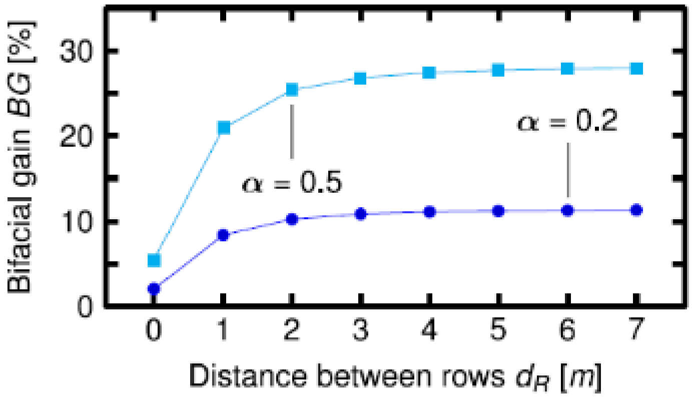


Figure 6 Bifacial gain in relative to row spacing in albedo 0.2 and 0.5. (PI Berlin, 2019.)

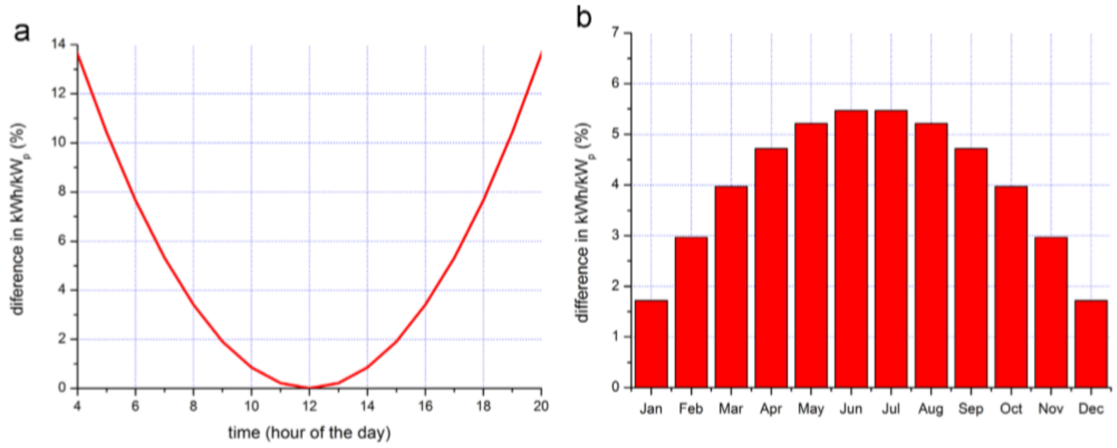
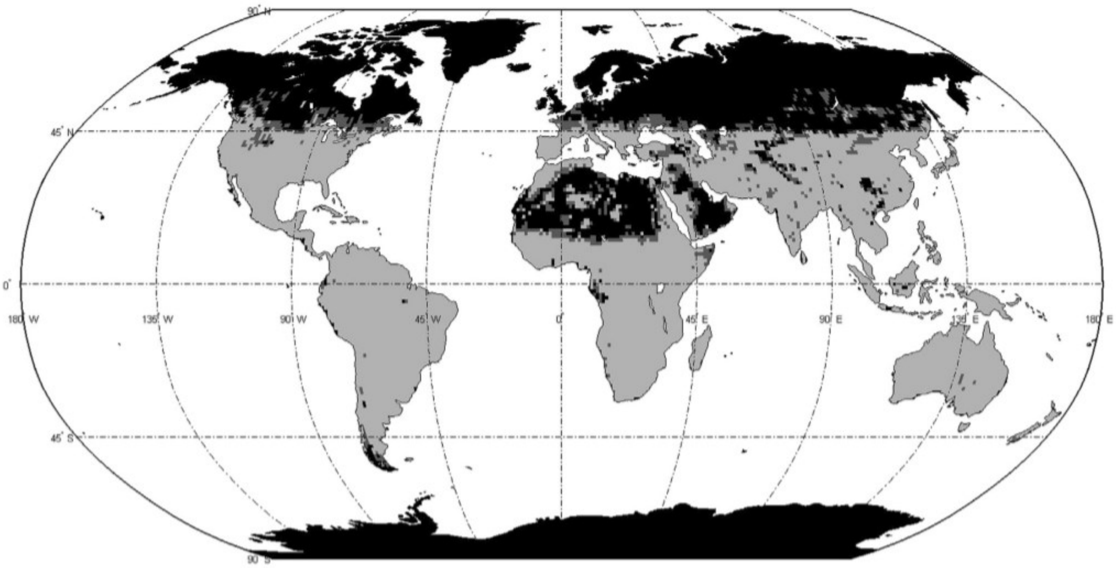


Figure 7 Daily and monthly percentual increase of production for bifacial PV panels in comparison to monofacial PV panels. Measured in the Netherlands. (Guerrero-Lemus & Al, 2016.)

Figure 7 section a shows increase of production in similiar times of day as the effect on tracking of a monofacial PV panel shown in figure 9. (Guerrero-Lemus & Al, 2016.)

2.4.3 Vertically mounted bifacial PV

Bifacial modules are more versatile, due to two sides collecting the solar radiation. Bifacial modules can be installed facing south the same way as monofacial panels or vertically in an east-west position. A tested practical example of vertical bifacial PV is the usage of bifacial PV as road side barriers. This method is calculated to be more effective than south-facing monocafial modules mainly in northern hemisphere, as presented in picture 7. (Guo & Al, 2013.)



Picture 7 World map representing which technology is better in different locations; conventional monofacial PV, or vertical bifacial PV. Black: Vertical bifacial. Light grey: Conventional monofacial. Grey: Both technologies have similiar performance. (Guo & Al, 2013.)

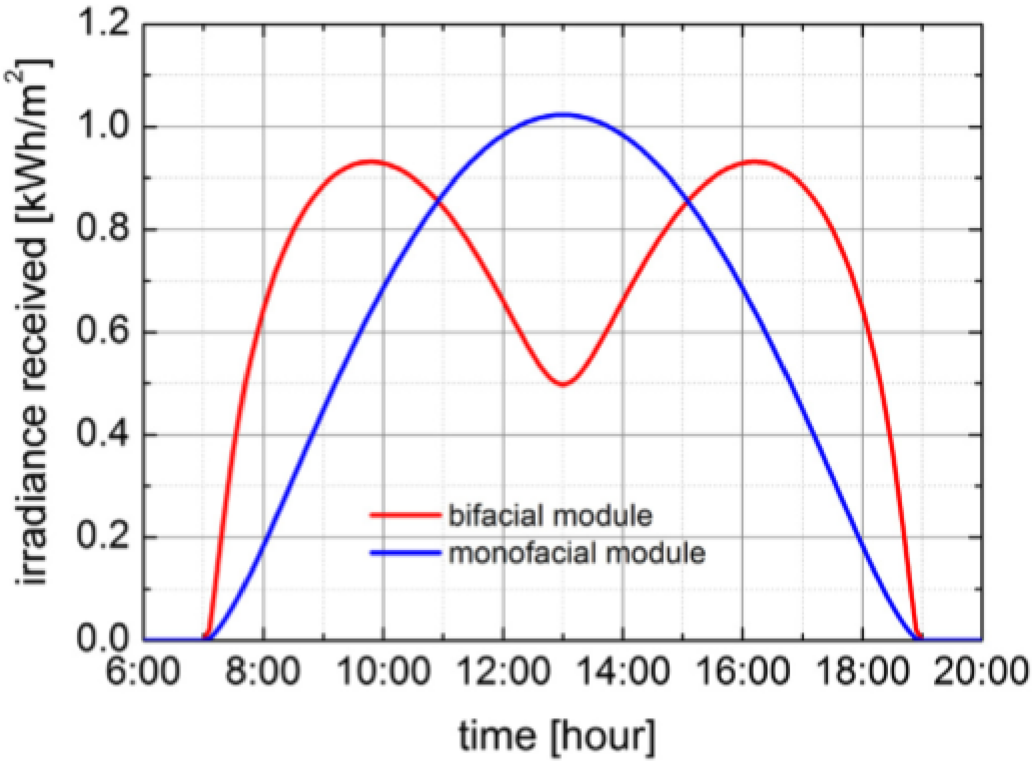


Figure 8 Simulated comparison of radiation reaching south tilted monofacial module and east-west mounteed bifacial module in clear sky condition in Singapore. (Guo & Al, 2013.)

Figure 8 presents additional benefit of vertically mounted bifacial module in comparison to south facing monofacial module. Two peak production times improves the grid conditions and provides electricity for a longer window of time. (Guo & Al, 2013.)

2.5 Solar tracking

As Earth rotates the sun and its own axis, sun is not in a constant position in the horizon. Therefore there is not one optimal angle for solar panels from which the surface of the solar panel could be directed directly towards the sun at all times. In theory the goal of sun tracking is to have the PV panel directed directly towards to sun at all times when the sun is above the horizon.

Table three presents the potential of a single-axis solar tracker. The amount of solar radiation reaching the surface is notably higher than in any other method.

Table 3 Average daily solar radiation (kWh/day). (Chen, 2011.)

Latitude in degrees	30	40	50	60
Vertical, Facing south	3,72	4,57	5,25	5,60
Vertical, facing east or west	3,31	2,93	2,46	1,91
Horizontal	6,25	5,43	4,39	3,11
Latitude tilt facing south	7,27	7,21	7,08	6,77
Optimum single-axis tracking	11,50	11,50	11,50	11,50

2.5.1 Tracking methods

Tracking methods can be divided into passive and active. Passive methods use mechanical system to achieve tracking capabilities. This relies on thermal expansion caused by the heat in solar radiation. Therefore passive systems does not work properly far from the equator as they need a constant source of heat to operate the system. Active methods use an internal system function that is used to calculate and adjust the system position. Integral parts of the active tracking method are motor, control unit and coded software. In multi axis systems motors can be installed in each axis, or one motor, which is used to rotate multiple axis with mechanical means. Software can run by only mathematical means of predicting the Suns movement or it can use external measured data, like solar irradiance, to determine the correct angle of the panels. (Pulungan, 2018.)

Calculations for the tracking system requires information about the coordinates of the PV system. The sun tracking requires information about the Cartesian coordinates of the Suns position. Cartesian coordinates requires a direction and height and is measured from the observer. In the case of solar tracking is the PV panel is the observer in the coordinates system. (Chen, 2011.)

2.5.2 PV trackers

PV trackers comes in two forms; single-axis and double-axis. Single-axis trackers have one rotating axis. Single-axis trackers are used as so called east-west-trackers, following the altitude of the sun. Double-axis trackers are more complex structures as they need to be able to track both azimuth and altitude of the sun. The geographical location of the tracker affects the recommended choise for the tracker type. Single-axis trackers may be a more practical solution near equator, as the solar altitude does not have such a degree of variation. (Pulungan, 2018.)

Figure 9 presents data measured with a 9W solar panel on a span of clear days with similiar conditions for fixed panel and panel with a single-axis tracker. Fixed panel produces close to the maximum output value of the panel for appriximately two hours. Tracking panel produces close to maximum output value for approximately 5 hours. If no storage for excess energy is avalable, the tracker system gains extra benefit for the longer term stability of the production. Total output percentages of the panels for a 12 hour period were 39% for the fixed panel and 71% for the tracking panel. The power usage of the tracker was measured to determine the overall power efficiency of the system. When the power usage is substracted from the total output, the total efficiency is approximately 69%. (Rizk, 2008.)

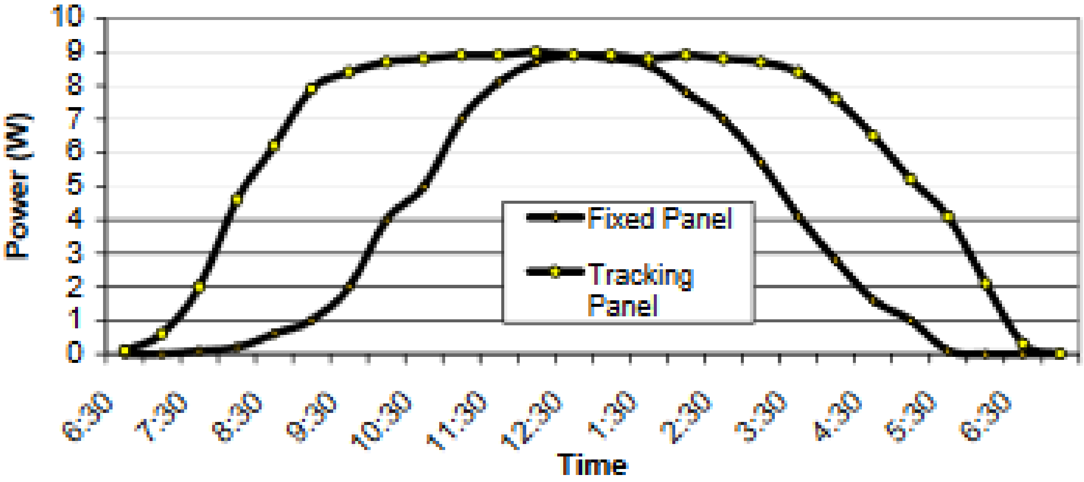


Figure 9 Comparison of output (W) for fixed panel and a tracking panel. (Rizk, 2008.)

On average the electricity output increase in single-axis tracker system is 27-32% and in dual axis system 35-40%. When calculating the overall value increase of the system, dual axis system has an overall performance multiplier of 1.04 compared to fixed panel system. Single axis tracker has an overall performance multiplier of 1.35 in comparison to a fixed panel system. Due to increased system cost in building and maintenance of a dual axis system the overall system performance is reduced, despite the improved output of a dual axis system. (Ray & Tripathi, 2016.)

2.6 Impact of policies for the growth of PV, Case: Germany

Germany has a long history of supporting PV technology. First grid connected installation was built with government support in 1983 producing an output of 4 kWp. In 1989 the total PV installation capacity reached 1MWp. (Lugue & Al, 2012.)

In 1990 Germany lauched a program called 1000 roofs. The goal of the project was to gain data and experience from cheap and reliable roof-mounted PV systems, their output and the effective use of the energy and effects on the grid. First plan was to built 1500 roof oriented systems with no trackers. The number was extended to 2250 systems. (Imamura, 1994). The total capacity of these installed systems were 5,3MWp in the span of 5 years the project was ongoing. The project was monitored very closely to bring more knowledge about the technology and its usage. This experiment was the inspiration for for further subsidy policies for PV technology. (Lugue & Al, 2012.)

Another plan started in Germany in 1990 was the FiT-program (Lugue & Al, 2012). Feed in tariffs are a guarantee for the producer of PV energy that the energy will be purchaced without depending on if the energy is used. The implementation was used to reduce risks and uncertainties from investors to gain more ground and improvement for PV technology. (Mabee & Al, 2012). The implementation of both FiT and 1000 Roofs program sparked the growth for PV. In 1998 The potential of installed PV in Germany was 54MWp (Lugue & Al, 2012).

In 1999 Germany lauched the 100 000 Roofs – program. The goal was to reach 300MWp in a span 6 years time. Methods to reach this goal were an increase in paid FiT and a reduced interest rate for loans for PV installations, starting at 0% interest rate. The aims of the program was to grow the PV market, brings more jobs, reduce CO_2 emissions, reduce cost of PV technology and increase the knowledge of the systems and technology. During the program (1999-2003) applications were accepted to install 345,50MWp of PV. (Stryi-Hipp, 2004.)

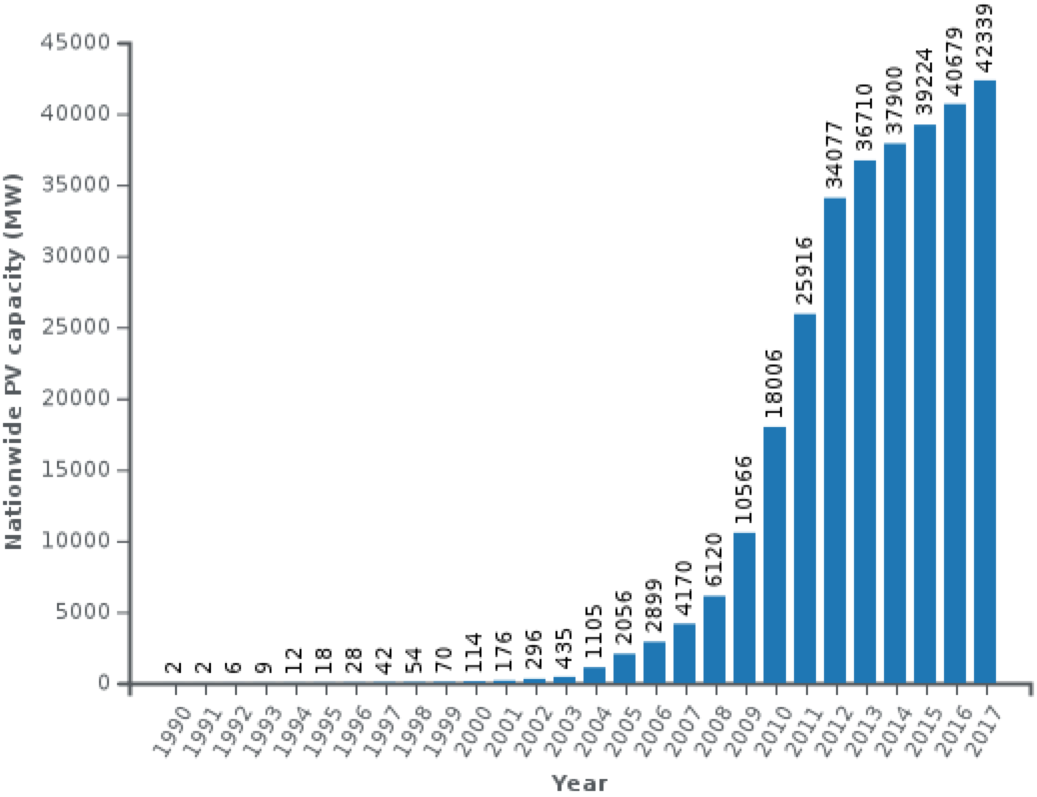


Figure 10 PV capacity in Germany 1990-2017. (BMWi, 2020.)

Additional benefit of the growth of new technolgy is the new need for workers. The effect in job creation of renewable energies in Germany can be seen in figure 11.

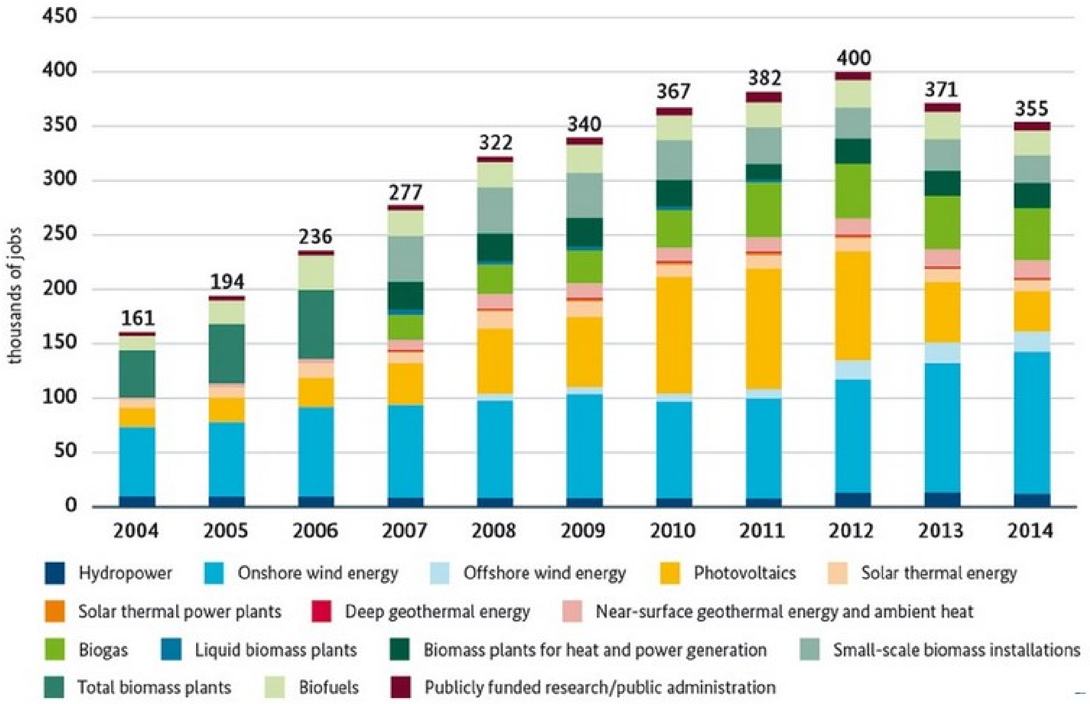


Figure 11 Jobs in renewable energy sector in Germany 2004-2014. (BMWi, 2020.)

2.7 Predictions of PV future

A study made 3 different models to predict the road map of solar energy to 2050. These models represent very optimistic, optimistic and pessimistic predictions of how solar energy will grow and overcome current issues of the technology. Figure 12 shows a visual representation of the three predictions. Main problems, that hinder the growth and needs solutions, are cost, efficiency, building integration and storage of energy. (Obeidat, 2018.)

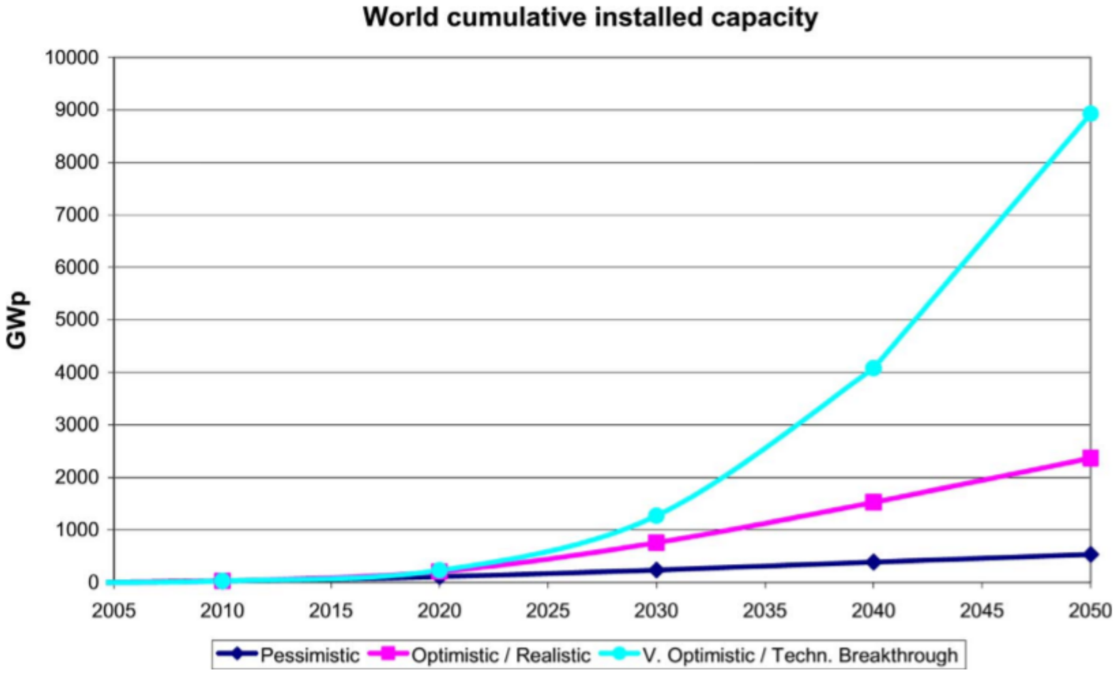


Figure 12 Prediction of installed PV capasity in three different scenarios. (Obeidat, 2018.)

Pricing is an important factor in the growth of PV technology. It is expected that the cost of PV systems continues to decline. Figure 13 represents the percentual value how the system cost and it’s components are predicted to decline until 2029. (ITRPV, 2019.)

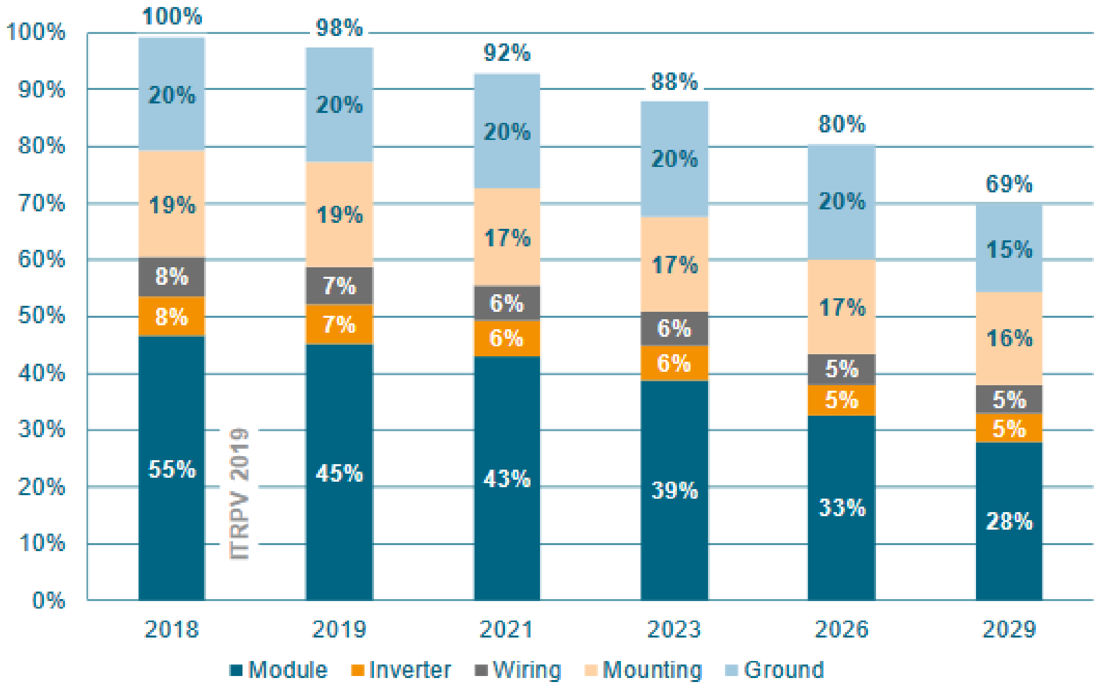


Figure 13 Cost structure and reduction for >100kW PV systems in Europe. (ITRPV, 2019.)

The market share percentage of c-Si PV systems installed with a single-axis system is expected to rise from approximately 30% in 2018 to 55% in 2029, making single-axis tracker installments most common installation method. 2-axis tracking system market share is predicted to stay at 1% between 2018 and 2029. (ITRPV, 2019.)

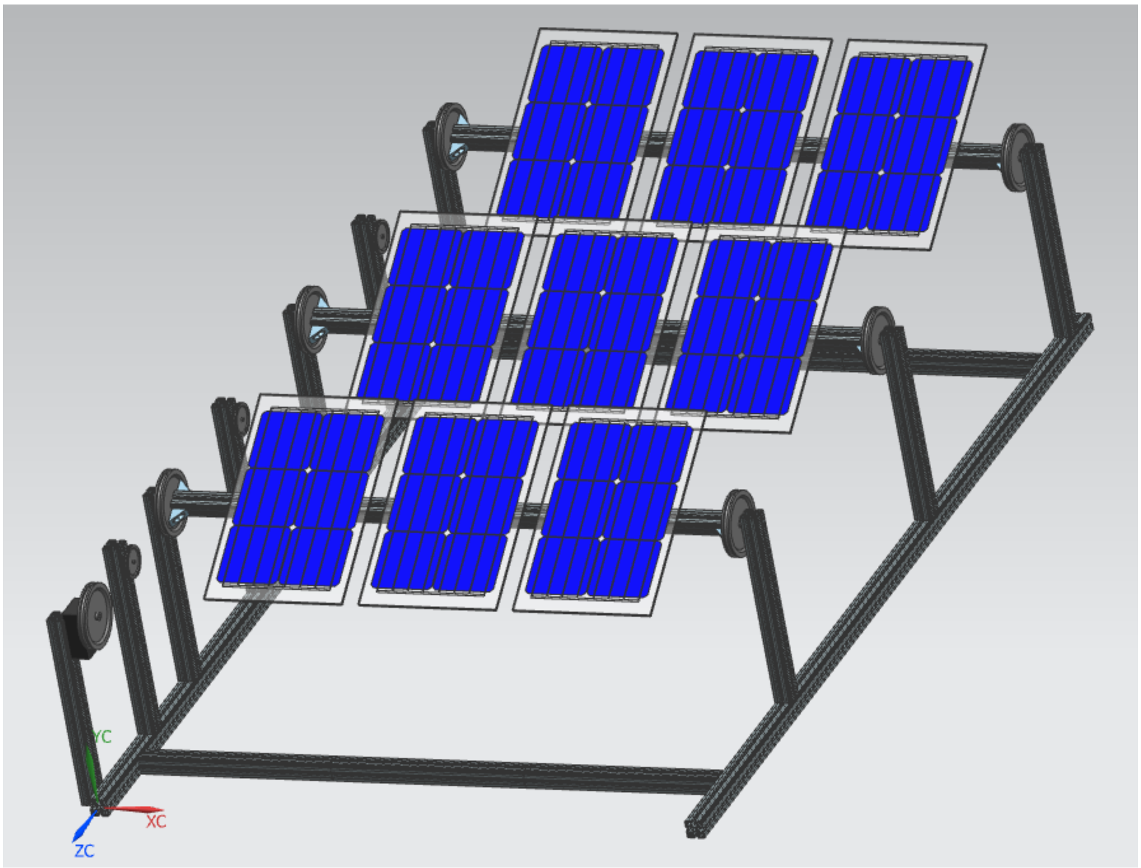
3 DESIGN OF A MINIATURIZED SINGLE AXIS TRACKER

The goal of the project was to build a single axis bifacial tracker that is small enough to be moved to another location with moderate effort by two persons and that fits on the limited space dedicated for the system on the roof where the system will be built, but large enough that the solar panels can be built from single solar cells and that the system will not be buried under minor amounts of snow. A compromise that provides solid data and has a well presentable appearance. Inspiration for sizing and styling was given by Biforot and Miniaturized test array, both located in and build by Zurich University of Applied Sciences (Nussbaumer, 2019), and commercial systems as the system should provide representative data of a full sized commercial system. Example of a commercial solar farm with a single-axis tracker can be seen in picture 8.

Picture 8 A solar farm with single axis trackers. (Bebon, 2016.)

3.1 First design

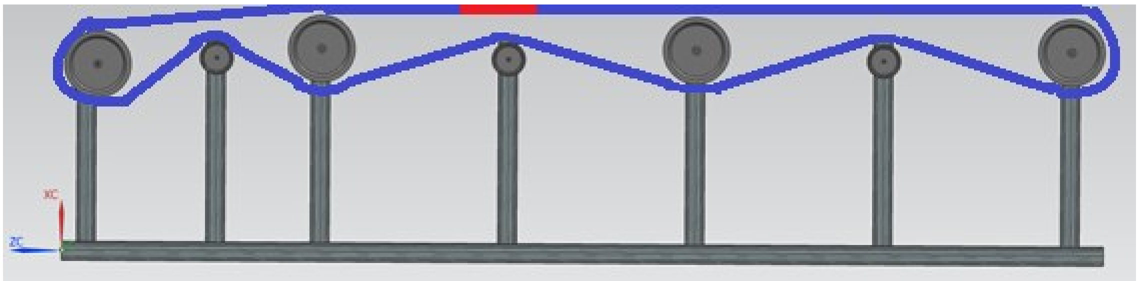
The model seen in picture 9 is a based on some of the early drafts for the system. The first design was lead by the sizing and drivetrain of the tracking system. The version was never finished as new information was found and better designs were though.



Picture 9 A representative model of the first design stages.

The original sizing of the frame was lead by portability of the system. The plan was to make it fit into a Volkswagen Transporter, which was said to be the car used to move the system to another place. The measurements of the smaller version on the Volkswagen Transporter are 2572mm in lenght measured at the longest point and 1244mm in widht measured in narrowest point (Vanguide, 2020.). The goal was to maximise the lenght of the system with the boundaries given. It was not possible to make the system horizontally fit the dedicated van, so some disassembly would have been necessary.

The tracking system had three stepper motors with worm gears, one per axis. Worm gears would be needed as the stepper motor would wear with an excessive rate with a constant load and still may not be able to hold the axis in the correct position. Worm gears would be used to lock the position of the panel in a passive and mechanical way. The design was considered to be too complex. Second worm gear design had one larger stepper motor with a worm gear located at the front of the system. The second worm gear deisgn is the one modeled in picture 9. Sheaves are installed to each axis and the motor. A wire would go around all the sheaves working as the method of turning the axis, adjusting the angle of the panels. A potential issue with the wire design is the uncertainty if the wire is able to hold the angle of the axis when affected by external loads. Wire could have been replaced with a chain and sheaves with gears, but it would increase the cost without cenrtainty of solving the potential issue. This design was scrapped due to the complexity and uncertainty of the system.



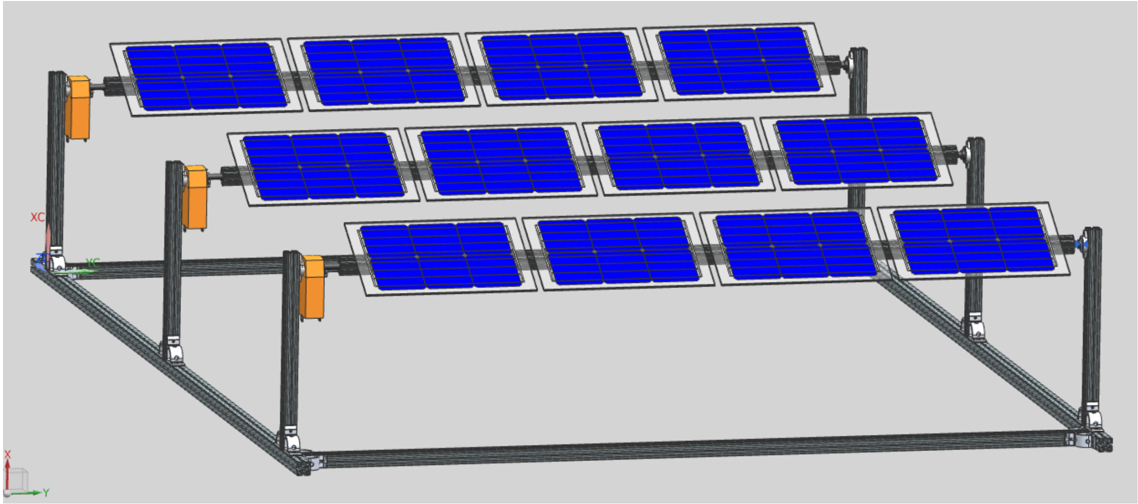
Picture 10 Wheel system of the first design.

Picture 10 presents the pattern for the design of the wheel system. Blue line represents the path of the wire and red represents the place for a component that would be used to adjust the lenght of the wire to keep the wire tight. If the wire is too loose it would not be able to turn the sheaves in the correct position or hold the correct position.

At the beginning the plan was to use small commercial bifacial PV panels, but no ideal choise was found for the scale. It was then decided that the panels for this project will be built from single bifacial PV cells. Scale for the panel was decided to be approximately 1:6 of full a scale 60 cell PV panel. There was an idea to build all three 1:6 panels of a row under one glass frame, which would be connected to the frame from each side. This would leave out the torque tube, which would reduce the shading loss under the panel. This design was scrapped, because it is not used in a full sized commercial systems this system is trying to simulate. The first design had three panel rows with three panels per row. The center panel of the system would be the only one being measured, as it represents the majority of the panels in a full sized system due to being surrounded by other panels. Surrounding panels provide possible shading losses for direct and scattered irradiation. Panels were planned to be mounted in a vertical position to make the system more compact in horizontal axis.

3.2 Final design

A model of the final version is seen in picture 11. The main goal for this model was to ensure the best data by removing some of the former limitations.



Picture 11 Model of the final version.

For the final model it was deemed necessary to get another datapoint in the middle of the system. This increases the amount of panels per row from three to four. The other middle point is used to install one monofacial PV panel next to the bifacial PV panel for data comparison to get further knowledge of the performance of bifacial PV techonlogy with a single axis tracker.

After further research of the necessary distance between the panel rows it was deemed necessary to remove the size restrictions based on the size of the van. The necessary distance was determined by the equation presented in Handbook of photovoltaic science and engineering, by Luque & Al, 2012.

$$GCR = \frac{c}{d}$$

In the presented equation GCR means ground cover ratio, c represents the lenght of the panel and d is the amount of space needed before next panel. Typical GCR values with single axis trackers are between 0,35 and 0,5. For a tilted single-axis tracker the GCR value should be approximately 0,2. (Luque & Al, 2012.)

Table 4 Lenght of a 3-axis system depending on GCR and panel mounting.

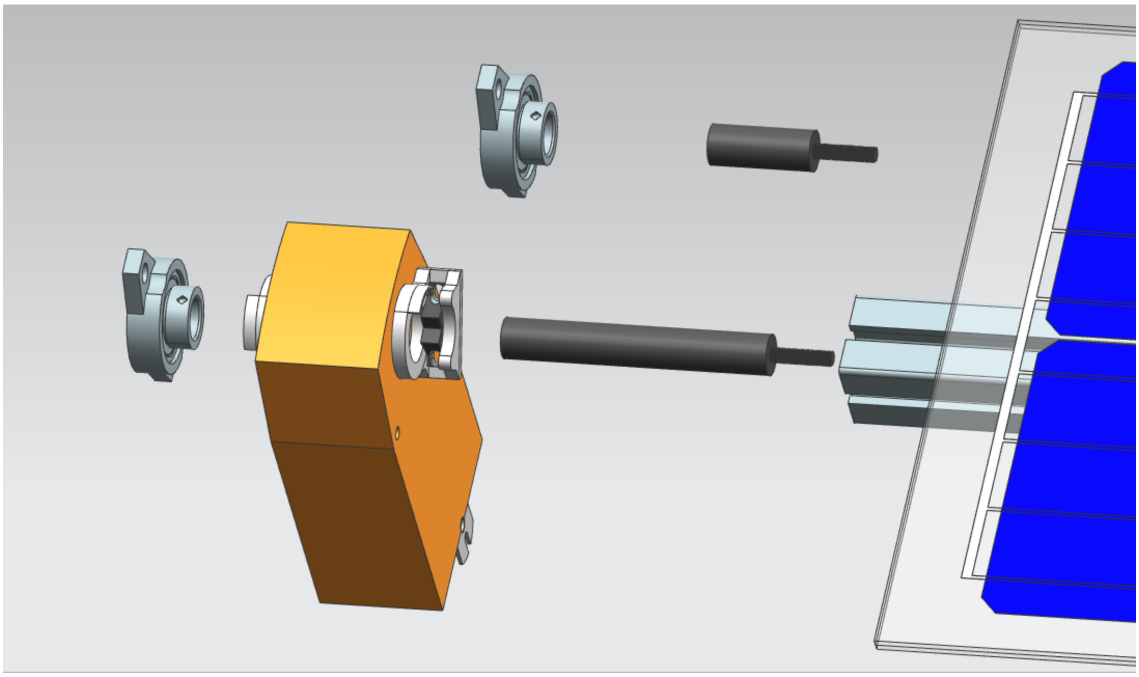
	GCR=0,2	GCR=0,35	GCR=0,5
Horizontal	3590mm	2040mm	1428mm
Vertical	5680mm	3246mm	2272mm

The sizing of the system was determined from the values presented in table 5. The panels were turned to a horizontal position to enalbe the possibilities to test the use of a tilted position withing the recommended margin. By turning the panels to reduce the excessive longitudal expansion of the system it was necessary to increase the widht. In the final system the longitudal beams are 3560mm in lenght and horizontal beams 2618mm in width. The system can be tested with vertical panel mounting using leveled positioning to explore the differences between mounting methods.

First guideline for the height was two similiar systems in bifi PV workshop, Klenk & Al and Guerrero. After calculating what would the height if this system be if calculated the height to the relative of the lenght of the panel when compared to the systems represented by Klenk and Guerrero. With horizontal panel mounting the calculated height would have been 240mm or 270mm, depending which study was used as a base point. It was decided to be too low. As can be seen in figure 5, the output of the backside of the panel is rising significantly until 0,5m. The vertical beams are 650mm in height and are mounted on top of the longitudal beam 45mm above the ground level giving them a total height of 695mm. The maximum level of the panels are slightly below that. It is possible to alter the height of the system. This makes it possible to test the affect of height for the output of bifacial PV and monofacial PV panels with a tracking system.

Stepper motor with worm gear was replaced for the final version with three damper motors, one per axis. Damper motor is simple to program and can hold loads by itself. This removes the need for other components, like worm gears, making the system simpler. The trade off of the damper motor is that it can rotate only 95 degrees instead of the generally used 110 degrees. This will slightly reduce the capability of the system, and therefore may reduce the authenticity of the data it provides.

The axis connection for the final version, Which is visible in picture 12, was made with a focus on simplicity and reliability. This system uses a pole with threads on each side. The poles will be screwed directly to the torque tube and other side will connect directly to bearing, which is bolted to the vertical post of the frame. The pole is longer n the other side the of the torque tube, as it needs to go through the damper motor. The damper motor will be connected to the pole and turn the torque tube.



Picture 12 Design of the axis connection of the final version.

3.3 Code for the tracker

Tracking system is planned to be done with Codesys-program using structured text. Code will be loaded into a PLC unit. Another student will do the coding for this project.

There is no simple way to do the equations with standard codesys libraries, but additional libraries can be downloaded from OSCAT. File oscat_basic_333 can be found on OSCAT-library. This includes the SUN_POS-function that can be used to calculate the position of the sun. This includes three input values: latitude, longitude and time in UTC.

As output from input values it gives three values: azimuth in degrees from north, astronomical sun height and solar altitude in degrees above the horizon.

For this plan for the code latitude and longitude were taken from latitudelongitude.org with address Lemminkäisenkatu 28, Turku, which is the address where this tracker is planned first to be built. UTC will be given for the SUN_POS function with the CAARealTimeClock-function, which can be downloaded as an additional library for Codesys. CAARealTimeClock is used to gain access to the current time, which is mandatory for the tracker.

Table 5 Input and output of the SUN_POS function

	Inputs:
Latitude:	60,446879
Longitude:	22,298810
UTC	CAARealTimeClock

	Outputs
B:	X
H:	Y
HR:	Z

For outputs the H:Y-value is not used for this project. HR:Z-value can be used if this tracker is used to run tests for altitude tracking systems. Output B:X is used to for the east-west tracker, which is the main function of this system.

If solar tracking is done between azimuth 90 degrees and azimuth 270 degrees, the system starting point will be set to east and the maximum turning point of the system to west. The output voltage to the damper motors that determine the degree of the system will be determined by the equation (V) from the output B:X. The same equation could be run to track solar altitude using output value HR:Z.

$$\frac{8 \times (X - 90)}{180} + 2 = V$$

From the Equation (V) can additionally be calculated the angle of the system with equation (alpha).

$$\frac{95 \times (V - 2)}{8} = \propto$$

Solar path from azimuth angles 0-90 degrees and 270-360 degrees are not necessary to be tracked. Solar radiation intensity is reduced during morning and evening hours so much that the output is not relevant (Energyplus, 2020). Additionally solar altitude is so low (SunEarthTools, 2020) that a large portion of the solar irradiation reaching the panel is reflected away from the panel (Suntekno, 2020; SunEarthTools, 2020).

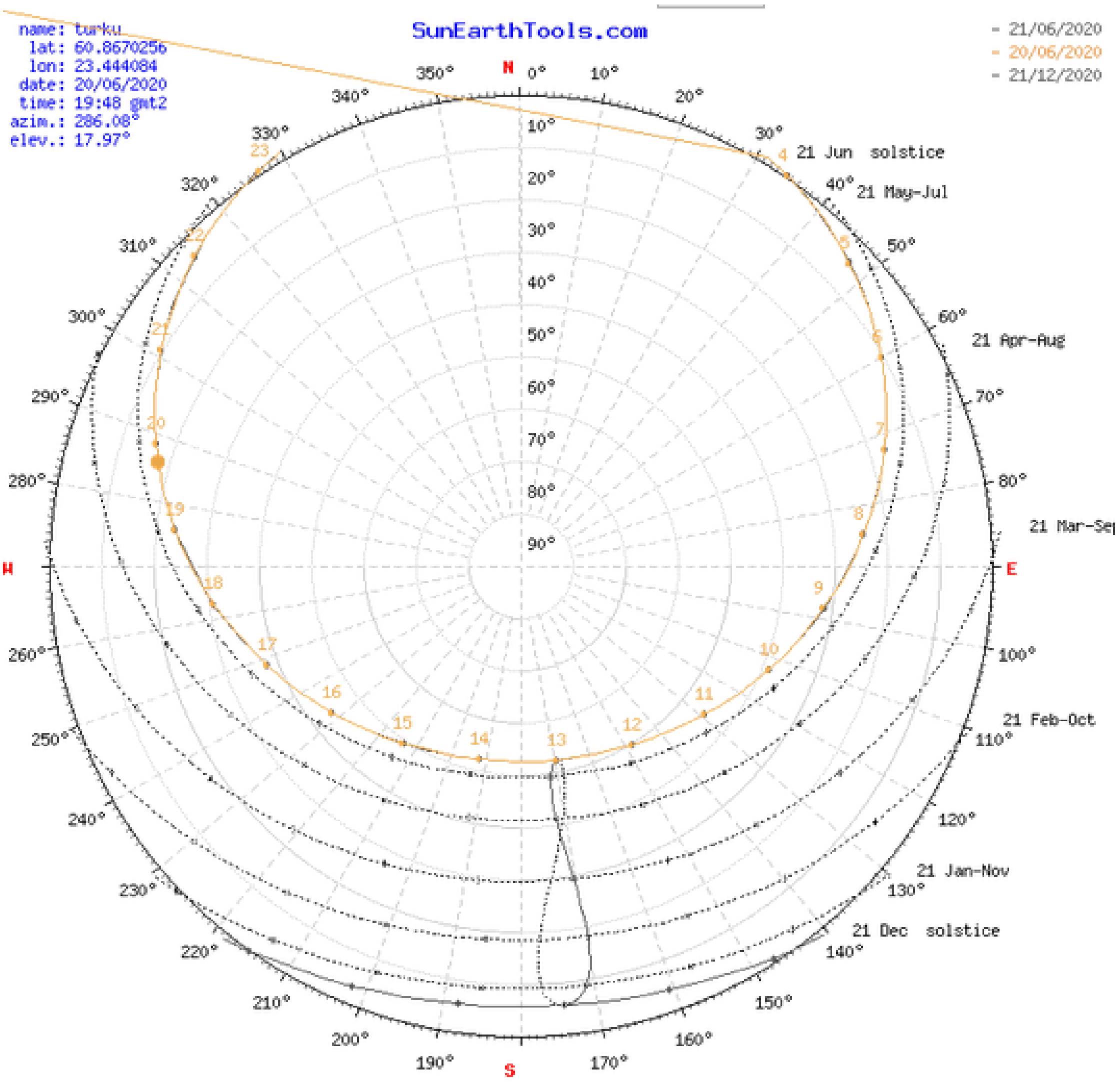


Figure 14 Solar path in Turku (SunEarthTools, 2020)

4 DISCUSSION AND FUTURE POSSIBILITIES

This project is relevant due to the environmental reasons mentioned in the introduction and the importance of solar energy of the shift towards a sustainable future. This specific field, bifacial PV tracking, is one that does not have much measured data from the northern hemisphere. Therefore this project was launched.

4.1.1 Possibilities for the future

As shown in figure 3, the amount of available radiation for the back side of the bifacial PV panel is influenced by the surface of the material under system. This is a valuable variable to study in the evaluation of the system performance and possibilities for maximum output. The roof where the system is first planned to be built has a surface made of black bitumen. Black bitumen have similiar charasteristics as asphalt. Asphalts albedo charasteristics can be seen in figure 3. Black bitumen can be used to provide a data point for low albedo conditions. High albedo measuring point could be white sand or white painted plywood. Plywood is cheap and easily tranportable.

To further experiment how different materials performs under the system in different circumstances, a change to panel elevation can provide more information for further optimization of performance. Due to the frame of the system, if a PV panel axis is set to a lower height, the vertical posts of the frame may cause major self shadowing, making direct comparisons of the data between the different heights possibly inaccurate. To prevent this, the reflecting surface itself could be assembled to a higher position.

This project is about a single axis tracker with an east-west rotating axis. Due to variance of the altitude of the sun, especially further away from the equator, it could prove to have a significant effect to alter the angle of the system to optimize the performance of the front side of the panel and analyze the effect it has on the total output of the system.

The torque tubes have a few centimeters of extra space on each side, making it possible to test the effect on output of the gap between individual panels.

Due to the way it is build, the system is expendable in height, lenght and width or in number of axis’, therefore adding more factors to explore in the future that adds to the lifespan of the design.

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