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VERTICAL BIFACIAL PHOTOVOLTAIC SYSTEM

– Design of a test system and preliminary analysis of performance and self-consumption characteristics

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VERTICAL BIFACIAL PHOTOVOLTAIC SYSTEM

- Design of the system and preliminary analysis of performance and self-consumption characteristics

The objective of the thesis was to construct a railing of bifacial photovoltaic modules and measurement- and data collection system at a location in Southern Finland (60°N 22°E). Measurement system included module level power, module temperature and string level irradiance -measurement from both sides of the system. Measurements were taken every second. By so, it was possible to study about the usability of this kind of technology commercially, as well as to present best practices when designing and building such a system. Additionally, a preliminary performance analysis and conformity of the sunny day production curve and average Finnish household consumption curve was studied.

The thesis was made in Turku University of Applied Science Solar laboratory, in an international collaboration with Sandia National Laboratories, which uses the data produced to understand the factors that affect the power production of bifacial photovoltaics.

The result suggest that the system is performing as desired. Measurement and data collection system has been reliable. No severe shadowing was observed in the module level production graphs. The experience gained from building this system also note, that it is important to consider the shading of the mounting fixtures as well as the rack itself when designing a bi-facial system. For vertical system, surrounding objects shading are also as important as for tilted systems. Standards and best practices regarding such system were also considered to be not efficient for commercial systems at the time of building, as customizations had to be made for components of the system.

The systems self-consumption potential in sunny weather situation was 8-16% better than the compared near South facing monofacial system, depending from the sizing of the system: The larger the peak power of the system compared to the consumption, the more did the bifacial system gain advantage. Biggest difference in this system was found when the system was sized 70% and 105% of the consumption. Going beyond 105% did not increase the advantage of the bifacial any further.

KEYWORDS:

Photovoltaic PV, Bifacial PV, Vertical East-West facing, Photovoltaic railing

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VERTICAL BIFACIAL PHOTOVOLTAIC SYSTEM

- Design of a system and preliminary analysis of performance and self-consumption characteristics

Työn tavoitteena oli rakentaa pystyyn asennettu kaksipuolinen aurinkosähköjärjestelmä osana Turun ammattikorkeakoulun aurinkosähkötutkimusta. Työ tehtiin yhteistyössä amerikkalaisen Sandia National Laboratories:in kanssa, ja he tulevat käyttämään järjestelmän tuottamaa dataa mallintaakseen kaksipuolisten aurinkopaneelien potentiaalia globaalisti. Kaidemuotoiseen järjestelmään rakennettiin myös mittausjärjestelmä, joka kykenee mittaamaan jokaisen moduulin sähkötehoa, lämpötilaa ja vertailtavaa säteilytehoa molemmilta puolilta järjestelmää. Projektin tarkoituksena oli tutkia tällaisen järjestelmän kannattavuutta sekä tuoda esiin esimerkkejä ja yksityiskohtia käytännön kautta. Tämän lisäksi työ sisältää alustavaa tuotannon analysointia sekä teoreettisen vertailun kyseisen systeemin omakäyttöasteesta, jossa käytettiin kulutuksena keskiarvoista suomalaiskotitaloutta.

Järjestelmä toimii kuten suunniteltu. Mittausjärjestelmä on toiminut luotettavasti eikä järjestelmässä ei ole havaittavissa vakavaa varjostusta. Suunnittelun ja rakentamisen aikana ilmenneitä kriittisiä alueita ovat varjostusten minimointi sekä rakennushetkellä tarvittavat muutostyöt kaupallisesti saataviin komponentteihin.

Omakäyttöasetta verrattiin lähes etelään (220°) suunnattuun yksipuoliseen aurinkopaneeliin. Rakennetun tutkimusjärjestelmän teoreettinen omakäyttöaste oli 8-16% suurempi kuin etelään suunnatun verrokin. Ero oli riippuvainen järjestelmän mitoituksesta: Mitä suurempi järjestelmän mitoitus oli, sitä paremmin kaksipuolinen järjestelmä suoriutui verrattuna yksipuoliseen. Ero oli suurin, kun järjestelmä oli mitoitettu 70% tai 105% kulutuksesta. Mitoituksen mennessä yli 105%, ei ero enää kuitenkaan kasvanut.

AVAINSANAT:

aurinkosähkö, kaksipuolinen aurinkopaneeli, itä-länsi järjestelmä, aurinkokaide

SISÄLTÖ

APPENDICES

FORMULAS

FIGURES

GRAPHS

TABLES

LIST OF ABBREVIATIONS, SYMBOLS AND TERMS

A/D converter	analog to digital converter
AM	air mass (The amount of atmosphere between a surface and a radiation source)
c-Si	crystalline silicon
Black body	theoretical colour of black that absorbs all light radiation
BSTC	bifacial standard test condition
Ground albedo	the amount of light the ground can reflect
Incidence	the difference in angle between a surface and direction of incoming radiation
Irradiance	power of the radiation/area
PCB	printed circuit board
PV	photovoltaic (conversion of light radiation into electrical energy)
RasPi	small single PCB computer

1 INTRODUCTION

1.1 Background

The development of photovoltaics has concentrated creating higher efficiency silicon PV-modules as well as finding completely new materials with superior properties for years. Silicon devices have seen new efficiency records being broken frequently in recent years and prices of commercial modules has been falling rapidly while demand has risen.

However, it has been estimated that silicon-based devices cannot go much further in terms of efficiency. Today’s laboratory devices are already close to what is theoretically estimated possible with silicon as the semiconductor material. This is one of reasons, why new magnitude of interest in dual sided or more commonly bifacial PV has woken. Bifacial technology itself is an old idea that has been developed as relatively minor technology but has not seen commercial applications until recent years. Bifacial modules could open new application for photovoltaics: Vertical rails that can produce as much or even more electricity than traditional system and act as sound barrier for motorway noise at the same time - for example. Vertically standing bifacial modules could also offer relief for the high peak loads on electrical grid and storage systems with alternative peak production times throughout the day.

Bifacial modules generally perform better at overcast-weather compared to monofacial, as there is twice the area collecting the highly scattered radiation. Also, vertical systems may benefit from low angle of incidence radiation compared to tilted systems in certain conditions, both which are profound characteristics of the northern location of the thesis system. The lower sensitivity to soiling and snow accumulation may also be important factor of vertical systems in some environments.

As new bifacial systems are commercialized, new practices, standards and support is needed for those regions of systems that cannot be straightly adopted elsewhere.

1.2 Objectives

The main objective of this thesis is to build a railing of bifacial photovoltaic modules to gain and share experiences of such systems, as well as produce production data for

further theoretical studies. The client for this thesis is an international collaboration between Turku University of Applied Sciences (Finland) and Sandia National Laboratories (USA).

Turku University of applied sciences has a growing, already diverse photovoltaic and New Energy research facilities located in the city of Turku, Western Finland. The thesis system is located at the rooftop of this facility, accompanied with other renewable energy projects. Overall purpose of the TUAS New Energy Research Centre is to respond to the key challenges of the energy transition: A focus on decentralized energy production (solar photovoltaic, wind power and bio energy), RES network integration, integration of the EV charging infrastructure, new converter technology, electrical storages and energy management systems (Turku University of Applied Sciences, 2019).

Sandia National laboratories in Albuquerque, New Mexico, USA, has long history of developing outdoor performance characterization methodologies for photovoltaic modules using two-axis trackers and novel test designs. Especially the Sandia PV Performance Array Model, which is a mathematical way of studying a performance of a PV system in various scenarios, has been considered the most accurate in the world. Sandia has also similar empirical study system of vertical bifacial photovoltaic system as this thesis system, and these systems are producing data to improve and understand of the many factors that affect the power production from bifacial modules (Sandia National Laboratories, 2015).

2 INTRODUCTION TO PHOTOVOLTAIC TECHNOLOGY

2.1 Overview on PV

Photovoltaic technology is one of the methods used to harvest energy from light radiation. Usually the source of this light is the Sun, simply because it is the most powerful emitter of light in the solar system. Photovoltaics are used to convert light energy into electrical energy, which is usable in extremely wide range of applications and relatively easy to transfer.

Other common method to harvest energy from Solar radiation is to utilize a heat collector, which converts solar radiation in to heat energy. In general language, both can be referred as “solar panels”, which might result to confusion. These technologies are fundamentally different and not to be confused. Devices that convert light directly into electricity are referred as photovoltaic devices.

2.2 Semiconductors

Semiconductors are materials that can either conduct or isolate electricity, depending on their temperature. As temperature rises, so does semiconductors conductivity. Thus, semiconductors conductivity is directly proportional to the temperature. With metals (conductors), this is the opposite: When temperature rises, conductivity decreases.

However, the conductivity of semiconductors at room temperatures are, by default, not sufficient in practical electrical applications. But semiconductors can be modified to achieve higher conductivity. This is done by adding a suitable material to the semiconductors atomic structure. The added foreign material has electrons that cannot find a partner to bond with within the semiconductor, these electrons become free to carry electricity at room temperatures. This process is called *doping,* and in the case explained above, *n-Doping*. In the other doping process, *p-Doping,* foreign material mixed with the semiconductor has less available electrons for bonding with the semiconductor's electrons. This results in *holes,* which can carry electricity similar to free electrons. The *holes* in the p-doped semiconductor have a positive charge, and the n-doped free electrons a negative charge. Because of their charge, electrons and holes inherently

want to recombine levelling the charges. By combining both n- and p-doped semiconductor, a *p-n junction* is created. Common electronic components like diodes, bipolar transistors and photovoltaic cell uses p-n junction to operate. In diode, p-n junction allows electricity to flow only in one direction, and in bipolar transistor, conductivity across the device can be controlled with external electrons (voltage) using two p-n junctions. In photovoltaic cell, the junction is used to convert light into electrical energy. (Mertens, 2013).

2.3 Crystalline silicon

Crystalline silicon (c-Si) is the most commonly used semiconductor in electronics and in photovoltaic applications. This is mostly because it is wildly available in the Earth's crust, it is nontoxic and relatively easy to manufacture (Pizzini, 2012). It also has already existing extensive development and manufacturing industry.

In photovoltaic applications, the c-Si can be in multi-crystalline or monocrystalline form. Monocrystalline being superior in terms of performance, but more expensive to manufacture. Multi-crystalline c-Si is manufactured by casting purified silicon at high temperature and controlled cooling. Monocrystalline c-Si is manufactured layer by layer, by growing a seed crystal by dipping it in to a melted silicon bath and then withdrawing it slowly in rotating motion. This is a relatively slow and expensive process, but yield's in a smoother surface silicon compared to the casting. Both multi-crystalline and monocrystalline process results in a silicon ingots, which is then cut into wafers with a diamond saw. Monocrystalline silicon cell can be usually identified by its rounded edges compared to multi-crystalline, that usually has sharp edges. This is because the multi-crystalline ingot can be casted to a specific shape and cut in more material efficient way, but monocrystalline growing process results only to cylindrical shape. Similar but higher quality monocrystalline silicon wafers are used also in microelectronics (Goetzberger, et al., 2002).

2.4 Photovoltaic energy conversion and its efficiency

A photovoltaic cell converts light radiation directly into electrical energy. This conversion happens by exposing the p-n junction to the energy carriers in light radiation: Photons. Photon agitation of high enough magnitude raises electrons energy level, freeing

the electron to form an electron-hole pair within the p-n junction. This generates a *photovoltage* across the junction, which then results to a *photocurrent* flowing in reverse direction through the p-n junction when connected to a load. In simplified terms, the load creates an electrical path from n side to the p side of the junction. The attraction between holes in p-side and electrons in n-side creates movement of electrons trough the load. Load being a device where the electricity is consumed. Extreme simplification would be imagining p-n junction as a pump, that pumps electrons and holes in opposite directions using photons as an energy source. Light is converted into direct current.

However, if the photons energy level is not sufficient to raise the electrons energy level, no voltage is created and thus no current flows through the p-n junction. The energy of these photons is lost. This energy level is called an energy cap and it is material specific. On the other hand, if the energy level of the photon is greater than the energy cap of the material, this excess energy is converted in to heat until the energy level is equal with the energy cap. Energy level of the photon in incoming light radiation being too low contributes typically to about 19% loss in silicon cell and the photon being in too high energy state about 31% (Rockett, 2010).

The efficiency of a photovoltaic cell is sum of compromises with materials and processes: The energy cap of the doped semiconductor among other losses like electron-hole mismatches (16%), material impurities and transfer losses. Overall theoretical efficiency limit of a silicon PV cell in AM 1.5 sunlight (black body) spectrum is 29%. However, the actual achievable efficiency limit may be lower in real world conditions (Rockett, 2010). As for 2018, the record is 26.3% hold by Kaneka corp. (IEE, 2017).

3 MONOFACIAL AND BIFACIAL C-SI CELL AND MODULE

3.1 Monofacial PV c-Si cell

Traditional PV cell consist of silicon wafer that has the n-doped (n+-emitter) and p-doped (p-base) silicon sides forming the p-n junction(s) as seen in Figure 1. Doping material is usually phosphor for n-type and boron for p-type silicon. Between the doped layers is a space charge region. This region has an electrical field influencing the p and n sides acts as a center of the p-n junction. Space charge region is also the main contributor to the photocurrent converted by the cell, as most of the absorption contributing to the photocurrent happens here. Absorption of photons do happen in all layers of the cell, but most electron-hole pairs from the n- and deep p-doped areas recombine and never join the photocurrent flowing from the emitter to the base (Mertens, 2013). This recombination happens because of the energy cap being too high in this area, as explained in chapter 3.2. Space charge regions electric field separates electrons and holes. Pairs regenerated in this section have better change to find either the busbar (electrons) or the back contact (holes). The actual silicon wafer itself can be either p-doped as in Figure 1 with thin n-type coating or vice versa. In this case the cell is referred as p-doped cell.

Photocurrent is collected by the Busbar, which is a thin metal film with high conductivity. Busbar acts as a negative lead out from the cell. Back contact is a metal film that transfers current from the positive side when connected to a load.

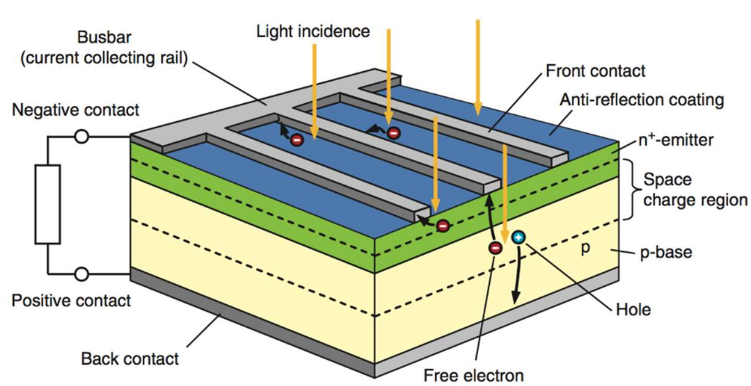


Figure 1. Structure of crystalline silicon p-type PV-cell (Mertens, 2013).

First layer of the cell is coated with anti-reflective material minimize reflection and thus maximize the absorption rate of light radiation.

3.2 Monofacial module

A photovoltaic module consists of several cells that are electrically connected together. Single cell is usually not enough in terms of power and voltage level to supply high power systems. By connecting several cells in series, voltage level can be raised to a suitable level. Current remains constant. Typical c-Si module has 60 to 72 cells in series which gives an overall open circuit voltage of around 30-36V.

Connecting cells in series has also drawbacks. If cells produce different amounts of energy due to their age, manufacturing defects and especially uneven irradiance distribution across the module (i.e. shading), leads to current flowing to the lower performance cell, which will heat up as a result. This is called cell mismatch and will lower the overall performance of the module, or in worst case can damage the module permanently. To lower the effects of cell mismatch, bypass diodes are added between the cell strings. Bypass diode will effectively limit the number of cells supplying the lower performance cell. Typical module has one bypass diode per 20 cells.

Module also provides a mechanical structure and protection for the brittle cells. Front of the module is typically tempered class with anti-reflective coating, attached to an aluminum frame. Glass-glass structures without aluminum frame is used in some monofacial and typically all bi-facial cells.

3.3 Bifacial cell

In bifacial cells the differences to the monofacial cells at macro level are subtle. The basic idea of a bifacial PV cell technology is simply to harness also the backside of the cell to the electricity production. This is done by using a back contact similar design than the busbar in front side. This will allow the absorption of light to happen from both

sides of the cell. A second anti-reflective coating is also needed in the backside to enhance absorption performance.

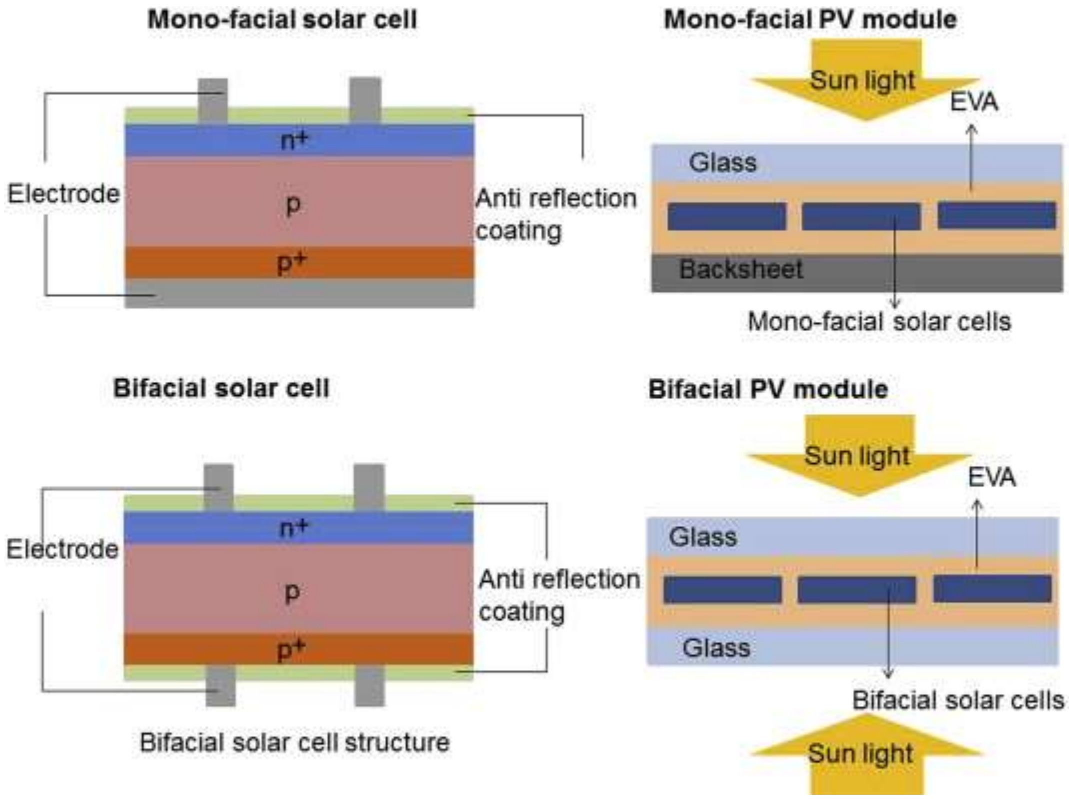


Figure 2. Different types of PV-cells and PV-modules (Guoa, et al., 2013).

The manufacturing process of PV-cells needs to be optimized specially for bifacial cells to obtain high efficiency levels from both sides. Also, extra steps are needed in the manufacturing of a bifacial cell. Like the extra doping process for the back side as well as the busbar construction. Raw material consumption used for both mono- and bifacial process are at the same magnitude, with bifacial offering double the surface area (Moehlecke, et al., 2013)

The efficiency of back side of the cell is not equal with the front side. Due to manufacturing methods, lower efficiency is achieved in the back side of the cell. The ratio between the front side and back side efficiency is called bifacial ratio or bifaciality of the cell. Bifacial ratio depends on the processes used to manufacture the cell and is usually 50-90% in production cells. Ratio of 90% means that the back side of the cell produces only 90% of the production of the front side in same conditions.

3.4 Bifacial module

Bifacial cells need a module design different from the typical mono facial. Bifacial module consists of glass on both sides of cells to allow light to pass. Also shading of the backside of the module is to be avoided. Frameless glass-glass design is usually preferred over the typical aluminum frame, but frameless design is usually heavier. Connection box, which has the electrical connections of the module, must be also designed to avoid shading of the backside.

Bifacial cells can also be used in more typical monofacial module design by using reflective surface behind the cells (Moehlecke, et al., 2013).

3.5 The geographical aspects of bifacial and monofacial module

The optimal tilt angle of a PV module depends heavily on the location of the system and time of the year. Systems near the equator benefit from lower tilt angle while systems near the poles perform better with high tilt. Low angle produces higher output in the summer while high angle has higher output in the winter. Studies have found, that traditional mono-facing modules have globally the highest long period performance when facing towards the equator with tilt angle of the latitude of the system minus ~10° (Guoa, et al., 2013). However, the actual practical tilt angle varies on the preferred peak production times of the system and should be chosen system specifically.

With bifacial modules, ground albedo and fraction of diffused radiation are bigger factors when choosing the tilt angle compared to monofacial. Bifacial modules can collect more scattered radiation because the higher total PV surface area, and the tilt angle affects the total absorption rate of scattered light. The effect of ground albedo to the output of a module is higher with bifacial modules (Stein, et al., 2017). Because of this, bifacial modules benefit from higher tilt angle, especially when the ground albedo is high (Sun, et al., 2017).

Mounting height is also important with bifacial modules. The self-shading of a module can be significantly reduced by lifting it up from the ground. Higher albedo of the

ground and lower latitude of the system require higher elevation of the module for best performance (Sun, et al., 2017).

A group has studied the global effectiveness of vertical East-West facing bifacial system versus a South facing monofacial by means of simulation. (Figure 3).

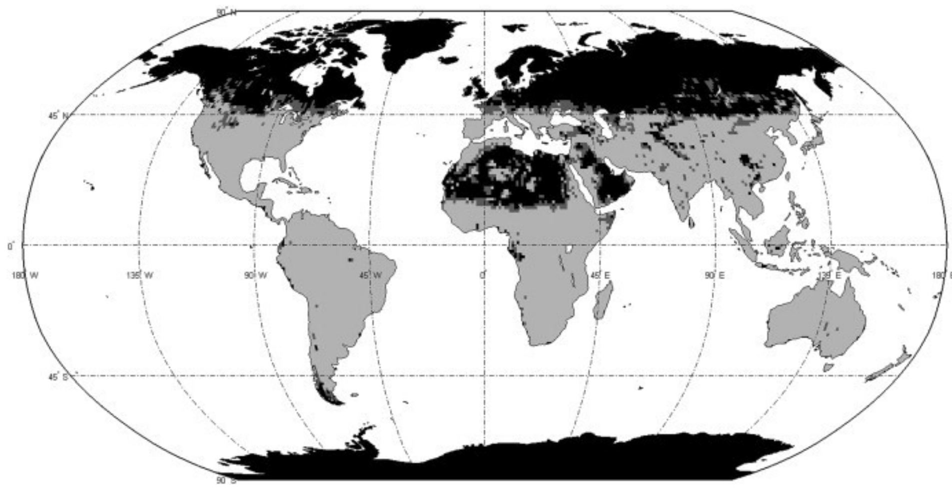


Figure 3. The simulated outperforming system type around the world. In black: E-W facing vertical bifacial. And in grey: equator facing optimal tilt angle monofacial (Guoa, et al., 2013)

However, it might be more interesting to compare a vertical bifacial system to another type of bifacial installation (Figure 4).

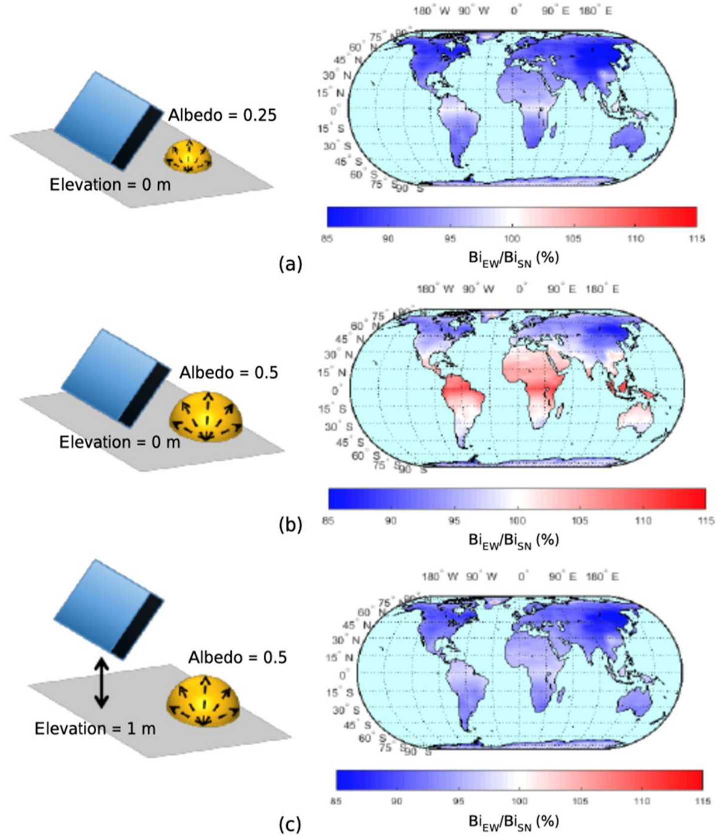


Figure 4. Global simulated energy yield ratio of bifacial E-W 90 system (preferable areas in red) and S-N optimised tilt angle bifacial (preferable areas in blue) with different ground albedo and module elevations (Sun, et al., 2017).

It was found that the best tilt angle of the bifacial E-W system was always 90° everywhere in the world, while the optimal angle for the S-N system varied. The group also showed, that self-shadowing of the module plays a major role in how the bifacial E-W 90° system performed against bifacial S-N system. Interestingly the E-W 90 system outperforms S-N system when its self-shading is high (low latitude and low elevation of the module, b in Figure 4). Lifting the module 1 m up from the ground causes the S-N system to outperform globally. At higher latitudes S-N system requires higher tilt angle, which causes less self-shadowing and thus allows more light radiation to enter the backside of the module.

4 THE PROJECT

The project of designing and building the test system started at in April of 2017, when mechanical structure was first drawn in CAD. The designing was simple and familiar supplier aluminum profile was used, which also made the 3D drawing simple.

The electrical system, measurement and data collection systems were designed with a collaboration with Sandia National Laboratories. Sandia has experience with a similar system that was built to their test facility in Albuquerque, New Mexico in 2016. Although several design changes were made, as not the least, adaptation the system to a centralized inverter with power optimizers, instead of separate micro-inverters.

After the basic layout and the components of the electrical system were decided, one wire diagram of the system was drawn (appendix 1). The design concept of the measurement system was to make it as modular as possible. The construction began with assembly of eight power meter housings and their accuracy verification. Only four were

needed for the system, and the most accurate ones were selected, although the variance seemed to be small: All meters had power measurement within 2% when the test current was over 0.5 A.

Figure 5. acuDC power meters and their housings

The location of the system was already decided to be at the roof of a technology center in Turku, Finland. This roof also hosts other systems in the test environment of Turku University of Applied Science. Placement of the system was then planned taking surrounding buildings and trees in to account avoiding shadowing in every possible way.

Construction and wiring of the data acquisition system and its auxiliary power supply was done next (Figure 6). For schematic, see appendix 2.

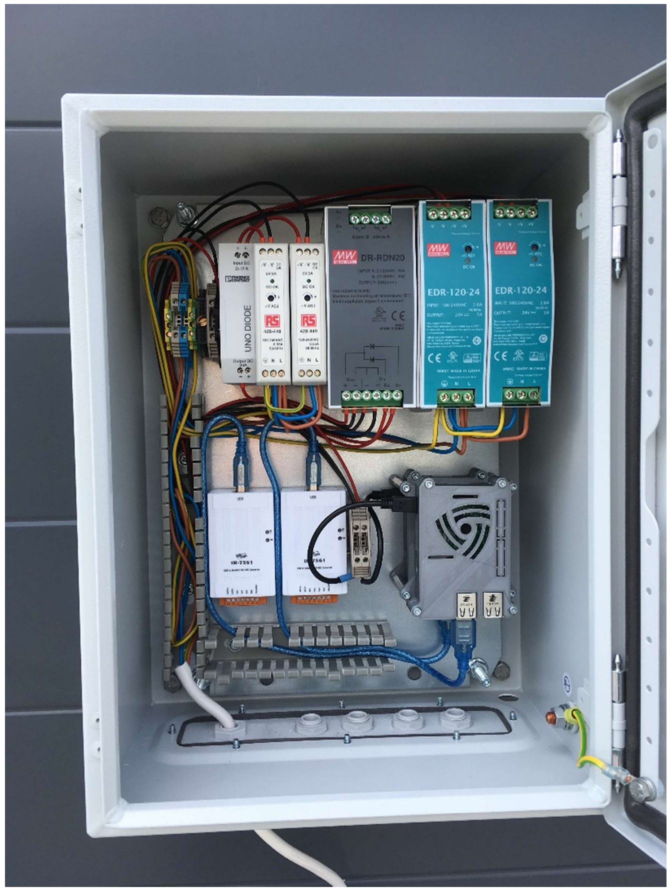


Figure 6. Data acquisition system and power supply

5 TEST SYSTEM

5.1 Prismsolar Bi60-375

In the test system, four bifacial modules are used as the center of the study. These are all Prismsolar Bi60 series modules with BSTC rating of 375W. The Prismsolar Bi60 uses 60 n-type bifacial monocrystalline silicon cells with combined module efficiency of 17.7% for the front side and 15.9% for the back. The modules were flash tested by the manufacturer. Bifacial ratio is 90%. Module has three bypass diodes, making one for each 20 cells. The design is frameless, consisting two tempered glass sheets with anti-reflective coatings.

The modules are orientated to East-West, East facing being the front side of the modules and backside to the West. Electronic compass was used to define the orientation. Compass was hold 1 m away from the modules, as interference was detected when compass was held close to the cells. The tilt angle of the modules is 90° (vertical).

5.2 Electrical connections

All four modules have separate SolarEdge DC optimizer keeping them at maximum power point. Optimizers also provide isolation between the module and the inverter side, and therefore may lower the noise in DC measurements. All modules are connected in series to a single string. In the same string, there is also three other modules that are not studied in this project. These modules raise the voltage to suitable range for the inverter.

A 2kW StegaGrid2000 single phase inverter is used to convert the direct current (DC) in to alternating current (AC). Inverter supplies a low voltage local (230V) grid with high consumption and high peak loads. These high loads include laser cutter, welding machines and high-power machining tools. The local grid is connected to three phase mains grid with dedicated medium voltage transformer.

6mm^2 solar cabling is used in all DC power lines with typical PV spring-loaded connectors. The Prismsolar Bi60 modules do not require device grounding due to non-conductive frameless design, but the aluminum rack that sits the modules is grounded for lighting strike damage prevention (Prism Solar Technologies , Inc, n.d.).

5.3 The rack

The rack was constructed from 45x45mm aluminum profile system with threaded and bolted connections. The lowest horizontal bars supporting the modules can be slided up and down, making the installation of the modules easier. The final assembly was done under compression in horizontal direction by cargo straps, making structure more rigid. 50 concrete blocks (250kg in total) are used as weights to prevent the rack from tipping over. Plywood sheets and extra layers of bitumen is used to protect the roof from the legs punching holes to the roof.

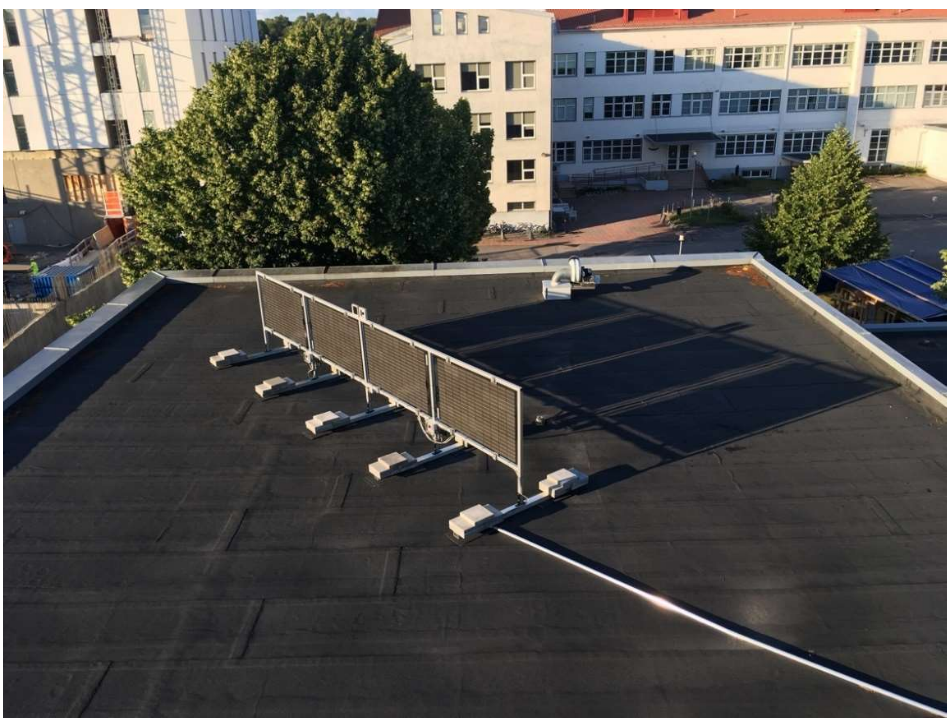


Figure 7. The finished system

The bi-facial modules are fixed to the aluminum rack with Schletter Clamp Profi- fasteners. The clamps are designed for glass-glass modules. However, they are not intended to mount the modules vertically. Absence of vertical mounting systems, an adapter was made from aluminum profile (Figure 8).

Figure 8. Mounting of the modules to the rack

6 DATA ACQUISITION SYSTEM

The data acquisition system consists of DC power meters, irradiance sensors, thermocouples and A/D converter run by two RasPi. microcomputers. After the collection and processing, copy of the data is written to permanent SQL database which is run on a local computer.

6.1 AcuDC 240 power meter

AcuDC 240 power meters are used to measure the DC voltage and current of each four modules before the optimizers at module level. The voltage measurement is common type of direct voltage input and current is measured via meters' internal shunt resistor. The accuracy of the meters is rated at 0.2% at full range for both voltage and current (ACCUENERGY, 2016) and the meters are shipped with manufacturer's test measurement tables.

AcuDC meter uses RS485 bus with ModBus-RTU protocol for data transfer. RS485 is optically isolated from the power circuitry internally in the meter. Meters are connected in single line topology with 120Ω anti-signal reflecting resistor at last device, as recommended by the manufacturer (ACCUENERGY, 2016). The cabling used for the RS485 is a pair shielded JAMAK 2x2x0.5+0.5. Shield is earthed from one end to common ground.

The meter housing and connections was designed in such way, that they are easy to remove from the system and repeat the accuracy verification in test bench. DC power connections are made with WM4 C connectors and data connectors are five pole sealed multicontacts. The meters are supplied by two redundant, switching-type 24V DC power supplies. These power supplies are wired through redundancy module, which will disconnect a failing power supply and prevent reverse feed if such event occurs. All meters are also separately isolated with PCB DC/DC converter located inside the meter housing. The high frequency switching DC/DC converter provides stable and low noise power to the meters. Isolation of the meter power supply was thought to be necessary, because the acuDC internal design was unknown and so was the true isolation level between power supply and measuring circuit. Because the solar edge optimizers isolate the modules in the string, the measuring sides of the meters needs to be

isolated too. Improperly isolated measuring circuit to power supply-side would couple the module outputs together before optimizers, which was thought to cause current flowing through measuring circuit to power supply.

Voltage, current, power and running energy readings are read by RasPi1 once every minute from all four meters simultaneously. Time stamp for the measurement is added in RasPi1 python code with separate time server to ensure correct time. Data is then copied to computer running SQL database using wired Ethernet.

6.1.1 AcuDC 240 accuracy verification

All four meters were tested in a test bench before installation. The test was executed with following equipment:

- GwInstek PSW160-14.4, 720W programmable switching DC power supply
- EA-PS 2042 20B power supply for AcuDC auxiliary power
- BK precision 8601, 250W programmable DC electronic load
- 6 mm^2 PV cabling with Weidmüller PV-Stick connectors, 4 meters in total cabling

Tests were done using supply voltage of 32V and incremental current with four different steps: 0.1A, 0.5A, 2A and 7A. The test voltage was selected from Bi-60 module rated voltage range and current steps from the thought field operating points as well as the limitation of only having a 250W electronic load. Below 1A current range was also thought to lead bigger inaccuracies. Tests were started from 0.1A and ended to 7A in effort to limit the temperature changes in devices and cables. Both power supply and the electronic load were in constant current mode during the test. To compensate voltage drop in the test cables, output cables had remote voltage sense wires inside the connector, which were connected to the electronic load sense input. Test procedure was manual, and meter readings were taken from acuDC software read through RS485. The reference readings were taken from the BK precision electronic load. These reference voltage, current and power readings were then compared with acuDC meter readings.

6.2 Reference cells

Two E.E.T.S PV- reference cells are used to measure the plane of array irradiance from both east and west sides of the system. The cells are placed to the centre of the rail, where no local shading that is not uniform to the whole system is present. Data is therefore collected at string level. Reference cells are mono-crystalline silicon with split in half wafer. Half of the cell is used for irradiance measuring and half for temperature measurement. Irradiance is measured using short circuit current I_{SC} which is, measured by voltage drop over a shunt resistor. This is then fed to ICP DAS A/D converter and is read every second by RasPi. The temperature corrected irradiance is then calculated in RasPi with following equation:

Equation 1

$$Irradiance_{Corrected}\left[{}^{W}/_{m^2}\right] = Irradiance\left[{}^{W}/_{m^2}\right] * \left[1 + Alpha\left[\frac{V}{K}\right] * \left(\frac{25 - Cell\ Temperature\ [°C]}{Isc_{@STC}[V]}\right)\right]$$

Where:

Irradiance = measured non-corrected irradiance

Alpha = Relative temperature coefficient for short circuit current

I_{sc} = Short circuit current at standard testing conditions

Final calculated irradiance is then averaged to minute data and saved to local SQL database. Raw short circuit voltage I_{SC} and temperature open circuit voltage V_{OC} is also saved to SQL database for backup reasons if there would be errors in calculations.

Photovoltaic reference cells are used instead of thermopile pyrometers in this kind of systems, where straight, same plane and angle irradiance reference to module is needed. Irradiance data is used to acquire understanding of the efficiency of the independent modules and the whole system. Because of the response of the reference cell to spectrum of radiance is more similar as the system's photovoltaic module used, the irradiance data is comparable. Photovoltaic reference cells convert irradiance by photovoltaic effect, which is wavelength depended and varies with PV technologies (Dunn, et al., 2012). This wavelength dependency is called the spectral responsivity (SR), and is defined with the following equation:

Equation 2

$$I_{sc} = A \int E(\lambda) \cdot SR(\lambda) d\lambda$$

Where *A* is the area of the PV cell in m^2, λ_1 and λ_2 are the upper and lower wavelength limits in nm, *E*(λ) is the spectral irradiance of the incident spectrum in $Wm^{-2}nm^{-1}$, and SR(λ) is the mentioned spectral response of the PV device in AW^{-1} (Dunn, et al., 2012).

In simplified terms, the SR is the short circuit current / power of irradiance at certain wavelength.

The PV reference cells calibration is based to the reference solar spectrum from IEC standard 60904-3 (Dunn, et al., 2012). However, the used E.E.T.S reference cells are calibrated indirectly to the IEC standard by using natural sun in outdoors and making comparison with primary IEC 60904-3 calibrated ref. cell. The primary ref. cell used is calibrated by TÜV Rheinland. E.E.T.S measurements are made over high-precision resistor and overall measurement uncertainty is estimated to be under 3%. (Energy Enviromental Technical Services, 2016). Reference cells calibrated to the standard can be used to measure irradiance of varying spectra (Dunn, et al., 2012).

6.2.1 Reference cell temperature measurement

The temperature measurement is needed for accurate irradiance reference, since the signal produced by the silicon is temperature dependent. The temperature of the reference cell is measured by half of the cell's silicon wafer. This is done by measuring the open circuit voltage V_{OC} produced by the temperature half. When V_{OC} at *STC* and the temperature dependency *Beta* is known by manufacturer's measurements, cell temperature can be calculated with equation:

Equation 3

$$\text{Cell Temperature } [°\text{C}] = \left[\frac{MeasuredVoc[V] - Voc_{@STC}[V]}{Beta[\frac{V}{K}]}\right] + 25°\text{C}$$

Where

Measured V_{oc} = measured open circuit voltage of the cell

V_{oc} = open circuit voltage of the cell at standard testing conditions

Beta = Cell output temperature dependency

The temperature measurement is under the same calibration procedure as described on chapter 3.2 and is thus within the same calibration uncertainty of below 3%.

6.3 Module temperature measurement

Temperature of all the bifacial modules are measured so the module temperature dependency can be monitored, and temperature corrected production can be calculated. Traditionally, temperature of the monofacial module is measured from the backside of the cell with relatively large surface area thermocouple or resistive thermometer. With bifacial technology, this method cannot be used because both sides of the cell are utilized for electricity production. The shading from the thermometer would cause the cell beneath it to act as an electrical load, which would lead to the cell being heated up. This would give incorrect result of temperature across the module and lower the overall performance of the module.

To overcome the temperature sensor shading the backside of the cell, small temperature sensor is connected to a point between the cells. The used sensor is T-type thermocouple wire. The point of measurement consists of simply twisting two wires together, which then acts the hot junction of the sensor.

Thermocouple is a temperature sensor that uses Seebeck's effect to measure temperature from two different conductive materials. Thermocouple has two points of measurement. Primary junction, which is the located near the point of temperature of interest. Other junction, the reference junction, is the point where the thermoelectric materials end. The primary junction is electrical in nature while the reference end junction is thermic and electrically isolated. Physically the reference end is usually located at the terminal of A/D converter. Temperature difference between primary junction and reference junction creates temperature proportional non-linear voltage across the two conductors. Temperature from the cold end needs to be known to calculate the temperature of the hot end with equation:

Equation 4

$$V_{TC}(T_{TC}) = V_{MEAS} + V_{TC}(T_{REF})$$

Where

V_{TC} (T_{TC})	is the voltage measured by the thermocouple assuming a reference junction temperature of 0 °C,
V_{MEAS}	is the voltage measured by the data acquisition device and
V_{TC} (T_{REF})	is the voltage that would be generated by the same thermocouple at the current reference temperature assuming a reference junction of 0 °C (National Instruments, 2011).

The materials used for the junction effects to the voltage created, so different types of thermocouples exist. These are identified with single letters. For example, J, K, T and E types of thermocouples are available. Every type of thermocouple has its own look-up table for created voltage versus temperature of the primary junction. All types of thermocouples create output voltage in the millivolt range, which is prone to interferences. For this reason, thermocouple wires should be kept short and away from power cables.

6.4 Analog to digital converter, ICP DAS M7019R

Programmable 8-channel 16bit A/D converter is used for digital transformation of the module temperatures, reference cell temperature and irradiance output. The ICP das M7019R unit has internal automatic thermocouple reference junction compensation and lookup tables for several types of thermocouples. All analog channel input ranges can be programmed with simple graphical software and input type with physical jumpers on the input terminal. Digital output utilizes RS485 interface with Modbus protocol and is optically isolated from the input. The internal accuracy of the unit is rated at 0.1%. This was also tested to be true with the shipped unit with a signal calibrator at the solar lab.

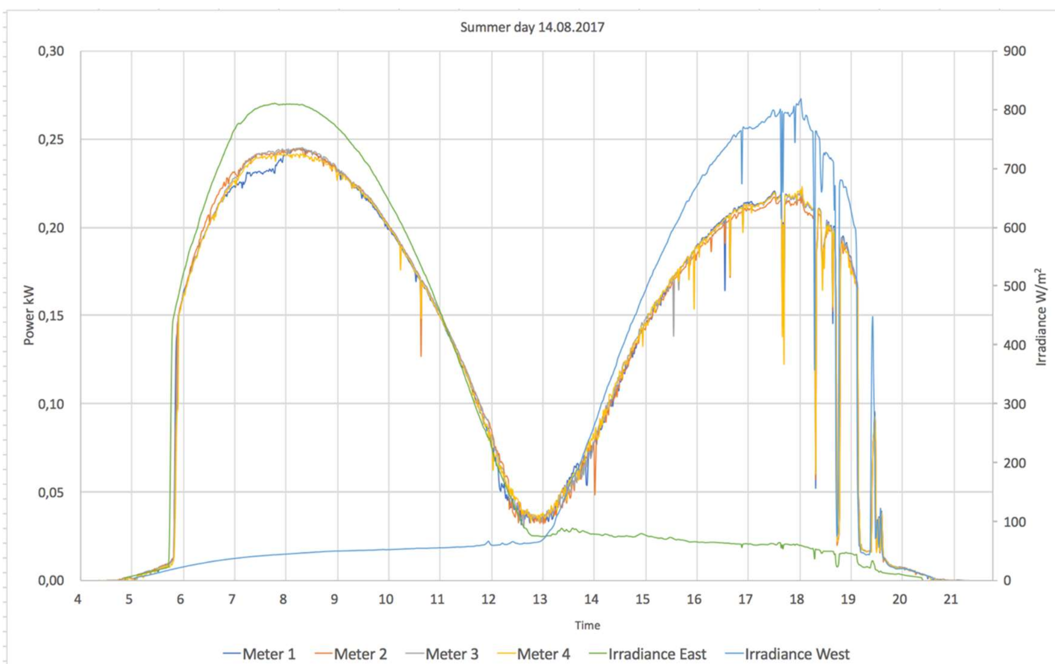
The unit is located at the centre of the modules to keep the analog wires as short as possible. Sealed plastic housing protects the unit from the outdoor elements and does not have any other components inside to keep even temperature across the housing. The unit has only one temperature measurement for the thermocouple compensation, so external heat points could result in module temperature errors.

7 PRODUCTION DATA ANALYSIS

7.1 Production performance and shadings

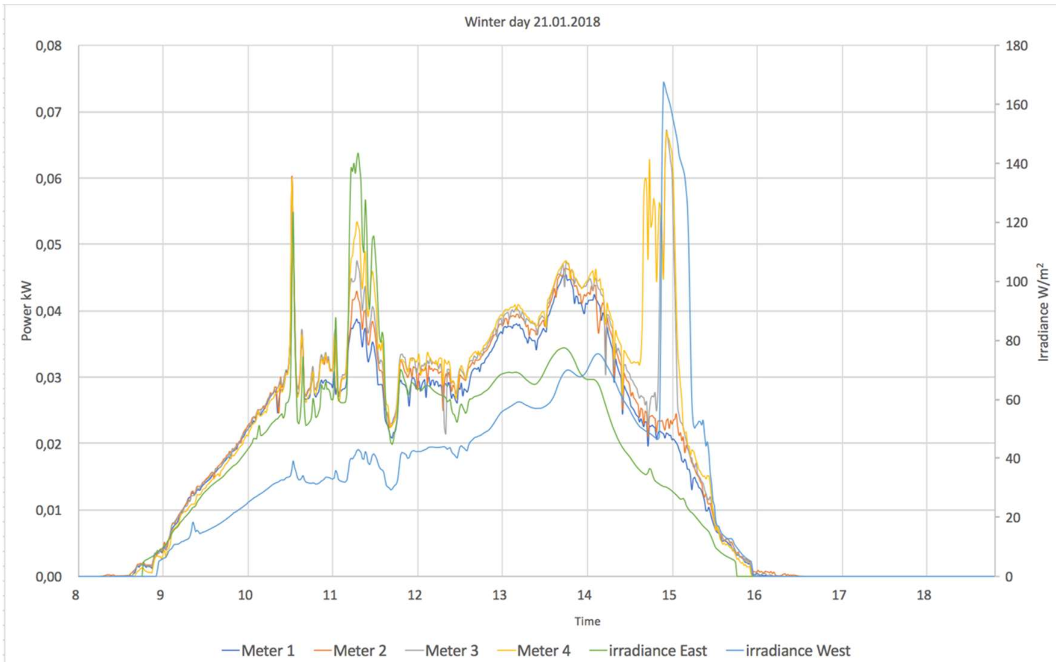
Sunny day performance can be determined from Graph 1. Clear two production phases can be seen. As the sun rises from the East, irradiance from the East side reference cell rapidly rises and power of the modules follow in uniform manner. Front sides of the modules are now at high production. Action that seems to be shadowing from meter 1 can be seen between 7 and 8. When the Sun is at noon, irradiance and power drops as the Sun is now shining perpendicular to the PV surfaces. After the Solar noon, production from the West side starts to rise. This is now the back side of the modules producing most of the power. Some effects from light clouds can be seen in the evening production period.

The evening production of the modules can be seen to be lower compared to the morning. This is due the lower efficiency of the backside of modules (bifacial ratio) and higher ambient temperatures on evenings.



Graph 1. Power of all four modules and irradiance at the plane of array on clear summer day.

In clear winter day similar production peaks can be seen, but they are much less prominent. With the high albedo of the snow, much more scattered radiation can be seen (Graph 2).



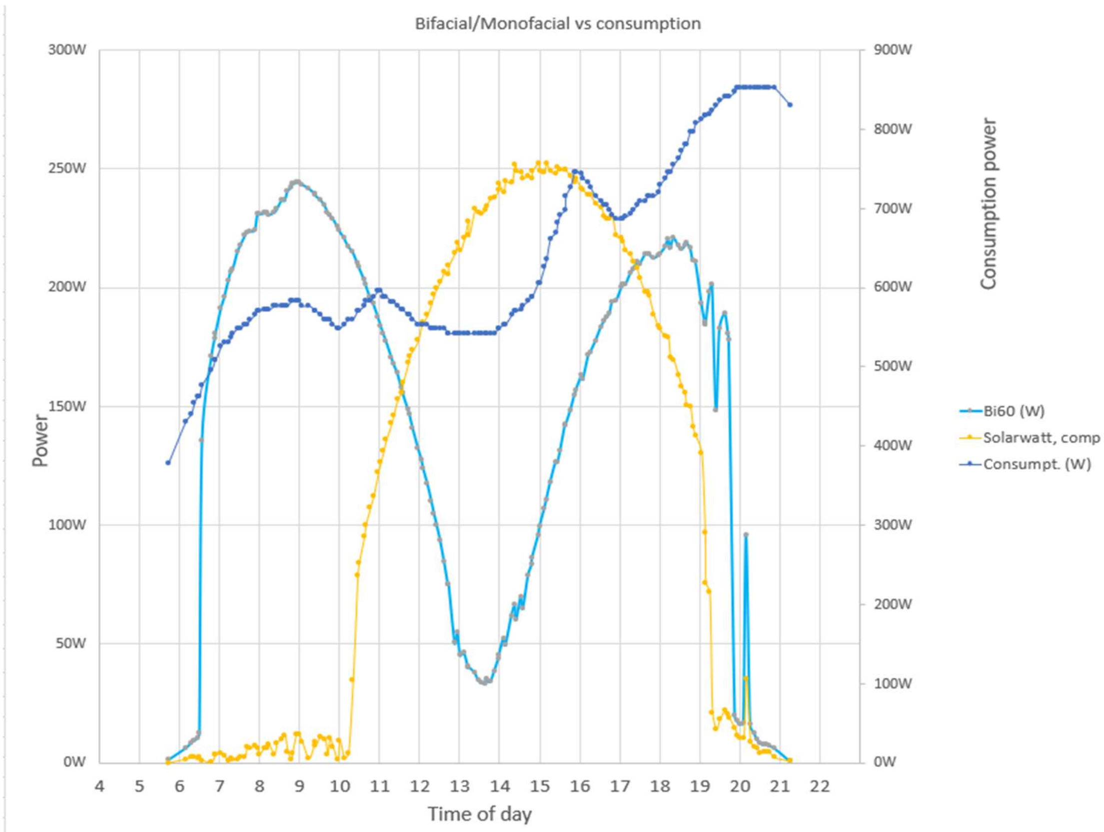
Graph 2. Power of all four modules and irradiance at the plane of array on clear winter day with snow.

7.2 System production and average household consumption model

Bifacial production profile was compared with traditional tilted monofacial module. The module in question was a Solarwatt BLUE 60p 265Wp with tilt angle of 43° and azimuth of 220°, located at the same roof. The production of the monofacial module was normalised to the average single sided power of the bi-facial module, taken from the manufacturers flash test. This was done to obtain more comparable data, since the bifacial modules have higher single sided power also.

The production profile of a daily household consumption is an estimated average over the whole year, obtained from Finnish research centre VTT. It presents a Finnish non-electrically heated detached house profile in the year 2006. The profile was constructed using one-year data which was then averaged into one day. (VTT Energia ja

metsäteollisuus; Aalto-yliopisto; Lappeenrannan teknillinen yliopisto; Itä-Suomen yliopisto, 2010).

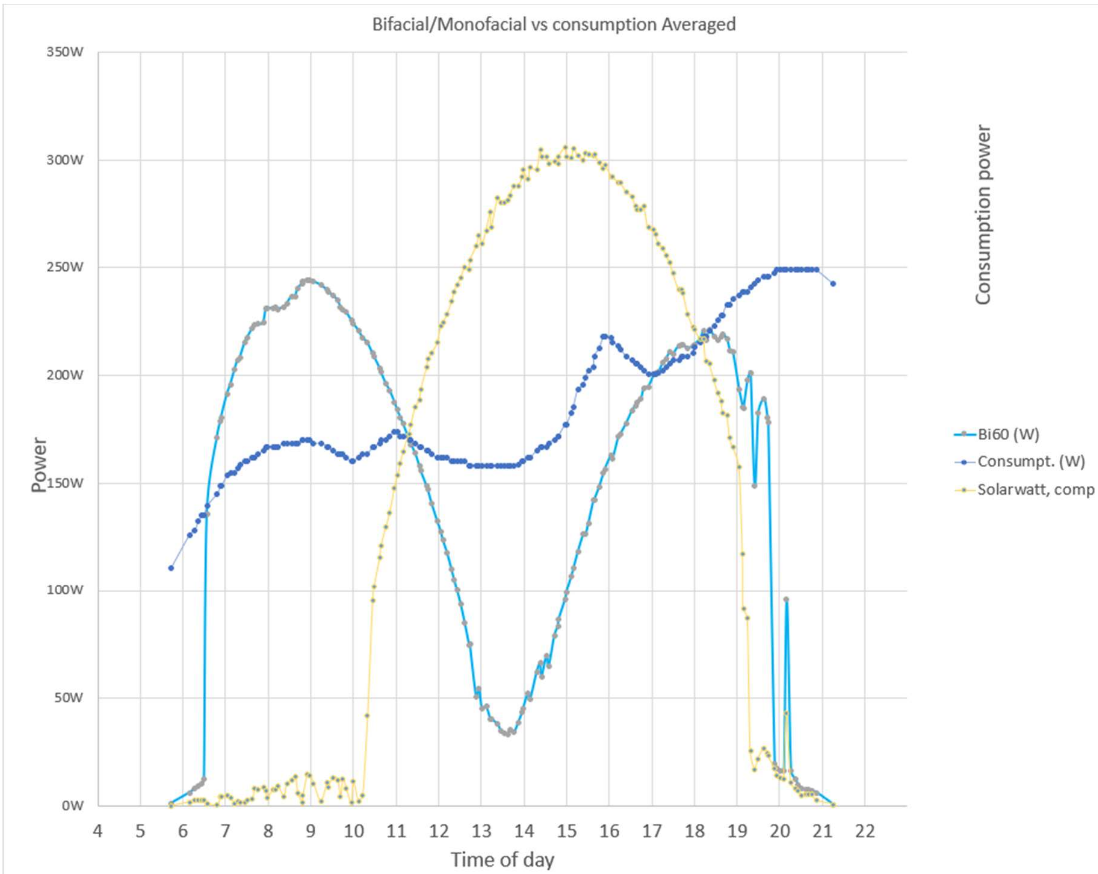


Graph 3. Vertical bifacial module (light blue), power normalised monofacial 43° facing 220° module and yearly daily average household consumption (dark blue, axis 2).

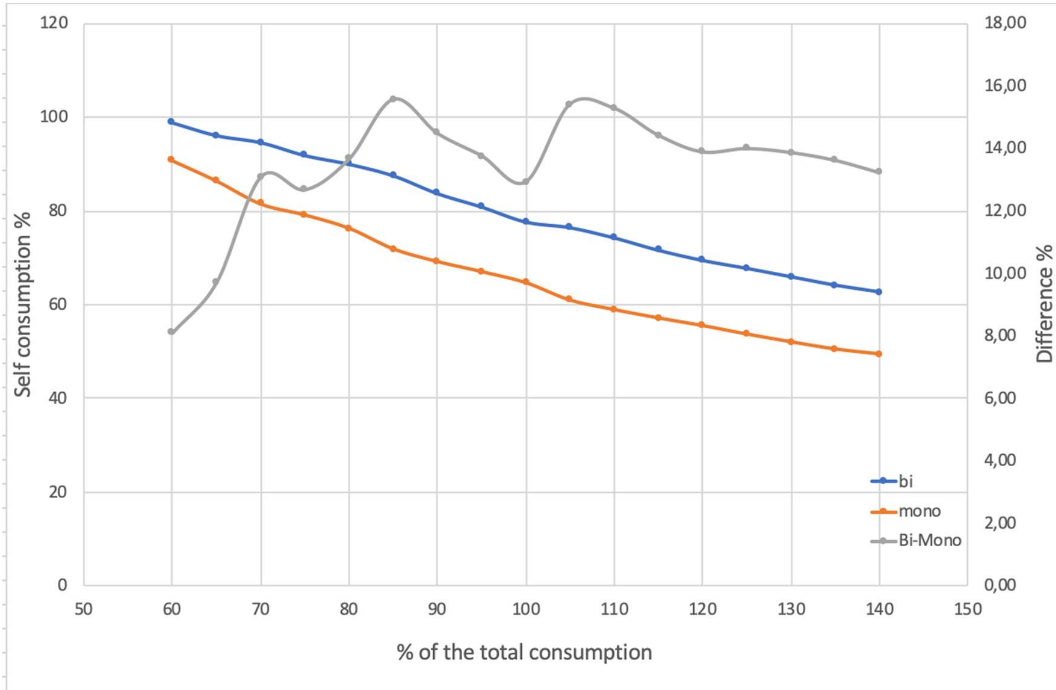
Table 1. Graph 3 in numbers.

Type	Avg. power	Total energy	% of the con-sumption
Bifacial	149 W	2282 Wh	23.9%
Monofacial (norm.)	123 W	1885 Wh	19.6%
Consumption	637 W	9760 Wh	100%

In Graph 4, the monofacial module was normalised to the same total energy production of the bifacial module (2282 Wh). Also, the consumption model was brought down to level where the modules produced 80% of the consumption each. This way the differences in self-usage could be studied.



Graph 4. Both modules normalised to the same daily energy production (2282Wh). 80% of the consumption (2850Wh).



Graph 5. Self-consumption of vertical bifacial module (blue), tilted monofacial module (orange) and the difference (grey, axis 2).

8 RESULTS AND CONCLUSION

Overall, the system is performing as designed. Slight shadowing can be seen from module 1 at early mornings. This is most likely caused by the tree located north of the system. The bifacial modules production clearly matches better with the morning consumption, as the mono facial has no production at all yet. However, the mono facial starts to catch up at noon when the bifacial modules output experiences the distinct vertical system dip. The lower efficiency of the backside of the bifacial module and higher ambient temperature causes the evening production to be lower, and thus the mono facial production equals to the bifacial system despite the later time.

With both module total energy output at 80% of the consumption, the bifacial production model had self-consumption of 90% while the monofacial achieved 76%. With the system sized to cover 90% of the consumption, the self-consumption values were 84% and 69% respectively. The dominant factor is how well does the middle day production of the monofacial system match the middle day consumption. If the system is sized so that maximum middle day production is equal or smaller than the base consumption, the difference between the two is smaller than 8%. When system size is increased, the bifacial system starts to gain more from the stretched production period. The difference peaks at 16% when the system covers 70% or 105% of consumption. If system size is increased even further, the two peaks of the bifacial production also go above the base consumption, and the bifacial system do not gain any more difference. But the bifacial system still has around 13% higher self-consumption rate. The overall self-consumption of course goes down as the system size is increased beyond the consumption.

The comparison of self-consumption is highly dependent of the consumption model, which can vary significantly from house to house. Also, only sunny day production was used in this comparison to isolate only one situation out of many. More in depth study with long term self-consumption rate would be needed to say which system performs better all year around in this particular environment. The monofacial module studied was not the most ideal comparison with tilt angle of 43° and azimuth of 220°. Comparison with module directed straight to South might be more useful but was not possible at the time of construction. Also, turning the bifacial system so that the more efficient front side would face West would impact the self-consumption rate. The rate might be higher with the consumption being also larger in the afternoon

8.1 Winter conditions

The system is performing as designed also in winter conditions. No snow accumulation was observed, although rapidly changing conditions did cause some ice to form to lower corners of the modules. The high albedo of snow and low direct irradiation results in flatter output, compared to the summer production. The module temperature measurement has proven to be difficult to do with high reliability, especially in cold temperatures. Efforts were taken to attach the thermocouples to the glass with many types of glues, tapes and combinations of both. But changing conditions and accumulation of ice between the glass and thermocouples still resulted in poor connectivity.

High speed wind from east or west causes the photovoltaic rail flex noticeably. While wind from North or South causes low frequency oscillation of the system. Additional bracing was added to the system to reduce the twisting torque at the end of the system where the vertical pillars meet the legs.

9 DISCUSSION

The project itself was interesting and I consider the subject as an important one. These kinds of systems seemed to be quite new, which did make some challenges, but resulted in rewards. I did also enjoy the hands-on aspect of this thesis, as I did get to build the system myself with the help of Turku university of applied sciences photovoltaic laboratory. Longer term results and more analytical approach to the data would be good next step for this study. I am interested to see what kind of applications or new innovations this kind of technology has ahead. During the of writing this thesis, it felt like increasing attention was towards bifacial modules. Although this might be due to increasing personal interest and following, but a lot of new pilot projects and tests did pop up. One big movement seemed to be using bifacial photovoltaics in tandem with agricultural business. Instead of using farm fields solely to produce energy, with bifacial modules which allow light to pass through, farming is possible underneath them. This would be specially interesting in densely populated counties like the central European ones, which have already seen land that was previously used for food production to be converted into solar power plants due to profitability.

I would like to thank Turku University of Applied Sciences for the possibility and the ongoing support for the thesis, as well as Sandia National Laboratories for their extensive interest and openness towards a common goal.

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