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UTILIZING SOLAR ENERGY IN HATCH COVER OPERATIONS

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UTILIZING SOLAR ENERGY IN HATCH COVER OPERATIONS

The objectives of this thesis were to study the possibilities of utilizing solar energy with electrically powered cargo hatch cover systems and the general potential of photovoltaic energy on ships. The thesis also includes an impact test for flexible CIGS PV module to assess its suitability in cargo ship environment.

The client of this thesis was MacGregor Finland Oy which is part of Cargotec group, the leading provider of cargo and load handling solutions. MacGregor's electrically operated MacRack hatch cover system is used as the research subject. Utilizing solar energy with MacRack was studied by creating several scenario configurations consisting of PV and battery systems. The operation of these scenarios was modelled using solar irradiation and electricity consumption data. The solar energy potential on ships was studied by creating several irradiation profiles for ocean areas using satellite data and estimating yield potential for solar modules based on that data. The CIGS module was tested by dropping rocks on the module and determining the effect of the impacts on the power of the module with electric measurements.

The results suggest that the irradiation on oceans gives good facilities for utilizing solar energy on ships. No technical obstacles for utilizing solar energy with MacRack was found, but none of the modelled scenarios was found financially viable. At the request of the client, the public version of the thesis describes only the general outline of the MacRack study. The background data, the test procedure and the results are described in detail in a confidential appendix delivered to the client. The CIGS test proved that if installed on cargo carriers, the modules need to be protected from the largest impacts. In conclusion solar energy is a great potential for ships, but utilizing it with MacRack should be discovered together with other systems on board.

KEYWORDS:

photovoltaics, battery energy storage, cargo ship, solar irradiation, CIGS thin-film

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AURINKOENERGIAN HYÖDYNTÄMINEN LASTILUUKUN OPEROINNISSA

Työn tavoitteena oli tutkia aurinkoenergian hyödyntämistä sähkökäyttöisten lastiluukkujen operoinnissa sekä aurinkoenergian potentiaalia laivoilla yleisesti. Näiden lisäksi työhön sisältyy taipuisan CIGS-paneelin mekaanisen kestävyyden selvitys, jonka perusteella arvioidaan paneelityypin soveltuvuutta rahtilaivaympäristöön asennettavaksi.

Työn tilaaja MacGregor on osa Cargotec-konsernia, joka on johtava lastin- ja kuormankäsittelyratkaisuja tarjoava yritys. MacGregorin valmistama sähkökäyttöinen MacRack-lastiluukkujärjestelmä oli tutkimuksen kohteena. Aurinkoenergian hyödyntämistä tutkittiin laatimalla useita aurinko- ja akkujärjestelmistä koostuvia skenaarioita, joiden toimintaa mallinnettiin auringon säteily- ja sähkönkulutusdatan pohjalta. Aurinkoenergian yleistä potentiaalia tutkittiin laatimalla satelliittidatan pohjalta merialueille useita säteilyprofiileja ja arvioimalla niiden perusteella aurinkopaneelien mahdollista tuottoa. CIGS-paneelin kestävyyttä tutkittiin pudottamalla paneelin päälle kiviä ja määrittämällä sähköisillä mittauksilla iskujen vaikutukset paneelin tehoon.

Tulokset osoittavat, että merialueiden säteily antaa hyvät edellytykset aurinkoenergian hyödyntämiseen laivoilla. Aurinkoenergian hyödyntämiseen MacRackin kanssa ei havaittu teknisiä esteitä, mutta yksikään skenaarioista ei ollut taloudellisesti kannattava. Toimeksiantajan toiveesta MacRack-tutkimus on kuvattu opinnäytetyön julkisessa versiossa ainoastaan pääpiirteittäin. Tutkimuksen lähtöarvot ja tulokset kuvataan yksityiskohtaisesti toimeksiantajalle toimitetussa salatussa liitteessä. CIGS-paneelin testi osoitti, että rahtilaivakäytössä paneelit tulee suojata isoimmilta iskuilta. Tuloksista voidaan päätellä, että aurinkoenergian hyödyntyntämiseen laivoilla on suuri potentiaali, mutta sen hyödyntämistä MacRackin kanssa tulisi tutkia yhdessä muiden käyttökohteiden kanssa.

ASIASANAT:

aurinkosähkö, akkujärjestelmä, rahtilaiva, auringon säteily, CIGS-ohutkalvo

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating current
Ah	Ampere-hour
BESS	Battery energy storage system
BoS	Balance of system
CAPEX	Capital expenditures
CIGS	Copper indium gallium selenide
DC	Direct current
ESS	Energy storage system
FF	Fill factor
I_{SC}	Short circuit current
kWh	Kilowatt-hour
kWp	Kilowatt peak
LCOE	Levelized cost of energy
MPPT	Maximum power point tracking
OPEX	Operational expenditures
P_{MAX}	Peak power
PV	Photovoltaics
RE	Renewable energy
VFD	Variable frequency drive
V_{OC}	Open circuit voltage
Wp	Watt peak
η	Efficiency

1 INTRODUCTION

1.1 Background

Climate change is one of the biggest challenges the world is facing today. Global warming caused by increasing level of greenhouse gases in the atmosphere has many effects such as increasing global temperatures, rising sea levels, changes in precipitation, and expansion of deserts. Extreme weather events are also likely. This includes events such as heat waves, droughts, heavy rainfall and floods. (IPCC, 2013) The change is happening too fast for plant and animal species to adapt and these changes have a negative effect on agriculture which can drive more people into poverty (National Geographic 2015). There exists a scientific consensus that global warming is extremely likely caused by human actions, primarily due to the emissions from fossil fuel combustion.

The marine transportation accounts for 2,5 % of global annual greenhouse gas emissions. Although shipping is an effective transportation method compared to air or road transportation, the volume makes it a significant source of emissions. Without curbs, the emissions of the shipping sector are predicted to increase 50 % – 250 % depending on the future developments. This kind of growth is not aligned with internationally agreed target of keeping the global temperature rise +2 °C comparing to the pre-industrial levels. (European Commission 2017.) In addition to the environmental issues, the shipping emissions are connected to serious health issues and according to a conservative estimate over 50 000 premature deaths annually in Europe alone (CEEH 2011).

The industry itself has recognized the need for emission reductions. International maritime organization (IMO) has set mandatory requirements of 10 % improvement on energy efficiency for all new-built ships from 2015 and 30 % improvement from 2025. IMO is currently preparing a detailed roadmap for CO_2 reduction. The roadmap will be published and agreed upon in 2018. The world’s principal shipping organization ICS has urged IMO to adopt ambitious regulation to keep the emissions below the 2008 level and to reduce the emissions per tonne-km to 50 % by 2050 comparing to the 2008 level. (ICS 2017.)

To reach this kind of emission reduction, the means the ships produce their energy needs to be rethought. One of the ways to improve the energy efficiency of a ship, is to improve the use of renewable energy (RE). Amongst other RE technologies, solar energy poses a great potential for reducing the emissions caused by shipping. Over the last decade photovoltaics (PV) markets have experienced exponential growth when the technology matured to be commercially viable around the world. The market growth and technological development are ongoing, and PV has become the fastest growing energy form in the world. PV technology is approved, and known technology and it has been utilized in different environments all over the world. However, despite the growing interest, there has been almost none large-scale commercial applications in marine environment as the existing applications are either small-scale systems or proof-of-concept projects. There is great potential for PV in marine use, but the special environment requires research and tailoring the technology.

This thesis was ordered by MacGregor Finland Oy which is a part of Cargotec group, the leading provider of cargo and load handling solutions. MacGregor is specialized in marine cargo handling and its products include hatch covers, lashing systems, cargo handling cranes, RoRo equipment, winches and offshore load handling equipment. The company has 2000 employees in 32 different countries. The sales in 2016 were 788 million euros. MacGregor sees sustainability as a business opportunity and has embedded it into the product development. (Cargotec 2017.)

1.2 Objectives

The main objectives of this thesis are to study the possibilities of utilizing solar energy with MacGregor’s MacRack electrically operated cargo hatch cover system and PV energy potential at ships in general. The thesis also includes an impact test for a CIGS PV module. The impact test aims to determine if the module type can endure the bulk carrier environment.

PV energy potential is studied mainly by gathering solar irradiation data from NASA SSE database, creating general irradiation profiles for the seas and deriving the PV yield potential from that data. Utilizing solar energy with MacRack is studied by modelling several test scenarios using the created irradiation profiles and an energy consumption profile derived from MacRack test bench measurements. The results are used to determine the costs and feasibility of such device configurations. The CIGS impact test is conducted by stressing the module with heavy impacts simulating the bulk carrier’s deck environment and measuring the possible changes in output power with an IV-tracer.

2 OVERVIEW OF PHOTOVOLTAIC TECHNOLOGIES

Generally, photovoltaics is understood as direct conversion of solar radiation into electric energy. It is based on the photovoltaic effect discovered by Alexandre Becquerel already in 1839. After various discoveries and technological advances, the first real solar cells were created on 1950’s and soon they were used as the energy source for satellites. In the following decades the use cases for PV were limited to satellites and remote locations on Earth. Technological development, national legislations and subsidies, and especially Germany’s Energiewende (energy transition) lead PV market to boom in 2000’s and PV soon became the fastest growing energy source.

The basis of a PV system is the photovoltaic cell which converts the sunlight into DC electricity. In a PV power plant multiple solar cells are connected in series to form solar modules which are further connected in series and parallel. Due to this modular structure PV can be scaled from powering very small appliances like pocket calculators to gigawatt-scale power plants. PV technology is utilizable all around the world, but the power and the yield are highly dependable on the available solar irradiation. Thus, PV plant’s output varies greatly depending on the plant location, weather conditions and the time of day and year. (Mertens 2014.)

2.1 Global market status

Photovoltaics market has for the last decade been an exponential curve. In 2016 installed capacity grew 50 %, being the fastest growing energy source of the world. The growth has been mainly due: feed-in tariffs, tax breaks and other incentives offered by governments and the falling costs caused by maturity of the technology and economies of scale. The uptrend of installed capacity and decreasing system costs are expected to be maintained in the following years. (IRENA 2017a.) PV’s share of global electricity production is anticipated to rise significantly in the following decades. DNV GL envisions that PV will provide one third of world’s electricity in 2050 (DNV GL 2017a).

2.1.1 Installed capacity

At the end of 2016 the total installed PV capacity amounted 303 GW globally (IEA Snapshot 2016, 7). This is over 50 times more than in 2006. The global cumulative growth of installed PV capacity is presented in Figure 1. The market growth was led by Germany until China overtook it in 2015 as the world's leader in installed PV capacity. China, USA and Japan are currently top 3 countries for annual installed capacity. The markets in China and USA are growing rapidly and 2016 was the first year when the global markets were growing although two major markets (Europe and Japan) were declining. Besides China and USA, the major developments of PV installations in 2016 too place in Japan, India and the UK. In the following years the growth is expected to be centered in China, India and USA as well as in the Gulf and Asian Pacific countries. (IEA 2016.)

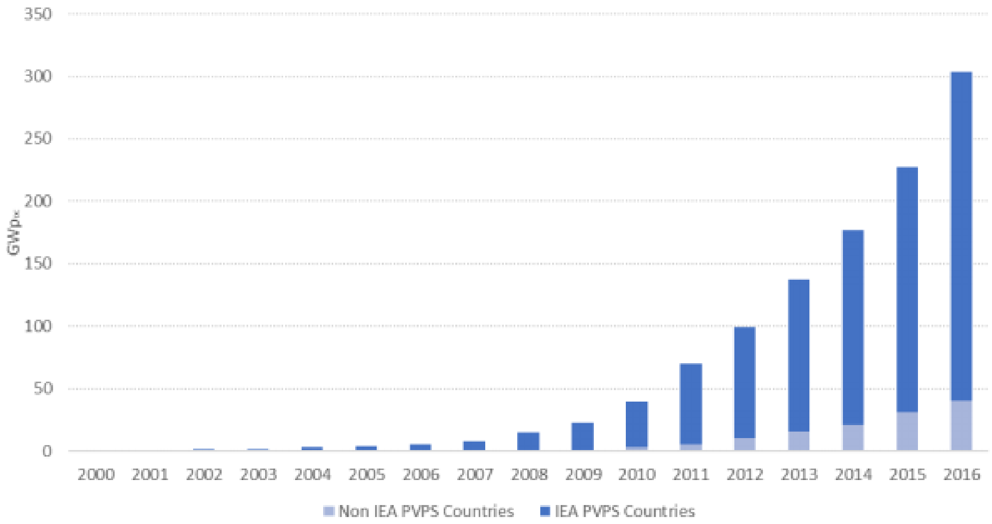


Figure 1. Cumulative globally installed PV capacity (IEA 2016)

Large utility scale systems have been dominating the markets in recent years. In 2015 over 60 % of installed capacity was centralized utility-scale systems the rest being smaller distributed grid-connected systems. The portion of off-grid systems is less than one percent. The share of utility scale systems is expected to keep growing. (IEA 2016.)

2.1.2 Cost of PV

Figure 2 shows the past and expected cost-structures for a utility scale system. Prices are global weighted averages. As it can be seen the current price development have been mainly due rapid decrease in module prices. The system costs are expected to maintain the downward trend, although module prices are not expected to decline at the current rate. The decline is assumed to be caused mainly by decline in prices of inverter, racking and other balance of system components (BoS) and installation and engineering work.

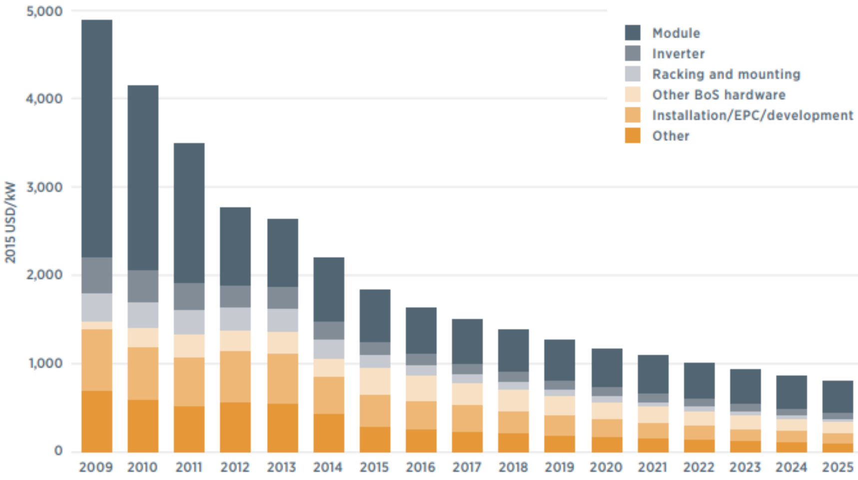


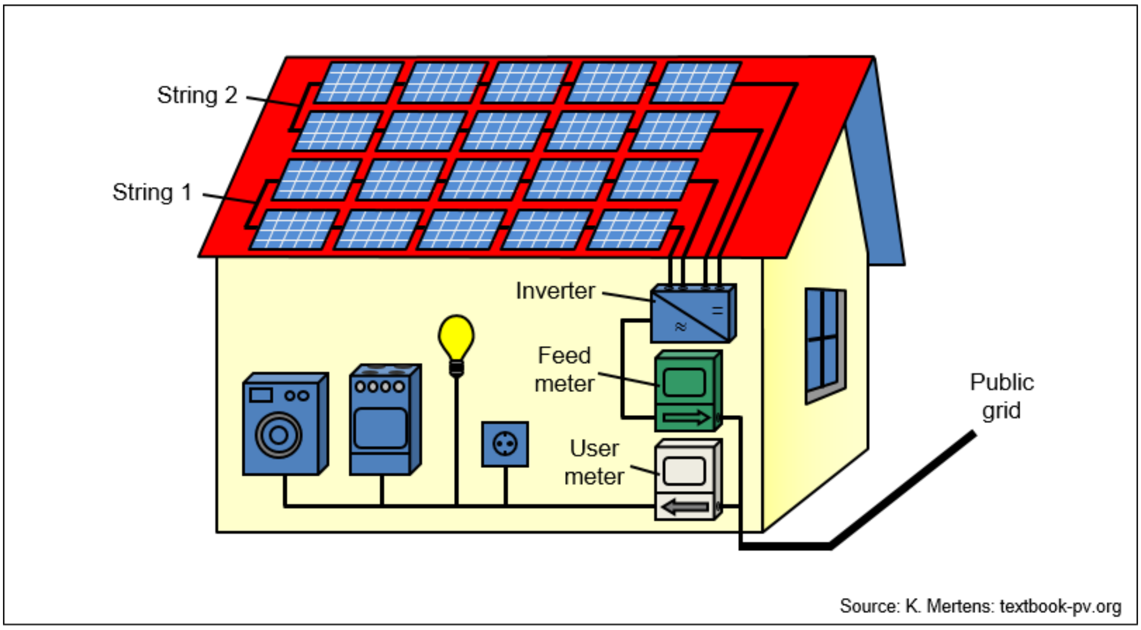
Figure 2. Cost break-down of utility-scale PV (IRENA 2017a)

2.1.3 PV in energy mix

Excluding hydropower, PV represents 29% of the installed RE capacity in the world. In 2016 PV covered 1,2 % of the global energy demand although the portion is significantly higher in some countries. Honduras has the highest percentage with over 12 % portion of PV. Italy is leading the IEA countries with its 8,4 %. Depending on distribution grid quality, high shares of PV can cause problems with the grid voltage regulation and power quality. (IEA 2016.)

2.2 PV systems

The main components of a typical PV system are the PV modules, the inverter, the cabling and the mounting system. The PV modules are connected in series called strings and the strings are connected to the inverter. Residential systems have usually one or two PV strings, but utility scale plants can have thousands of strings. All the strings together form a PV array. The array converts the sunlight into DC electricity, then the solar inverter converts the DC to AC electricity and after that the electricity can be consumed by electrical appliances or fed into the utility grid. A schematic diagram of a typical residential PV system is presented in Picture 1.



Source: K. Mertens: textbook-pv.org

Picture 1. Schematic diagram of a residential PV system (Mertens 2014)

PV systems can be divided to grid-connected and stand-alone systems. Grid-connected systems can be further divided to distributed and utility scale energy generation.

Distributed generation

In distributed generation the PV plants are usually located near the load and provide energy for a single end-user such as a residential house, a farm, or a business. A typical plant is a residential or commercial rooftop installation sized to fit the end user's consumption with surplus energy fed into the grid. Unlike utility scale generation, distributed generation can be readily utilized in any geographic location.

Utility scale generation

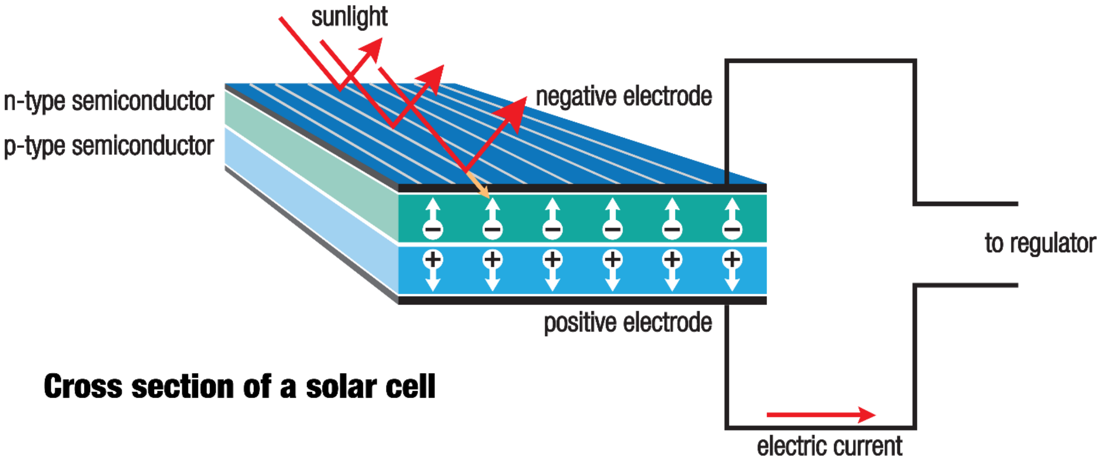
Utility scale PV plants typically provide a large amount of power to many end-users via the transmission grid. The plants consist of thousands of modules and are in MW-scale They are usually located at the point of best resource availability, in a high irradiation area but close to utility grid.

Stand-alone systems

Stand-alone or off-grid plants are usually located in remote areas where connecting to the main grid is not possible or it is too expensive. They can be for example farms, research stations, mines or villages in developing countries. Depending on the needs, the grid can be either AC or DC. The sizes vary from very small few hundred Wp to MW-scale plants powering whole communities. To ensure sufficient power and energy off-grid systems are often coupled with battery storage and other energy production such as wind turbines or diesel generators. (MIT 2015.)

2.2.1 PV module

The basis of every PV plant is the solar cell. The solar cells are made of semiconductor materials, usually silicon, introducing it to foreign atoms to create a p-n junction which forms an electric field. The operating principle is presented in Picture 2. When the sunlight hits the solar cell, it knocks electrons loose on the n-type semiconductor. If the layers are connected to a circuit, the loose electrons flow to the p-type layer forming an electric current.

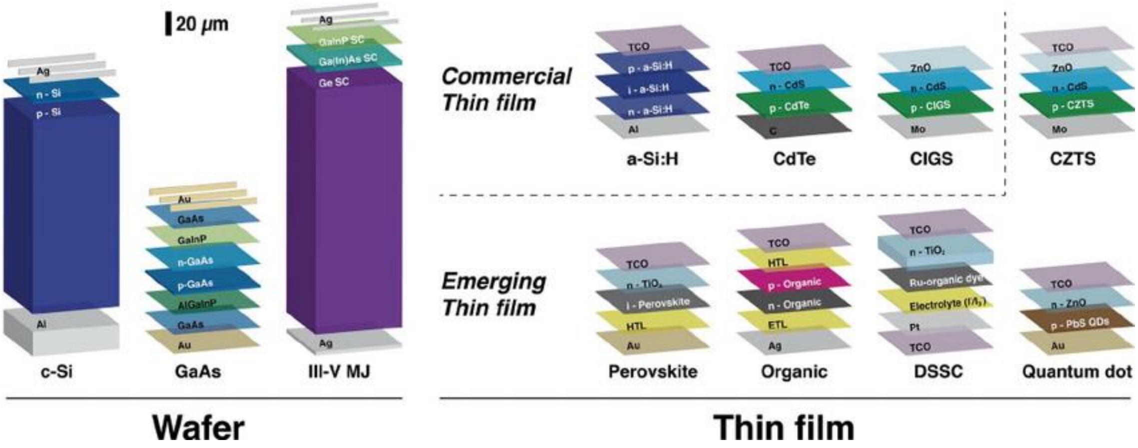


Picture 2. The operating principle of a solar cell (Visual Capitalist 2017)

Solar radiation creates a voltage of approximately 0,5 V. To achieve a usable voltage, the cells are connected in series to form a solar module. Solar modules are usually encapsulated and sealed between glass and plastic layers to protect the cells from environmental influence like moisture or mechanical impacts. The cells are interconnected using conductive strips which are combined in a junction box. The junction box has the conductors to connect the module to other modules and the load. (Mertens 2014.)

Cell technologies

Although crystalline silicon (c-Si) dominates the PV markets, there exists a wide variety of different cell technologies on the market and in development. They are usually named after the semiconductor material used (Picture 3). Cell technologies can be divided into wafer-based and thin-film technologies. Thin-film technologies can be further divided to commercially available and emerging technologies.



Picture 3. Cell technologies available (MIT 2015)

Crystalline silicon (c-Si) is the dominant cell technology accounting for over 90 % of the PV production. C-Si cells can be divided to mono- and polycrystalline cells. Monocrystalline cells have a single-crystal structure and they have the highest efficiency and longest estimated lifetime of all commercial PV-cells. Polycrystalline cells consist of several small crystals. They have slightly lower efficiency and shorter estimated lifetime than monocrystalline cells but since they are more cost-efficient to manufacture, they are the most common PV cell type on the market. Other wafer cell technologies GaAs and III-V multijunction are breaking the efficiency records in the laboratory but have not been viable for commercial manufacturing.

Thin-film solar cells use materials that absorb light 10-100 times more efficiently than silicon and thus the films don’t need to be more than few microns thick. The cell structure can be deposited on many different surfaces, such as glass, metal or plastic. Depositing the thin-film on flexible plastic makes building integration and other unconventional applications possible. Compering to c-Si, the manufacturing process is less complex and uses less materials. Commercially available thin-film cells are primarily amorphic silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). There are also several emerging thin-film technologies like organic or perovskite solar cells. Although they are under extensive research and have showed great potential, even in best case these technologies are still years away from commercial products.

A-Si is a non-crystalline form of silicon. It used to have a significant market share, but it failed to keep up with price of c-si and efficiency of other thin-film technologies. CdTe cells are the leader of thin-film technology in installed capacity. It also has a good commercial efficiency and affordable price. Toxicity of cadmium and scarcity of tellurium is making it unideal cell technology. CIGS has faced challenges manufacturing a consistent product in the past but in recent years it has become a true rival for CdTe. But like with CdTe, scarcity of indium and tellurium may be a major barrier for achieving large-scale deployment and reduction is production costs.

C-Si cells dominate the markets and will keep dominating in at least for the next decade. Although, it has many disadvantages such as high initial cost due complex manufacturing process, fragile and rigid structure. The thin-film technologies have the potential to decrease the production cost and the module's carbon footprint. The future visions of high PV shares are not dependable on technological development and can be achieved despite of the limitations of c-Si and other current cell technologies. (MIT 2015.)

Characteristics

PV module's electrical characteristics are dependable on solar irradiation and to a lesser extent on temperature and other ambient conditions. That's why the nominal values for modules are defined in laboratory in so called Standard Test Conditions (STC). In STC the irradiance is 1000 W/m^2, cell temperature is 25 °C, light spectrum is 1.5 AM.

The most important characteristic for solar module are: short circuit current (I_{SC}), open circuit voltage (V_{OC}), peak power (P_{MAX}), fill factor (FF) and efficiency (η).

Short circuit current is the current delivered by solar module when it is short circuited, and the voltage is thus 0. It is the largest current possible to be drawn from a solar module. The second extreme is open circuit voltage which occurs at zero current. It is the maximum voltage available from solar module. Peak power or maximum power point is the maximum power output of the PV module. Figure 3. presents how it can be defined as the largest rectangle that can be fit under the I/V curve. (Mertens 2014.)

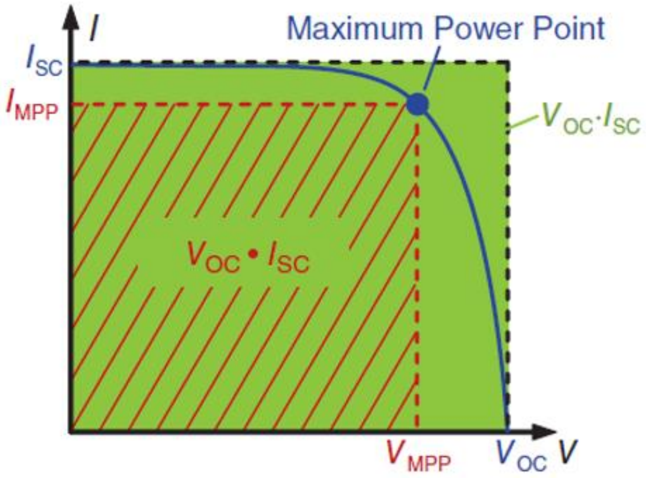


Figure 3. Maximum power point of a solar cell (Mertens 2014)

Fill factor is a measure of quality of the solar cell. It is a ratio of the maximum power and the theoretical maximum power. It can be defined using the following equation:

$$FF = \frac{P_{MAX}}{V_{OC} I_{SC}}$$

where

FF	fill factor
P_{MAX}	peak power
V_{OC}	open circuit voltage
I_{SC}	short circuit current

Solar module’s efficiency is the ratio of the output electrical power and input optical power incident on the module. Efficiency can be defined using the following equation:

$$\eta = \frac{P_{MAX}}{P_{IN}} = \frac{V_{OC} I_{SC} FF}{P_{IN}}$$

where

η	efficiency
P_{MAX}	peak power
P_{IN}	solar irradiance on module’s aperture area
FF	fill factor
V_{OC}	open circuit voltage
I_{SC}	short circuit current

2.2.2 Inverter

The purpose of solar inverter is to convert the DC electricity produced by PV modules into a utility frequency AC and get the maximum power output from the PV array using maximum power point tracker (MPPT). The purpose of the MPPT is to obtain the maximum power in varying conditions by constantly sampling the output from the modules and applying the proper resistance. The inverter is an essential system component as it allows the use of AC-powered equipment in PV systems. Solar inverter configurations can be divided to string inverters, central inverters, micro-inverters and DC-DC power optimizers.

String inverters are used in all sizes from residential to utility scale PV-systems. A string inverter has typically one or two string inputs with separate MPPTs. A PV string is controlled as one unit. Central inverters are designed for large commercial and utility-scale plants. They are basically just large string inverters with only on MPPT that can be connected to up to hundreds of strings. The module strings are connected to the central inverter through a combiner box where the strings are combined. In central inverters the cost per kWp is lower than with string inverters but in recent years the price difference has decreased, and string inverters have become popular in large-scale as well.

Micro-inverters are installed for each separate PV module and the DC-AC conversion takes place at module. Micro-inverter offers MPPT and monitoring for every individual module. This is good especially when there is shading or if the modules are facing to different directions. DC-DC optimizer has many of the same benefits as micro-inverters.

The difference is that DC-DC optimizers do not convert the electricity to AC but tunes the DC output to the string inverter. Optimizers also tend to be more cost-efficient. Micro-inverters and DC-DC optimizers have become more popular in recent years especially in residential systems. (Energysage 2017.)

2.2.3 Other components

Other components include DC and AC-cabling, the mounting system and the monitoring system. The mounting system is the supporting structure where the modules are physically fixed to. There exist various kinds of commercial mounting systems for roof and ground installations, a custom-made mounting system can also be used or in some cases a mounting system is not needed for example if the modules can be attached to a roof using adhesive. In a typical mounting system aluminum bars and clamps are used for fixing the modules. In some PV installations the mounting system includes a solar tracker, which is a device that orients the modules towards the sun to maximize the power. Trackers were more common in the past but due the decreased PV module prices they are cost-effective only in areas with high irradiation and majority of it being direct radiation.

A monitoring system is an essential part of a proper PV system. It is used for monitoring the output power and yield of the system and making certain that the system is operating as intended. In residential systems a sufficient system is often provided by the inverter manufacturer and the monitoring can be made from the inverter’s screen or from an online service. For commercial systems there exists separate monitoring systems and services with more diagnostic tools. (Mertens 2014)

2.3 Solar radiation

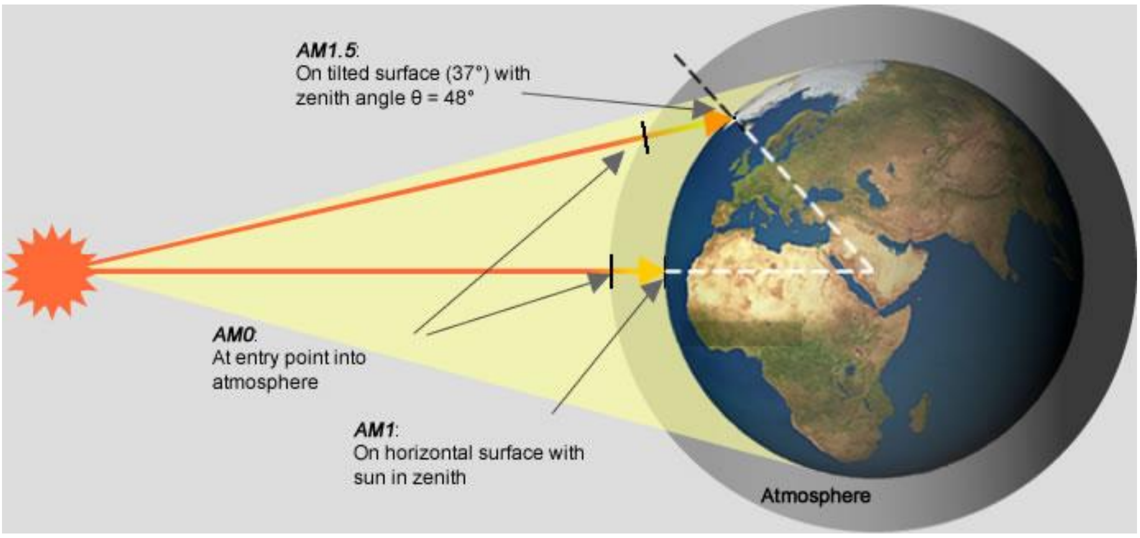
PV can be utilized anywhere where there is solar irradiation. The yield and output power of a PV system is highly dependent on the available irradiation and its spectrum. The Sun is a radiating constantly at the power of $P_{Sun} = 3.845 \times 10^{26}$ W in all directions. At the Earth’s orbital distance, the power density of the solar radiation, or irradiance, is 1367 W/m^2. This value is called solar constant and it represents the irradiance outside the Earth’s atmosphere and thus the theoretical maximum irradiance on any surface on the

Earth. Earth receives 1.119 · 10^{18} kWh of radiation energy in a year. That is more than 7000 times the worlds yearly energy consumption. (Mertens 2014)

2.3.1 Spectrum

When the radiation passes through the atmosphere its spectrum changes for various reasons. Some of the radiation is reflected away from atmosphere, some parts are absorbed in the atmosphere's molecules and some radiation scatters due to molecules, aerosols and dust particles. The effect of the spectrum changes is greater, the longer the light travels in the atmosphere. The air mass coefficient (AM) is used to characterize the spectrum. It is based on the length of the path light travels in the atmosphere.

This depends on the Sun's height angle which varies with the latitude of the observation point, the time of the day and with the passing of the seasons of the year. Outside Earth's atmosphere the spectrum is referred as AM0. AM0 This value can be used for space power applications. As seen in Picture 4, AM1, the shortest possible path through the atmosphere, is achieved when the Sun's height angle is 0° and it's directly overhead. AM1.5 is considered as average year's spectrum and is used as a standard spectrum for measuring solar modules. (Mertens 2014)



Picture 4. Different air mass coefficients (Green Rhino Energy 2013)

2.3.2 Global radiation

The radiation scatters in the atmosphere and if the whole AM1.5 spectrum is summed up, the result is 835 W/m^2, which is only 61 % of the radiation outside the atmosphere. This is so-called direct radiation. In addition to this, some of the scattered radiation arrives from various directions forming the diffuse radiation. Direct and diffuse radiation together form global radiation, which is the total irradiance on horizontal surface on the Earth.

$$E_G = E_{Direct} + E_{Diffuse}$$

where

E_G	global radiation
E_{Direct}	direct radiation
$E_{Diffuse}$	diffuse radiation

On a clear sunny day, the maximum global radiation is approximately 1000 W/m^2 which is used as a standard value for STC. Higher radiation may occur when the portion of the diffuse radiation is increased from the reflection of snow, ice or clouds.

The amount of global radiation in different locations around the world varies highly. Even on the same latitudes the differences can be big because of the influence of the climate, the local weather conditions, geography and pollutions. Radiation is measured in weather stations around the world. The radiation data is usually integrated over time to irradiation, typical unit being kWh/m^2. Irradiation data is gathered in databases and irradiation maps which can be used for planning PV plants or evaluating solar potential for different locations. (Mertens 2014)

3 OVERVIEW OF BATTERY ENERGY STORAGE SYSTEMS

The PV systems modelled in this thesis are coupled with battery storages. For that reason, the basics of battery energy storage systems should be covered.

A battery energy storage system (BESS) is a type of electrical energy storage system. There are various other ways to store electrical energy such as a flywheel, compressed air or super capacitors, but BESS is the choice for most applications due to the high efficiency and energy density of batteries. The use of an energy storage system enables storing electricity and utilizing it when it is the most beneficial for system operation. Typical applications for BESS are powering portable devices, reducing fuel use in hybrid power systems, balancing the electrical grid, and implementing renewable energy sources.

A battery is a device that stores electrical energy using electrochemical reactions. The Italian inventor Alessandro Volta invented the first electrochemical battery already in 1799 and the first practical applications were introduced already in the 1800's. Nowadays the use of batteries is increasing due various reasons including: technological development, lower energy demand, increased demand for portable devices, electrical vehicles and increased use of renewable energy. The commercialization of lithium-ion batteries has provided new possible applications for batteries and the falling costs of storage (Figure 4) make sure that batteries will have a major role in the future power systems. (Rahn & Wang 2013.)

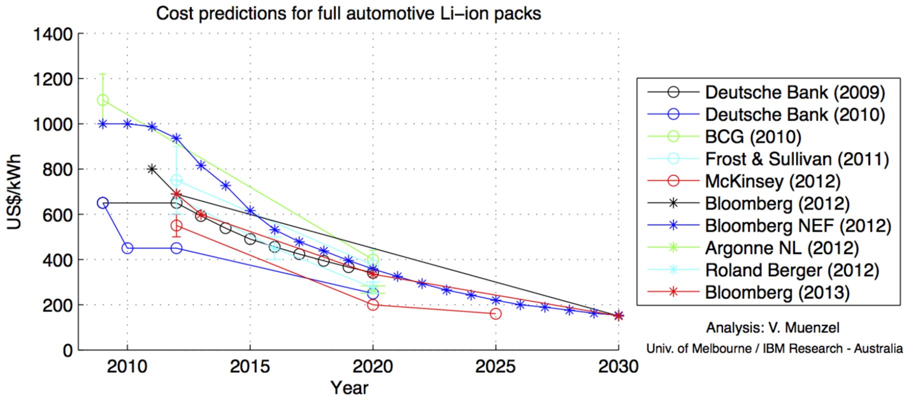


Figure 4. Cost prediction for EV batteries (Solar Heroes 2017)

3.1 Battery energy storage system

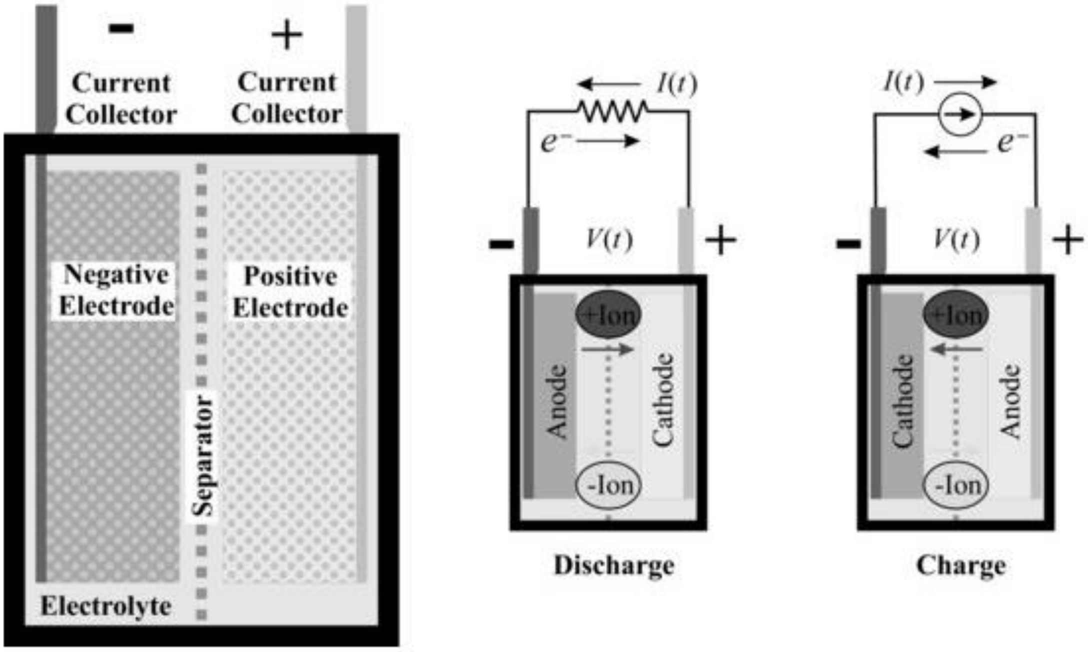
A battery energy storage system (BESS) converts electrochemical energy into electrical energy while discharging and electrical energy into electrochemical energy while charging. BESS consists of battery storage, a power conversion system and a battery management system. There are wide variety of different type batteries on the market. The characteristics vary greatly between different batteries depending on the battery’s technology, chemistry, manufacturer and model. In general, the batteries are optimized either for high-power or high-energy use but not for both. The battery should always be selected based on the needs of the application. (IRENA 2017b.)

3.1.1 Secondary batteries

Rechargeable electrical batteries are referred as secondary batteries to differentiate them from disposable primary batteries. They can be divided to low temperature (li-ion, lead-acid), high temperature (molten salt) and flow batteries. The scarcity of some component materials is a limiting factor for larger-scale manufacturing. A selection of some of the most common battery technologies are described in the following.

There are many different battery technologies, but they all operate on the same principle based on electrochemical reactions and the flow of electrons and ions inside a battery cell. There are two circuits, the internal which allows the ions to move and the external that completes the circuit and allows the electrons to move. A battery cell consists of four main components: two electrodes: an anode, which connects to the negative terminal and a cathode, which connects to the positive terminal; a separator which separates the electrodes from each other; and the electrolyte which functions as the internal circuit. The anode builds up negative charge and the cathode builds up positive charge, this creates the cell voltage.

In discharging process an oxidation reaction occurs in the anode leading it to lose positive ions and electrons. The positive ions move to the cathode via the electrolyte and electrons flow through the external grid. The cathode collects the electrons and a reduction reaction occurs in the cathode material leading it to gain electrons and releasing ions to the electrolyte. In a charging process outside power is provided in the external grid and the process is the opposite. The oxidation reaction occurs in the cathode and the reduction reaction in the anode returning the battery back to its original state. (Rahn & Wang 2013.) The charging and discharging processes are presented in Picture 5.



Picture 5. Charging and discharging mechanism of a Li-ion battery (DNV GL 2016)

Lithium-ion battery

Lithium-ion batteries were first introduced in the early 90’s and due to their high energy and power density, they soon became the most important technology for mobile consumer devices. Increased costs made them attractive choice for electric vehicles too. The growth of electric vehicle markets lowered the battery prices and made Li-ion an economic choice for stationary BESS as well.

In general Li-ion batteries offer high energy and power density, excellent round-trip efficiency, relatively long lifetime, good cycle life, and high-power discharge capability. The main disadvantages include safety concerns which require additional features and arrangements, and relatively high cost. Although Li-ion batteries are often discussed as a homogenous group, there exists many different chemistries such as NMC, LMO NCA, LFP, LTO, etc., and each chemistry has their own advantages and disadvantages. The chemistry used should be selected based on the requirements of the BESS application. For some applications for example high energy density is required while some systems are optimized for low-cost or long lifetime. Li-ion is still relatively new technology and it is under very extensive development. It has a lot of cost-reduction potential and it is anticipated to experience a boom across all sectors. (IRENA 2017.)

Lead-acid battery

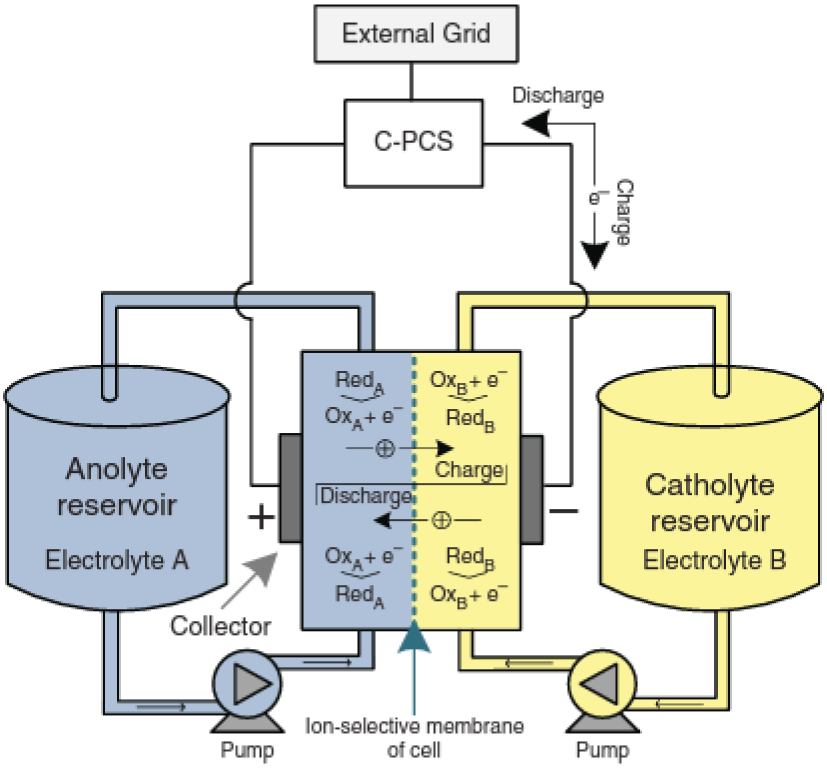
The lead-acid battery is the most used battery type and it has been commercially used since 1890's. It is a mature and well-researched technology which is used both in stationary and mobile applications. Its typical applications are emergency power systems, PV off-grid systems, vehicle starter batteries and mitigation of output fluctuation of wind turbines. The advantages of a lead-acid battery are the low cost, simple charging technology and high recyclability. The major disadvantages include the low energy-density, limited number of full dischargers, poor cycle life and high maintenance. Despite the disadvantages it is widely used in various applications. (IRENA 2017b.)

Molten salt batteries

As the name suggests, molten salt batteries use molten salt as an electrolyte and thus require high temperatures to operate. The most common molten salt technologies are sodium-sulphur (NaS) and sodium nickel-chloride ($NaNiCl_2$ or ZEBRA). NaS batteries use sulphur as the positive electrode and molten sodium as the negative electrode. They have relatively high energy density and efficiency. NaS batteries can offer affordable storage for long lifetimes in stationary applications like peak-shaving. The disadvantages include the relatively high operation cost as NaS batteries need to be heated to over 300 °C to keep the electrodes molten. $NaNiCl_2$ uses nickel chloride as positive electrode and its minimum operating temperature is 157 °C. It was originally developed to electric vehicle use and has better safety characteristics and higher cell voltage than NaS batteries. It features also good energy density and low maintenance. Besides electric vehicles it can also be used in stationary applications. (IRENA 2017b.)

Flow battery

Just like conventional batteries, the operation principle of flow batteries is based on electrochemical reactions taking place in electrochemical cells. The operating principle is presented in Picture 6. Unlike in conventional batteries, the electrolyte is not permanently located in the cells. In flow batteries two aqueous electrolytes, A and B, are in two separate containers. During the charging process, the electrolytes are pumped through electrochemical cells where electrochemically active material dissolved in electrolyte A oxidizes the anode and active material in electrolyte B reduces the cathode. The discharging cycle is the opposite.



Picture 6. Operating principle of a flow battery (Díaz-González, F. et al. 2016)

Flow batteries have many benefits. They are easily scalable and can offer almost unlimited energy capacity simply by using larger electrolyte containers. They are also suitable for long-term storing as the self-discharge rate is very low or even nonexistent and can be fully discharged without damaging the battery. Flow batteries can also be recharged without power simply by replacing the electrolytes. Unlike with conventional batteries, the power and energy components are separate and can be optimized regardless of each other. The disadvantages of flow batteries are the relatively low efficiency and poor specific energy and energy density which make the batteries much bigger and heavier when compared to li-ion batteries.

Currently the most mature flow battery technologies are vanadium redox battery (VRB) and Zinc bromine battery (ZBB) but other chemistries are also being developed. Flow batteries have many great advantages but due to their limitations they are best suitable for large stationary use such as grid storage. The technological and economic development look promising and in the future flow batteries are expected to challenge li-ion batteries in smaller applications as well. (Díaz-González, F. et al. 2016.)

3.1.2 Super-capacitor

A super capacitor is technically not a battery, but it was included here as its operating principle is similar and in many cases, it can be used the same way as batteries. The main difference between super-capacitors and batteries is that in super-capacitors the electricity is not stored in electrochemical reaction but in an electric field. This difference allows super-capacitors charge and discharge much faster than batteries are capable of. In addition to very fast charge and discharge rates, the main advantages of a super-capacitor are very long cycle life, high efficiency and high-power density. The disadvantages include very low energy density, high self-discharge rate and high cost. Super-capacitors are under extensive research and they are anticipated to have a significant role in future energy systems. (Díaz-González, F. et al. 2016.)

3.1.3 Other components

Besides the battery, a BESS has other mandatory components. The other main components are the power conversion system and the battery management.

Power conversion system

The power conversion system is a device used for charging and discharging the battery, typically it is a battery charger. Its configuration depends on the grid topology but typically in AC grid it is a two-way AC-DC inverter and in DC grid a two-way DC/DC converter. If the BESS is coupled with a PV system, the battery can in some cases be charged with a PV battery charger as well. In this case, a separate battery inverter is also needed.

Battery management system (BMS)

The BMS is a system in charge of monitoring and controlling the battery to ensure proper and safe operation. It has many inputs for measuring and estimating the battery's voltage, current, temperature, state of charge (SoC), depth of discharge (DoD) or state of health (SoH). By controlling and monitoring these parameters, the BMS has a great influence on battery's lifetime. (Díaz-González, F. et al. 2016.)

3.1.4 Battery characteristics

There are many specific terms and units used to describe the characteristics and condition of a battery. A collection of the most important terminology is presented in Table 1. (MIT 2008.)

Table 1. Basics of battery terminology

Term	Explanation
C-rate	Used for describing the battery's charge or discharge current. For example, 1C rate means that the discharge current will discharge the whole battery in one hour.
Specific power (W/kg)	The maximum available power per unit mass.
Specific energy (Wh/kg)	The nominal energy per unit mass.
Energy density (Wh/l)	The maximum available energy per unit volume.
Power density (W/l)	The maximum available power per unit volume.
Capacity (Ah)	The total amp-hours available at a certain C-rate from 100 % to cut-off voltage.
Energy (Wh)	The total watt-hours available at a certain C-rate from 100 % to cut-off voltage.
Cycle life	The number for discharge-charge cycles the battery will last before it fails to meet specific performance criteria
Cut-off voltage	Minimum allowable voltage. At this voltage the battery is usually considered "empty".
State of charge (SoC) (%)	The present condition of battery capacity in percentage of maximum capacity.
Depth of discharge (DoD) (%)	The percentage of battery capacity discharged as percentage of maximum capacity.
Terminal voltage (V)	The voltage between the terminals while under load. Varies with current and SoC.
Open circuit voltage (V)	The voltage without load. Depends on SoC and increases with it.

3.2 BESS in marine environment

Battery energy storage systems provide the same benefits in marine use. A BESS makes it possible to store electrical energy and use it when it is the most beneficial for system operation. The space required and expected lifetime of lead-acid or NiCd batteries made larger storage systems impractical. Commercialization of li-ion batteries have made large scale applications on ships possible. These applications include hybrid and fully electric propulsion systems, providing auxiliary systems and electrical appliances, and integrating renewable energy sources. When designing a BESS for marine use a special emphasis should be put on the safety of the selected technology. In larger storage systems international regulations apply (see 3.3.1). (DNV-GL 2016.)

Two examples of battery energy storages in marine use described in the following. The first one is a hybrid ferry and the second one is a fully battery-powered autonomic container ship.

FinFerries Elektra

FinFerries Elektra is a hybrid ferry that started operating in the summer of 2017 between Nauvo and Parainen in the Turku Archipelago. The ferry is 98 meters long and has the capacity for 90 cars. It was built in Crist S.A. shipyard in Poland. The 1 MWh lithium-ion battery storage is charged at each end of the 1,6 km route with shore-side electricity. In addition to the batteries it has three 420 kWp diesel generators to ensure sufficient propulsion power during winter in difficult ice conditions. Elektra is also equipped with 30 kWp of solar modules that produce electricity to the crew facilities. (FinFerries 2017.)

YARA Birkeland

Norwegian fertilizer producer YARA and maritime engineering group Kongsberg are developing the first fully battery powered and autonomous ship to manage regional deliveries. The ship will be 79,5 meters long, it will have deadweight capacity of 3200 mt. It will be propulsed with an electric system powered by battery storage with the capacity of 7-9 MWh. The ship has no ballast tanks as battery pack is used as permanent ballast. It will start testing in 2018. (Kongsberg 2017.)

3.2.1 DNV GL class rules and regulations

DNV GL is world’s largest maritime classification society with tonnage market share over 27 % of ship-newbuilding classification contracts. It sets class rules, standards for ships. These class rules comprise safety, reliability and environmental requirements that all vessels operating on the international waters must comply with. (DNV GL 2017b)

DNV GL has published tentative rules for using battery systems on-board vessels. These rules focus primarily on appropriate and safe installation and operation of battery systems. The rules include notations about system design such as proper dimensioning and arrangement of components; operational environment control; proper operation; testing and monitoring the system; fire and other safety assessment. The safety requirements for Lead Acid and NiCd batteries are specified in DNV GL Rules Part 4 Chapter 8. Lithium-ion and all other battery types are covered in Part 6 Chapter 2.

There are two class notations, Battery(Power) and Battery(Safety). Battery(Power) is mandatory when the battery power is used as propulsion power during normal operation. Battery(Safety) is mandatory for systems using battery power as an additional source of power and has the battery capacity exceeding 50 kWh. If the safety requirements are met, the class notation Battery(Safety) can also be given to battery with smaller capacity. (DNV GL 2016)

4 MACRACK-SYSTEM

MacRack is MacGregor’s electrically operated system for side-rolling cargo hatch covers on bulk cargo vessels. An electric system offers many advantages when compared with conventional hydraulic systems. The installation is faster and less complicated as there is no need for pipes, pumps, valves and other hydraulic components. Drive and lift operations are combined, making separate hatch cover lifters unnecessary. Monitoring the system is easier and more reliable. Maintenance is easier and more cost efficient. There is also no risk of environmental damage from hydraulic oil leaks. (MacGregor 2015.)

4.1 Technical details

The main components of the system are: MacRack units for each cover panel (Picture 7), control stations for each hatch and two control cabinets installed in a sheltered area. The MacRack units consist of a drive unit connected to the hatch coaming and the weather deck and lift consoles, rack extension and panel rack connected to the underside of the panel. The control stations are used for operating the hatches. Every MacRack unit is connected to the control stations which are connected to the control cabinets.

Picture 7. A MacRack unit

The control cabinets are connected to 3-phase ship power (380-440 V) and they function as power input and logic for the MacRacks. One of the cabinets contains the variable frequency drives (VFD) and the other one the programmable logic controllers (PLC). The hatches are operated by connecting portable operation units to control stations. The drive unit contains an electric motor which rotational force is converted into lifting and horizontal movements by the unit's mechanics. The power fed to the motors is controlled by the VFD and PLC so that the switch from lift operation to drive is automatic and the used power is always optimized.

In case of blackouts on the ship or other system failure, MacRack has an auxiliary operating unit (AOU) as a backup system which can be connected to shore power (380 - 440 V). It is built on a hand truck, so it can be pushed next to each hatch and connected to the control station where the hatch panels can be manually driven. (MacGregor 2015.)

4.2 Energy consumption

The energy consumption profile is essential for accurate sizing of the PV and battery systems. The energy consumption of MacRack consists of the consumption from operating the hatch covers and heating the idle motors to prevent condensation. Hatch cover operations form only a small portion of the total energy consumption although the required peak power is high. The peak power varies depending on the panel sizes and how many groups are operated simultaneously. One group consists of two MacRack units installed on one hatch. Typical setup allows 1-3 groups to be operated simultaneously but this can be adjusted according to customer wishes. To cut the peak power, it is possible to operate the groups in a multistage so that the lift operations of the groups won't overlap.

MacGregor conducted tests on their MacRack test bench in China. The MacRack system was driven in various loads representing different hatch panel sizes. Electrical parameters like voltage, current, output power and torque were acquired from the electric motor and frequency converter. As it can be seen in Figure 5, the power needed is not constant and is peaking during the lift operation.

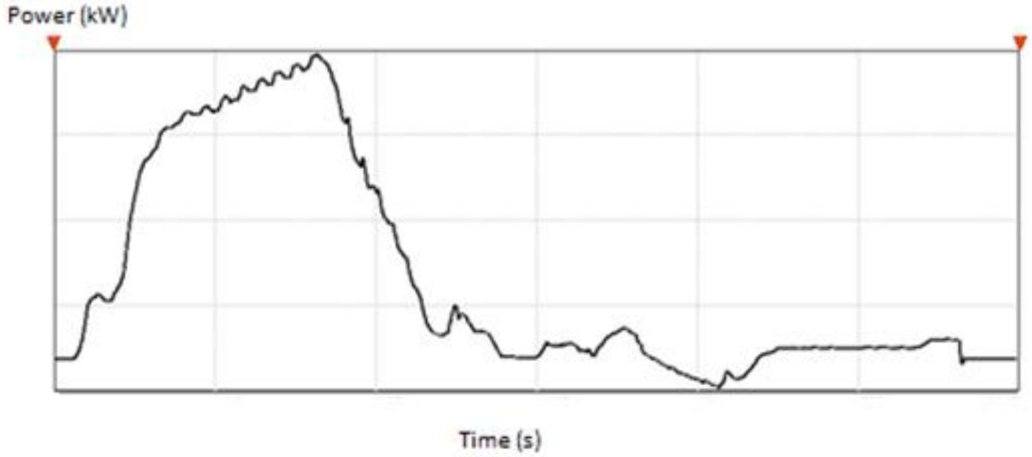


Figure 5. Graph of the power needed when operating a MacRack unit (screen capture from a monitoring tool)

Anti-condensation heaters

The motors are not hermetically sealed and thus moisture condensation may occur and cause corrosion inside the motor. To prevent condensation the surface temperature inside motor needs to be kept above the dew point. In the current MacRack design condensation is prevented by running the motors periodically while idle. In the future design, the electric motors will be replaced with a different model and the motors are equipped with anti-condensation heaters. The heaters can be set to heat on constant power or the power can be controlled based on relative humidity inside the motor or the temperature difference between the inside and ambient temperature. Anti-condensation heating forms a majority of the consumption of MacRack and oversized heaters would increase the consumption significantly. Without the inside and ambient temperature and humidity data, proper sizing is impossible. These calculations use the assumption that the heaters would be heating constantly on 100 W power.

5 SOLAR ENERGY POTENTIAL ON SHIPS

The emission reductions IMO is planning for the shipping sector require completely rethinking the way the ships produce their energy. Renewable energy technologies will have a big role in that change. Beside other RE technologies, there is a lot of untapped potential in solar energy. Figure 6 shows that the oceans are areas of high irradiation. Many of the busiest shipping lanes are in those high irradiation areas and thus there is great energy generation potential for PV energy on ships.

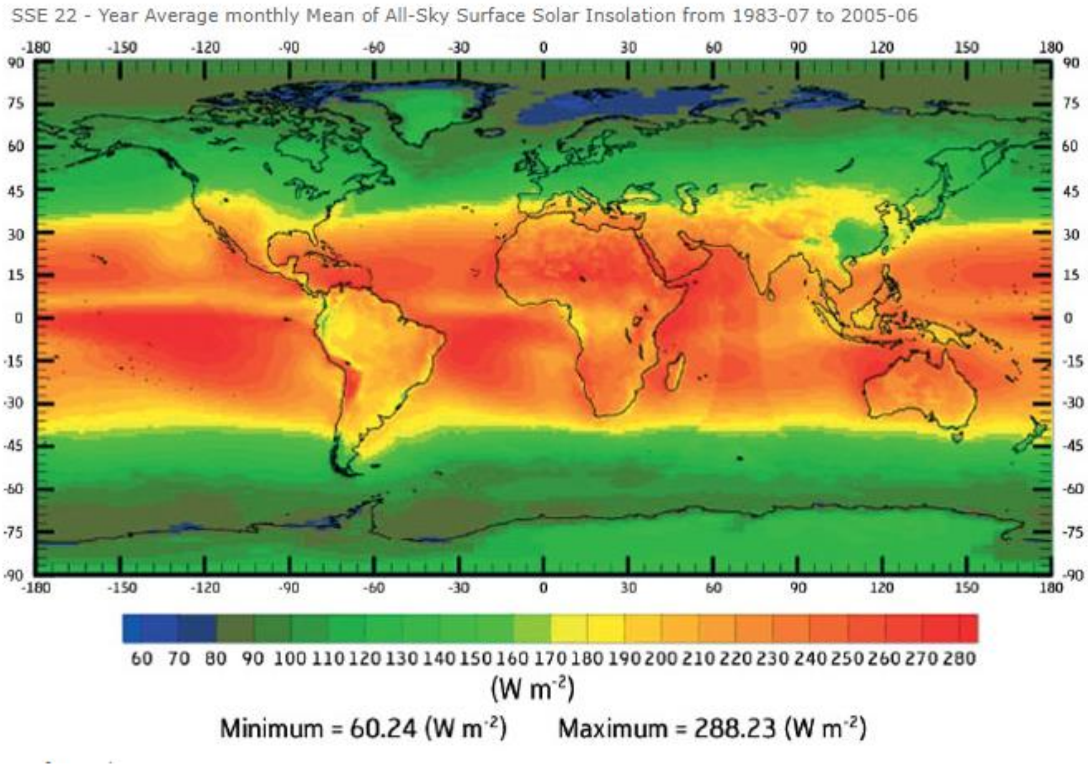


Figure 6. Year average solar insolation globally (ESA 2011)

While solar can already be used as the main energy source for smaller specialized vessels, it is very unlikely that there will ever be fully solar-powered cargo ships. Nevertheless, PV has the potential to be a significant augmentation for ship’s power and help to reduce the fuel costs and emissions. The benefit of PV increases at the ports when the main engines are shut down and up to 75 % of the fuel consumption is for generating electricity (Ecofys 2015, 14). The auxiliary engines used at ports generate a lot of vibration, noise and air pollution linked to health issues and premature deaths in the surrounding population. Especially large bulk carriers can spend several weeks in ports and thus individual ship’s emissions can be considerable locally. By utilizing PV energy, the use of auxiliary power, and thus the negative effects, could be significantly decreased.

5.1 Examples of PV utilization on ships

In the following there are two examples of utilizing PV on marine vessels. TÛRANOR PlanetSolar is experimental fully solar powered boat and K Line Drive Green Highway is commercial car carrier which uses PV to improve its energy efficiency.

TÛRANOR PlanetSolar

Tûranor PlanetSolar is the largest fully solar-powered boat in the world. It was built in Kiel, Germany for Switzerland-based PlanetSolar and it cost 15 million euro. The 35-meter-long and 23 meters wide catamaran is covered with 537 m^2 of solar modules with the total peak power of 93,5 kWp. PV energy is stored in Li-ion LCA battery bank with the capacity of 1,3 MWh. The boat has four electric motors with a combined power output of 176 kW and 20 kW on cruising speed. Maximum speed is 14 knots and the average speed is 5 knots. (Ship Technology 2017.)

K Line Drive Green Highway

K Line Drive Green Highway is a 200-meter car carrier that is equipped with over 900 CIS PV modules that have the combined output of 150 kWp. CIS modules where chosen for their higher yield compared with c-si modules. The system is used to power all the led lights on the vehicle decks. It is first of eight similar vessels to be built under K Line’s Drive Green project. In addition to the PV modules, Drive Green Highway uses various environmentally friendly and energy-saving technologies. These technologies and PV together reduce the CO_2 emissions by 25 %, NO_x by 50 % and SO_x by 90 %. (Solar Frontier 2017.)

5.2 Modelling solar irradiation on shipping routes using satellite data

Accurate solar irradiation data for the location is an essential requirement when estimating PV production potential. For most areas, the irradiation data is easily available. Most of the PV design tools are connected to a weather database where they import the irradiation data for the selected site location automatically.

The irradiation data from the database can be either measured at the weather station closest to the location or the data can be interpolated from the measurements of several weather stations. There are very few weather stations at ocean regions, so the irradiation data is not available, or it is an inaccurate interpolation. Bigger limitation of the design software is that they are meant to be used for planning stationary plants and therefore offer no options for simulating the irradiation on ships sailing around the world.

5.2.1 NASA SSE-dataset

The lack of weather stations does not mean that there is no data. NASA has provided satellite-derived data to the study of climate for decades. This data is valuable in the remote areas where the surface measurements are sparse or non-existent. As all this research has been tax-funded NASA has made the data public domain and available free of charge. It is also making a lot of effort to improve the accessibility of the data and encouraging the developers for creating new applications.

The irradiation data used for this simulation was gathered from Surface meteorology and Solar Energy -dataset (SSE). SSE is a continuous and consistent dataset containing over 200 parameters formulated for assessing and designing renewable energy systems. The dataset is based on the satellite and reanalysis-derived insolation and meteorological data for the years 1983-2005 and the results are provided globally for 1° latitude x 1° longitude grid system. The intention of the data is not to replace ground measurement data but to fill the gap where ground measurements are missing and augment the existing data. Irradiation data is calculated with a complex algorithm using data from several satellites with the primary inputs including: visible and infrared radiances, cloud and surface properties, temperature and moisture profiles and column ozone amounts. (NASA 2016.)

Uncertainty of SSE data

The uncertainty of the satellite data is naturally a great interest when using the data. Generally, ground measured data is considered more accurate than the satellite modelled data. It is estimated that most routine operation ground stations have end-to-end uncertainties of 6-12 %. NASA SSE data has been validated by comparing it with radiation measured on-ground from the BSRN project. The standard deviation between the datasets for the global daily mean is 20,57 %. This gets better in longer time spans, for the global monthly mean the standard deviation is 15,37 %. These numbers don't directly describe the accuracy of the SSE data, but the correlation with the BSRN dataset. NASA SSE data is found more uncertain than ground measured data but accurate enough for the purposes of this thesis. (NASA 2016)

5.2.2 Creating a shipping route irradiation profile

The irradiation data was gathered based on a fictional shipping route covering the most important regions (Figure 7). To ensure the use of actual sea lanes, Marine Traffic's Voyage planner –tool was used for planning the route, as it is based on actual recorded voyage data. The route is designed to cover the most important sea lanes and the ocean areas on different longitudes and latitudes so that the gathered data would be a representative sample of irradiation available at the shipping routes. Daily coordinates for the route were gathered using the Voyage planner and daily irradiation data for years 2000-2004 (kWh/m^2) was acquired from NASA's SSE-database for these coordinates.

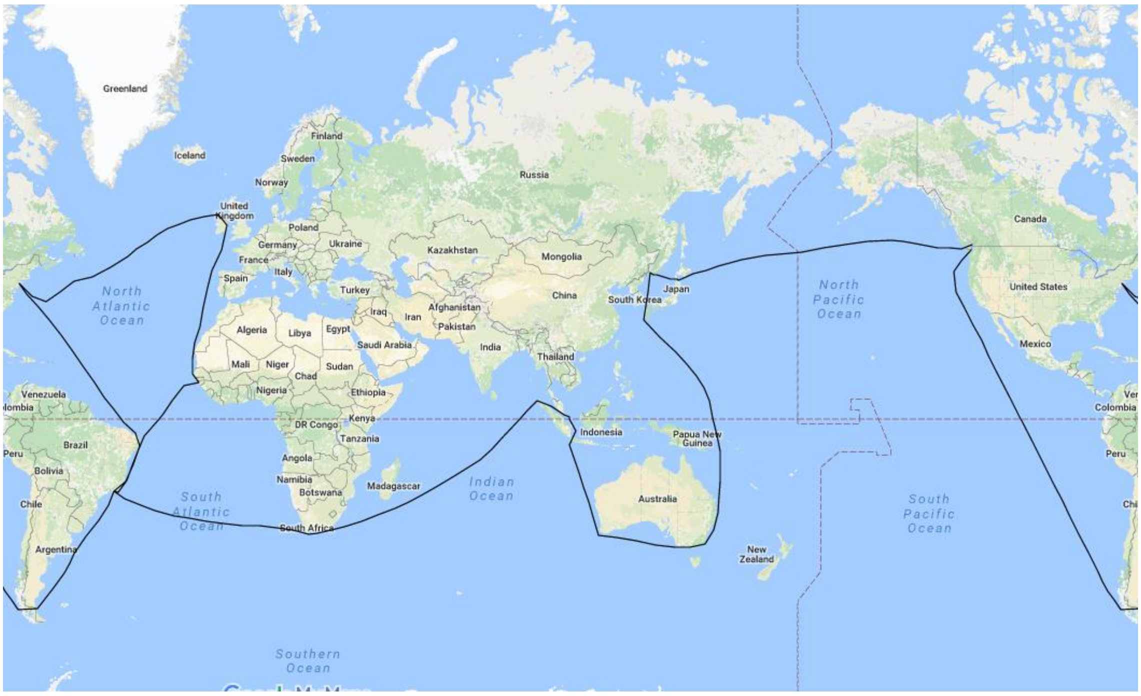


Figure 7. The fictional route for gathering irradiation data

The raw data was post-processed in Microsoft Excel. To get daily average irradiations, the five years of data was averaged to one average year, which was used in further operations. The irradiation varies vastly throughout a year. To cover all areas in different times of a year, the irradiation data was gathered for four different trips on the route. All trips start and end in Singapore, at 1st of January, 1st of April, 1st of July and 1st of October. The variance between the routes is presented in Figure 8.

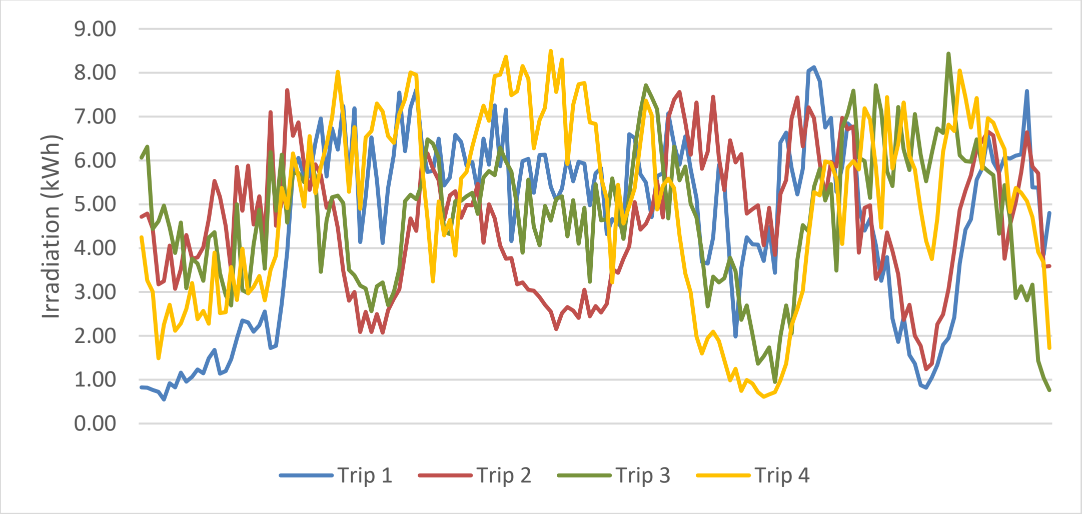


Figure 8. Irradiance on the simulated trips

The gathered data set was then used to determine average, minimum and maximum irradiations. Annual irradiation is rather high, and it is approximately the same as the irradiation in Portugal. The electricity generation potential was estimated by calculating the yield for 1 kWp of installed PV and this yield was used to determine the PV production potential for different deck areas. The deck area potential values represent the ideal yield if the area is filled with PV modules. Yields were estimated for a scenario where all hatch covers of a nine-hatched bulker are covered with modules (2700 m^2) and another one where 50 % of the total deck area is covered with modules (6500 m^2). The yield estimations were based on 370 W PV module which efficiency is 16,1 % and area 2,6 m^2. Results are presented in Table 2.

Table 2. Irradiation and yield potential data on simulated route

	Day_{AVG}	Day_{MIN}	Day_{MAX}	Week_{AVG}	Week_{MIN}	Week_{MAX}	Year_{AVG}
Solar irradiation (kWh/m2)	4,7	0,5	8,5	33,5	5,4	55,3	1 730
Yield potential (kWh/kWp)	4,0	0,5	7,2	28,4	4,5	46,9	1 549
Deck area potential (kWh/m^2)	0,6	0,1	1,0	4,0	0,6	6,7	221
Potential for all hatch panels covered (kWh)	1 545	178	2 770	10 918	1 745	18 035	595 509
Potential for 50 % of deck area covered (kWh)	3 719	430	6 669	26 284	4 202	43 419	1 433 634

6 POWERING MACRACK WITH PV

The main objective of this thesis was to study the feasibility of utilizing solar energy with MacRack systems. This was done by modelling five different system scenarios. The models were based on MacRack consumption data derived from previously conducted test drive measurements and the solar irradiation profile created with the data gathered from NASA SSE -database. The feasibility was evaluated based on the modelling results.

6.1 System scenarios

To study the feasibility of utilizing PV with MacRack five different scenarios were modelled. The main setup is the same for all scenarios. Required electricity is generated with PV modules, stored in an energy storage system and converted to AC when needed. All models are based on the same initial data, but MacRack setups are slightly different. The models use the same bulker as the example vessel (Picture 8). The example vessel is a dry bulk carrier with nine cargo hatches with side-rolling hatch covers. It has MacRack system installed and represents a typical target vessel. All scenarios have the same main component setup.

Picture 8. The example vessel used for modelling the scenarios

Scenario A: Centralized PV and energy storage system (with motor heaters)

This scenario is the standard MacRack setup with ship power replaced with PV-battery power. The used energy consumption data includes the estimated 100 W constant heating power for every motor. All components are placed at proximity of MacRack control cabinets. It is supposed that there is enough space for the inverters and battery bank in the deck store and that the deck store is temperature regulated.

Scenario B: Centralized PV and energy storage system (without motor heaters)

This scenario is otherwise the same than scenario A, but anti-condensation heaters are not included in the consumption profile.

Scenario C: Decentralized PV and energy storage system (with motor heaters)

In this scenario there is an autonomic PV powered MacRack-systems installed between the hatches. Each system power and operate two groups or hatches. The setups and calculations in this study contain one of such system. The total number of independent MacRack-systems needed on the example vessel is then five.

Scenario D: Decentralized PV and energy storage system (without motor heaters)

This scenario is otherwise the same than scenario C, but anti-condensation heaters are not included in the consumption profile.

Scenario E: PV powered APO

This scenario is the standard MacRack setup where the hatches are operated with a battery powered APO-unit, batteries charged with PV. Motor heater consumption is not included.

6.2 Energy consumption on the example vessel

The system peak power and the energy consumption were required for selecting suitable components for the scenarios and sizing them optimally. The values were derived from the measurement data from the MacRack test bench. The data was gathered individually for each hatch panel size using a monitoring tool software, selecting the test data corresponding the panel weights. The exported data was further processed in Microsoft Excel. The averages and the peak values were defined and the energy consumption for operation cycles was derived by integrating the power over time. Daily and weekly consumption was gathered from this data for each scenario.

The consumption data shows that operating three groups simultaneously would requires a very high power output. This makes configurating the system very difficult. This was resolved by operating the groups in sequences to avoid overlapping the power intensive lift operations. With sequencing the maximum power could be lowered to nearly the same level as the peak power for one group (Figure 9).

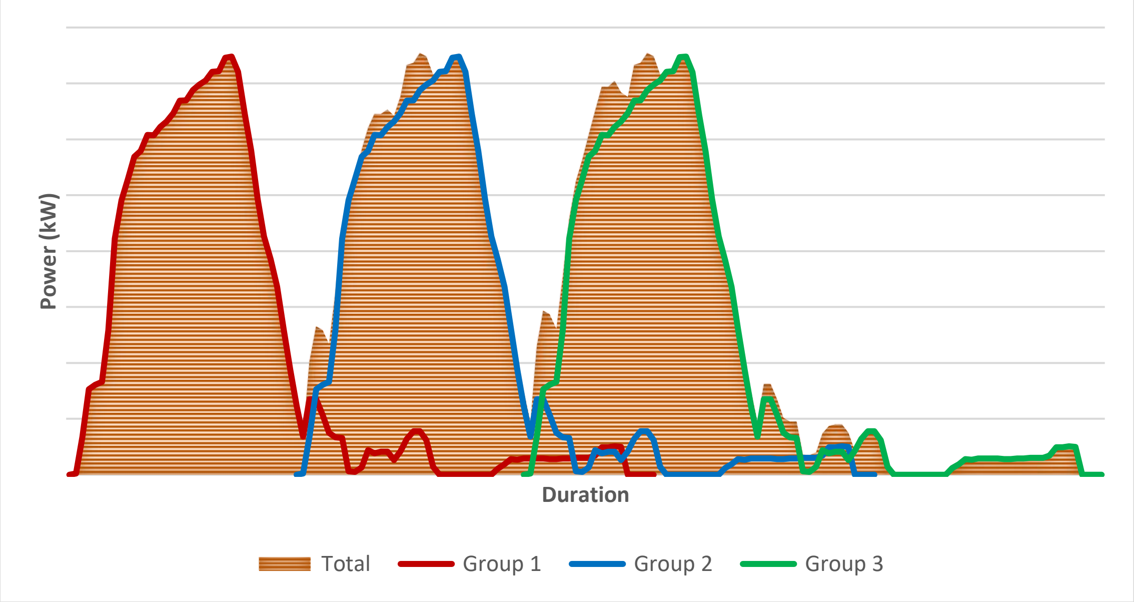


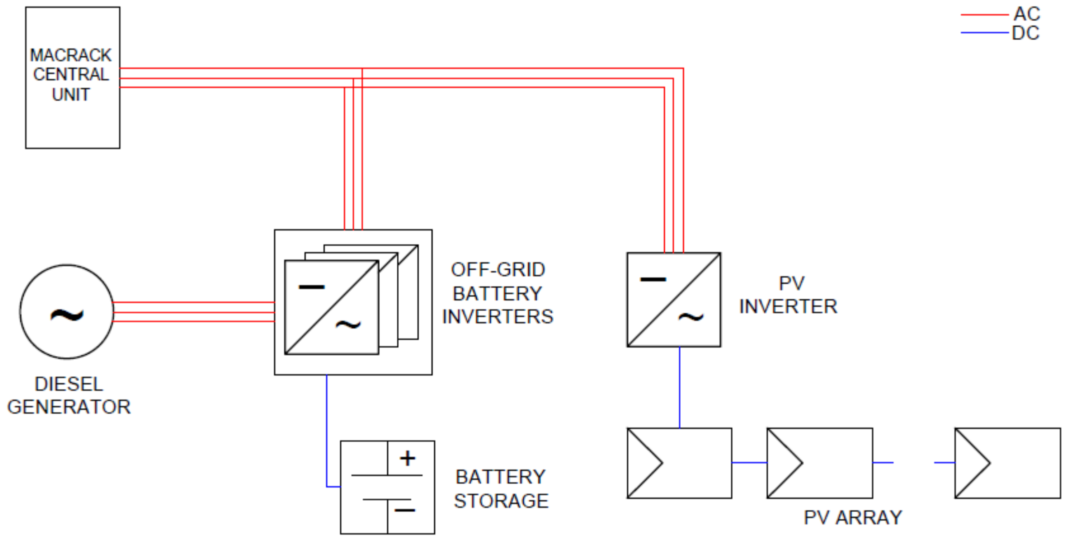
Figure 9. MacRack power usage when operating three groups simultaneously

The required energy and peak power for the modelling scenarios were defined from the consumption calculations made for the example vessel. Since the initial test data was gathered by measuring the output power of the frequency converter in the test bench, the frequency converter losses must be considered. There is no data or measurements available for the efficiency of the VFD alone, so an estimated efficiency value was used. With the estimated efficiency, the required minimum input power and the required daily and weekly energy could be defined.

6.3 Configuring the energy storage system

MacRack's requirement for high power and three-phase input set many limitations to selecting the energy storage system. Most of the systems available either can't provide enough power or are intended to be used in much bigger installations. The selected system was chosen as it can be modularly scaled from small few kWp systems all the way to several hundred kWp plants and it has a good compatibility with many well-known brands of batteries.

The system is essentially a local AC-grid with one or more types of power generation and a battery or other energy storage system. The core of the system is the battery inverter which creates and manages the AC-grid and charges/discharges the battery. A three-phase system can be created by connecting three inverters in parallel. The system is presented in Picture 9. PV arrays are connected to the local AC grid with a three-phase solar inverter.



Picture 9. A three-phase off-grid system

The inverter is managing the PV power by controlling the PV inverters with AC frequency shifts. This way the inverter can tell the PV inverters to reduce the output power and protect the batteries from overcharge when the batteries are fully charged and there isn't enough load. The system can also be coupled with other power generation like wind turbines. The battery inverter has inputs for an outside AC-source such as the ship power or a diesel generator. This is a good way to improve the reliability of the system as the system can start up the generator automatically if charge in the battery storage gets too low.

The configuration was similar in all scenarios. A 3-phase AC-grid is created with three inverters each feeding to its own phase. One of the inverters is operating as a master and the other two as slaves. The master is maintaining the energy storage, the AC-grid and limiting the PV-production if needed. The system can be monitored with a remote-control unit placed in the control room of a ship. If the system is connected to the internet, cloud-based monitoring is possible remotely at anywhere in the world.

6.3.1 Battery

The selected battery inverter system supports lead-acid and lithium-ion batteries. Lithium-ion technology was selected over conventional lead-acid batteries for their significantly longer life span, higher energy and power density, tolerance for variating charging methods, and them being maintenance-free. When selecting the battery, the emphasis was put on scalability, robustness and long service life and the lithium-ion chemistry was not the main selection criteria. The inverter manufacturer has released a list of li-ion battery models that are approved for the system. The battery type was chosen from this list for the best possible compatibility to ensure safe operation, the best possible performance and long service life.

The energy storage

The selected storage system is made by a well-known German battery storage system manufacturer which modular storage systems can be applied in battery storages of all sizes. The batteries use quality lithium NMC cells which are also used in electric vehicles. Advantages of this cell type are long service life, high C-rates, durability, and the fact that it doesn't contain any environmentally harmful heavy metals and is recyclable.

The selected BES series is optimized to be used with the off-grid battery inverter. The design is completely modular, where the base unit is 4,8 kWh battery module. The energy storage capacity can be built up with 4,8 kWh increments all the way to the MWh scale. The series can output constant power at the rate of 1 C with 4 C peaks. The components are designed to last 30 years or 8000 cycles which was an important selection criteria.

6.3.2 Storage capacity

The required energy storage was defined in the section 6.2. These figures don’t consider the losses accumulated in the inverter and the battery. To ensure that the system can serve enough energy through all its life, this loss is included in the capacity. Accurate battery capacities were calculated with these losses and the number of required battery modules was defined for different scenarios with the following equation:

$$Battery\ capacity_{MIN} = \frac{Required\ energy\ output}{\eta_{INV} \times \eta_{BAT} \times Capacity_{10years}}$$

where,

η_{INV}	the efficiency of the battery inverter system
η_{BAT}	the efficiency of the battery storage system
$Capacity_{10years}$	available battery storage capacity after 10 years of use

The results are presented in Table 3. Battery storages for scenarios B-E had to be oversized when compared to the required capacity to meet the demand for power output.

Table 3. Battery storage configurations

	Required min capacity (kWh)	Installed capacity (kWh)
A	56,6	57,6
B	2	19,2
C	14,1	19,2
D	0,5	19,2
E	2	19,2

6.4 Configuring PV

The PV systems consist of the PV array, the DC-cabling and the solar inverter. The modules are installed on the deck right next to the hatches so that an open hatch panel will cover the module and protect it from falling cargo during loading/unloading. This location is not optimal because of the shading but it can significantly extend the lifetime of modules. The junction boxes and cable connectors of the PV modules should be protected from impacts also when the hatch panels are closed. This can be done by welding a protective strip of steel in the hatch coaming so that the strip covers the connectors and the junction box. To minimize the cable use, the modules are placed as close to the inverter and MacRack control cabinets as possible. Cabling is done using the same cable tubing MacRack is using.

6.4.1 PV module

The operating environment on cargo ships is extreme and the components for onboard PV-systems should be selected carefully. The weather and impact loads put the solar modules to a lot of stress. Depending on the time of the year and the latitude, the deck's surface temperature can vary between -40 C° and +60 C°. The deck is also subjected to huge waves flowing through the deck and the standard water load used for calculations is 3,5 tons/m^2 on the deck is and 7 tons/m^2 on the stern. Another weather issue is ice and salt accumulating on the deck. The impact loads are caused mainly during loading and unloading the ship when bulk cargo, such as coal, falls from the height of several meters hitting the deck. The sea is also constantly bending the hull and therefor the modules installed on the deck are subjected to bending momentum.

Majority of PV module types cannot be considered for such environment. Crystalline silicon, the most common cells itself are very fragile and even though the protective sheet of glass is tempered and can withhold smaller impacts like hales, it cannot withstand impacts from falling cargo or even crew members walking on them. The requirement of glassless structure leaves mainly just thin film modules. Even though the thin film cells themselves are flexible, many of the modules have been made rigid with a glass structure.

CIGS PV modules

Flexible CIGS modules were chosen to be used in the scenarios as they are commercially available, affordable and have good characteristics. The selected manufacturer is the market leader in flexible thin-film modules and a representative of the manufacturer estimated that their modules might withhold the described marine environment.However, the module is not designed to be used in marine environment so additional testing was required to evaluate the module type’s suitability for this application. The impact test for a comparable flexible CIGS module is covered in Chapter 6.

According to the manufacturer, the module is the highest efficiency flexible thin-film product on the market today. The module is only 2.5 mm thick. The basis of the module structure is the stainless-steel foil where the semiconductor material, the actual cell structure, is deposited on. After the deposition a transparent conductive oxide is applied, and the cell interconnect mesh is laminated to the cell. The module is protected with water barrier plastics. The protective plastic back sheet has an internal aluminum film to protect the module from erosion caused by water transmission.

The module is designed to be installed especially on standing metal seam roof but can be installed on any even surface. The installation doesn’t require racking or any other supporting structure as the modules are attached directly to the surface with factory applied adhesive. This makes installation fast and simple lowering the installation cost. It also allows practically free module positioning anywhere on the deck.

The technology and manufacturing process would allow longer and wider modules but currently the selected module is the largest one in manufacturing.

6.4.2 Sizing PV arrays

PV arrays were meant to be sized so that they generate enough energy even during the low solar irradiation. As the difference between the average and weakest week/day is big and the surplus energy cannot be used, this leads to significant over capacity. In scenarios A and C, which are sized based on the daily irradiances, 100 % autonomy rate led to very unreasonable overcapacity. By simulating them with 80 % autonomy the required PV power shrunk to 1/6 of the power required for 100 % autonomy. So, the scenarios A and C were sized for 80 % autonomy. This means that during the days of the lowest irradiation, the system may not always be able to provide enough energy and the motor heaters cannot be powered. This can be compensated by connecting the battery inverter to the AC grid of the ship or a separate small few kW diesel generator.

The arrays were sized based on the irradiation data and the required energy using the following equation:

$$P_{Array} = \frac{E_{AC}}{E_{Sun} \times PR \times (1 - P_{LOSS})^n}$$

where

P_{Array}	PV array peak power (kWp)
E_{AC}	Demanded electric energy (kWh)
E_{Sun}	Solar irradiation (kWh/m^2)
PR	Performance ratio for PV system
P_{LOSS}	Annual module power loss due degrading (%)
n	Operation period in years

Performance ratio is the ratio of the actual and theoretical energy outputs. Typical PR used is between 0,75-0,85, as the modules are partially shaded PR of 0,75 was used. Module power decreases over the years due natural degradation. A typical degradation rate is 0,5 %/year and this was used in calculations (NREL 2012, 1). To ensure the proper function of the system for the whole lifetime, arrays are sized according to the module output values after 20 years. The results are presented in Table 4. PV power for scenarios B-E had to be oversized to meet the PV inverter's minimum input DC voltages. PV module area represents the minimum area the modules take when installed on the deck of a ship.

Table 4. PV array sizes and yields

	A	B	C	D	E
PV power minimum (kWp)	27,3	0,5	6,8	0,1	0,5
Installed PV Power (kWp)	27,4	7,4	7,4	7,4	7,4
Installed modules (pcs)	74	20	20	20	20
PV module area (m^2)	192,4	52	52	52	52

6.4.3 Solar inverter

As the local AC-grid is three-phase, the PV inverters need to be three-phase inverters as well. The off-grid inverter supports many different PV inverters but power limitation via frequency shifts works only with the manufacturer's own inverter models. Therefore, the scenarios use three-phase PV inverters of the same brand. The selected model is a robust inverter series for small, middle-sized and large-scale commercial PV installation. Its operating temperature range is wide (-25 °C - +60 °C) and it is IP65 rated. In most cases it can be installed outdoors but on a ship, it needs to be protected from the waves and installed in a sheltered area.

Typically, inverters are sized to fit the PV power but in these scenarios the actual PV peak power is not required as the PV arrays are oversized to meet the energy demand in low radiation periods. The actual peak power requirement for the PV system is just over the motor heater power (1,8 kW). The manufacturer allows under sizing the inverter down to 70 % of PV peak power without losing the warranty. Scenario A uses 20 kW_{AC} inverter and Scenarios B-E all use 5 kW_{AC} inverter, which is the smallest one in the series. The 5 kW inverter being the smallest three-phase inverter available meant that oversizing the PV power was required in scenarios B, D and E.

6.5 Evaluating the feasibility

The feasibility of the scenarios was examined from technological, financial and environmental angle.

6.5.1 Technological feasibility and the service life of the system

All the system components were selected to last at least 20-year service life. Bulk carriers are usually built to last 25 years, but in recent years the scrapping age has fallen to 21 years (Hellenic Ship News, 2017). So, with proper maintenance and minor component replacements the PV-battery system can be expected to last the whole lifetime of the ship.

All the scenarios are technically possible, although there is significant overcapacity in many parts of the systems. The technology available didn’t scale down to the smaller systems as anticipated. For that reason, the technological differences between scenarios are small. Due to the overcapacity Scenarios C and D offer nothing but higher expenses and while Scenario E can be built in theory, the APO unit would lose its mobility as the components weigh 500 kg.

6.5.2 System costs and LCOE

The system investment costs were estimated using current (2017) prices in USD. Prices for the PV module, the inverters and charge controller were acquired from Solartraders.com which is a B2B marketplace for companies in PV industry. The battery storage cost was based on a magazine interview with the company CTO. The cost of installation was estimated to be 10 % of the total capital investment which is significantly lower than the typical 25 %. This is partly due to the exceptionally cost-effective installation of the CIGS modules and low-cost labor at the Asian shipyards. The expense breakdown, the total investment cost (CAPEX), annual operational and maintenance expenses (OPEX) and the total cost lifetime cost were defined for every scenario.

One of the research questions was if PV could reduce the need for cabling and installation work and thus cut the expenses. In these scenarios and with the current MacRack setup, this was not possible as basically nothing of the existing components, cabling or installation work could be left out. Thus, it is not possible to determine a payback time for PV battery system and evaluating the financial feasibility is not meaningful. To compare the costs with present system energy costs, a levelized cost of energy (LCOE) was defined for the systems. LCOE is a method that makes it possible to compare the cost of PV generated electricity to other power sources like ship or shore power. It is an abstraction from reality and further calculations and analysis are needed for accurately evaluate the financial feasibility. LCOE was calculated using the following equation (Fraunhofer 2015, 52):

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX}{(1+i)^{t}}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^{t}}}$$

where

CAPEX	Investment expenditures in USD
OPEX	Operational and maintenance expenditure in USD
$M_{t,el}$	Produced energy in respective year in kWh
i	Real discount rate in %
n	Economic operational lifetime in years
t	Year of lifetime (1, 2, 3 …n)

LCOE was calculated with the system lifetime of 20 years. The results are presented in Table 5. Again, it should be noted that the figures for Scenario C and D contain only one system and the example vessel would require five systems. In Figure 10, the LCOE prices are compared with the prices of electricity generated in the ship and shore-side electricity bought from a port, as a growing number of ports require the ships to use shore-side electricity to decrease the emissions of the ship. In addition to the LCOE for the scenarios, the figure includes LCOE for the scenarios with full production capacity used and LCOE for similar sized PV plants without a battery storage. The cost of ship electricity is based on the average price of heavy fuel oil and its gross calorific value which equals USD $0,07 (SEAI, 2017). The shore-side electricity was estimated to be $0,12. In reality the shore-side prices vary greatly between the ports around the world. Further statistical analysis is needed to get a representative average price.

Table 5. LCOE for the provided energy and energy potential

	A	B	C	D	E
Provided energy (kWh)	325 960	840	72 450	200	840
LCOE (USD/kWh)	0,28	44,60	0,49	177,44	42,25
Percentage of potential used	48,3%	0,5%	39,7%	0,1%	0,5%
Energy potential (kWh)	674 870	182 400	182 400	182 400	182 400
LCOE full capacity used (USD/kWh)	0,13	0,21	0,19	0,19	0,21
LCOE PV only (USD/KWH)	0,04	0,06	0,05	0,05	0,06

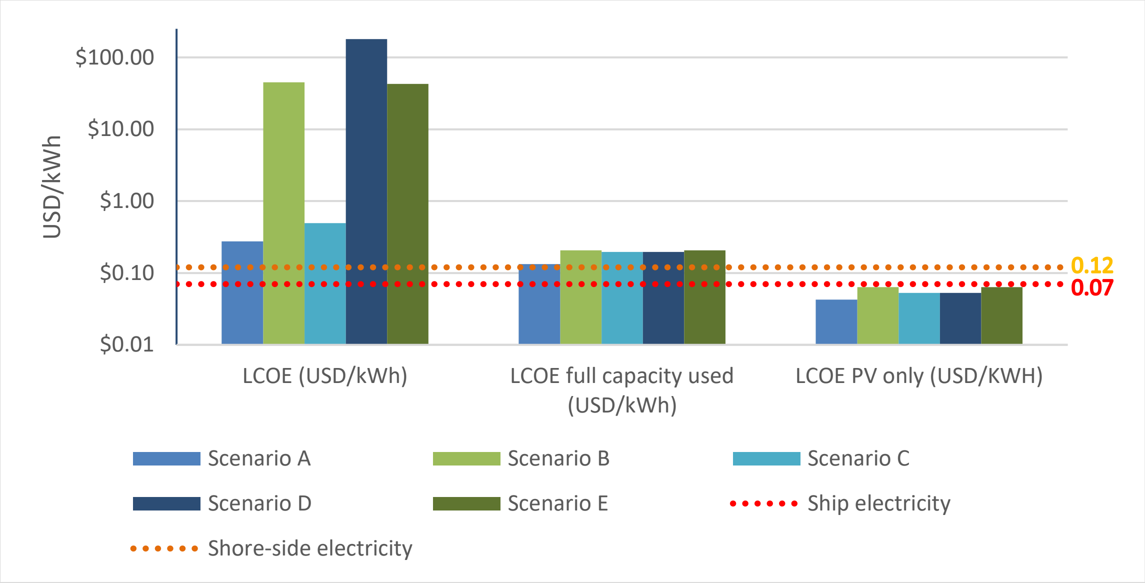


Figure 10. LCOE prices compared to ship and shore-side electricity

6.5.3 Ecological impact

The ecological impact of utilizing PV was evaluated briefly. The impact was evaluated solely based on reduced CO2 emissions and the energy payback time of PV modules. The energy payback time of the battery storage was not calculated, and other reduced emissions were not evaluated.

The local emissions are reduced when the required energy was not generated with the diesel engine of a ship. The CO2 emissions caused by electricity production on auxiliary diesel engines are approximately 700 g/kWh (European Commission, 2005, 16) and the direct emission reductions were calculated from that. The CO2 emission reductions are presented in Table 6. It can be estimated that manufacturing the modules consumes 312 kWh energy per module thus only in Scenarios A and B the provided energy would cover the electricity used in the manufacturing process (NREL 2004). On the other hand, if all of the energy potential is used, the energy pay-back time is less than a year.

Table 6. The impact on ships CO_2 emissions over 20 years

	A	B	C	D	E
Provided energy (kWh)	325 960	840	72 450	200	840
Reduced CO_2 emissions (tons)	228,2	0,6	50,7	0,1	0,6
Energy potential (kWh)	674 870	182 400	182 400	182 400	182 400
CO_2 reduction potential (tons)	472	128	128	128	128

6.6 Configuration for field testing

To gather information about how the specified system setups and selected components function under real-life conditions, extensive field testing is needed. The field tests can be conducted by building a test setup at the test bench in China (Picture 10) under many different natural sunlight conditions testing different peak loads and load patterns. As the test bench consists of only one MacRack, the required power is halved, and the battery capacity can be halved as well, which lowers the costs. The main system components were specified for this kind of setup.

Picture 10. MacRack test bench

6.7 Results

All scenarios are technologically possible, but most of them are not feasible due overly complicated technological setups and overcapacity. The MacRack system's requirement for high peak power, a 3-phase system and small amount of energy is conflicted as the PV-battery systems that meet the requirement for high power and a 3-phase system don't scale well down to smaller capacity systems. For this reason, the component setups for scenarios B-E are similar even though the energy requirements are different.

None of the scenarios makes it possible to remove any existing MacRack components or reduce the amount of installation work needed. On the contrary the number of components, installation work and costs all rise significantly. Therefore, savings are not possible with the current MacRack system setup. The feasibility for all the scenarios individually is listed in Table 7.

Table 7. Summary of feasibility of the systems

Scenario	Feasible	Details
A	Yes	Feasible but energy more expensive than the ship energy due slight overcapacity.
B	No	Overcapacity makes produced energy significantly more expensive than the ship energy.
C	No	Components do not scale to this small system and there is no benefit for multiple systems.
D	No	Components do not scale to this small system and there is no benefit for multiple systems. The energy costs many hundredfold more.
E	No	Components do not scale to this small system and there is no benefit for multiple systems. The setup weighs 490 kg and APO unit would not be mobile anymore. The energy is significantly more expensive.

7 IMPACT TESTING MIASOLÉ CIGS MODULE

7.1 Objective

The objective of this test was to evaluate the feasibility of using MiaSolé Flex-02 modules onboard of bulk carriers where they are exposed to the impacts caused by falling cargo during loading and unloading. The evaluation is limited to the module's durability against those impacts.

7.2 The test module

The test module was MiaSolé Flex-02 series module which is a CIGS module. The module doesn't have a product label, so the exact model could not be verified. Based on the peak power measurement performed before the impact test, it was assumed to be 110 Wp model. It is not the same model that was used in the scenarios, but it has similar physical and electronical characteristics. and the results can thus be used for making conclusions about the module type's suitability in bulk cargo ship environment.

According to MiaSolé Flex-02 will not decay or get damaged by the weather load, temperature changes or salt. The adhesive will also keep the modules firmly fixed on the deck despite the elements. The module is shatterproof and should in theory withhold the described mechanical impacts from bulk cargo although the module has not been tested for such impacts. High force impacts will scratch the module surface and the scratches will cause some yield loss. Also, the cable connectors and the junction box are not rugged and will need to be protected from high force impacts. (Rennen, R. 2017)

Flex-02 has passed hail tests done according to standards IEC 61646, IEC 61730 and UL1703 (MiaSolé N.d.). The standardized hail test is done by firing a series of ice balls on different locations on the module. The standard ice ball is 25 mm in diameter and weighs 7,53 grams and the test velocity used is 23,0 m/s. After the mechanical load test, the module is inspected visually for the signs of damage or defect and the insulation resistance is also measured. (IEC 61646 2009.) The actual circumstances on a bulk carrier are harsher and additional impact testing was needed.

7.3 Procedure

To define and document the starting point, the test module was characterized by defining the peak power and the characteristic curve. Next, the module was exposed to impacts imitating the impacts taking place on the ship deck. After the impacts, the module is characterized and measured again to determine the effects and possible damages and decay. The main principles of the used measurement method are described in the following.

Peak power and characteristic curve measurement

Peak power and characteristic curve measurement is a simple method of determining the maximum peak power and other characteristics of the module. The results can be compared with nominal values and thus the decay can be determined. The shape of the characteristic curve is also a simple way to see the defects on a module visually.

The measurement is conducted outdoors as the Sun is used as the source of light. The test equipment consists of an I-V-curve measurement device, a reference cell for irradiation measurement and a temperature module for measuring the temperature of the module. The I-V curve measurement device consists of a large capacitor and a microcontroller. During the measurement, the PV module is connected to the capacitor and it loads the capacitor for a small period. In that period, the test device runs through the whole I/V-curve from the short circuit point (empty capacitor) to the open circuit point (charged capacitor). The microcontroller is simultaneously measuring the voltage and current creating the characteristic curve and defining the maximum power point (MPP). When the irradiance and module temperature are measured during the MPP measurement, the results can be converted to STC values using the characteristic coefficients of the module. When the results are converted STC values they are comparable with the nominal values.

The limitations of this measurement method are the error tolerance of the results and the dependency on the weather. Usually, it is considered that to make reliable comparisons, the irradiance needs to be over 500 W/m2 and thus the measurements are not possible in cloudy weather or during winter. In the right circumstances, the method is a very effective way to provide information the peak power and detect possible defects of the module. (Mertens 2014)

7.3.1 Preparations

The CIGS module used in this test was unused and had been stored indoors away from the sunlight for over a year. When CIGS modules are dark-stored, they exhibit performance loss. To reverse this and to reach the nominal values of the module, it had to be light-soaked before performance testing. (Gostein & Dunn 2011.) The test module was connected to a load and placed outdoors in the sunlight for 48 hours allowing it to reach the nominal values and stabilize.

7.3.2 Performance testing before impact testing

To document the test module’s starting point, IV-curve and peak power were measured. The performance test was performed outside on sunny cloudless weather. The module was placed on a test bench which inclinations was 43° and azimuth 220°. The tests were conducted 28th September 2017. The sky was cloudless, solar irradiance was 742 W/m^2, air temperature was 12 C° and relative humidity was 76 %.

The peak power and the characteristic curve were measured using a PVPM1000X curve tracer and an ISET-poly reference sensor. The results came up to the expectations. The measured peak power was 109,7 Wp at STC. The IV-curve is presented in Figure 11 where the red curve is the measured one and the purple is the measurements converted to STC-values. The complete test report is in Appendix 1.

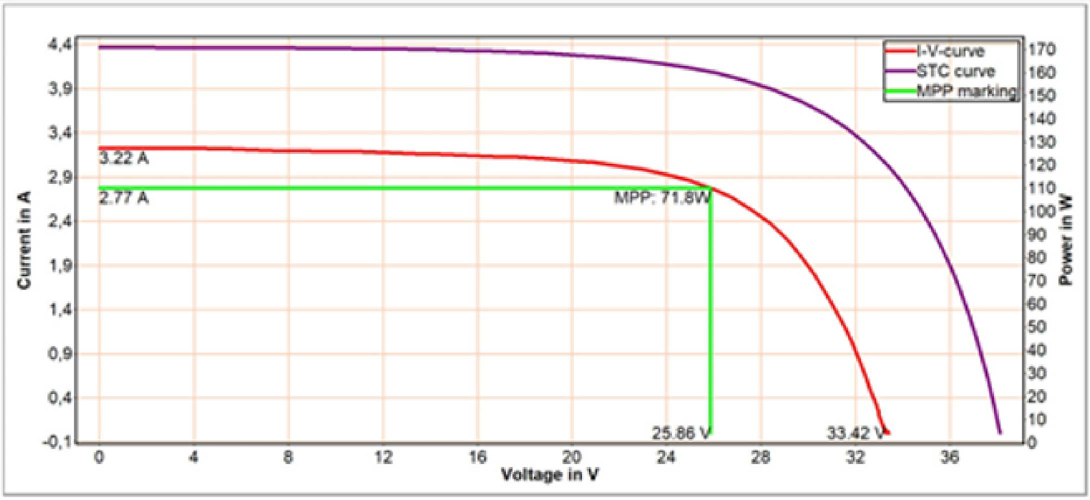


Figure 11. Test module's IV-curve before the impact testing

7.3.3 Impact testing

The test was performed by dropping different sized rocks from the height of 9.1 meters. The rocks were hand-picked to represent coal and other typical bulk cargo. The test module was divided in four zones. Zones 1-3 were impacted with the rocks and zone 4, which was half of the total module area, was used as control zone and left untouched. The test module was placed on a bed made of two pieces of 15 mm birch plywood. With the drop height the velocity of the rocks at the time of the impact can be calculated.

$$Velocity\ at\ impact = \sqrt{2gh}$$

where

g	gravitational constant
h	height of the drop

$$\sqrt{2 \times 9.81\, {}^{m}/_{s^2} \times 9.1\, m} = 13.4\ {}^{m}/_{s}$$

Using the velocity and the weight of the samples, impact force can also be calculated.

$$Energy\ at\ impact = {}^{1}/_{2}\, mv^2$$

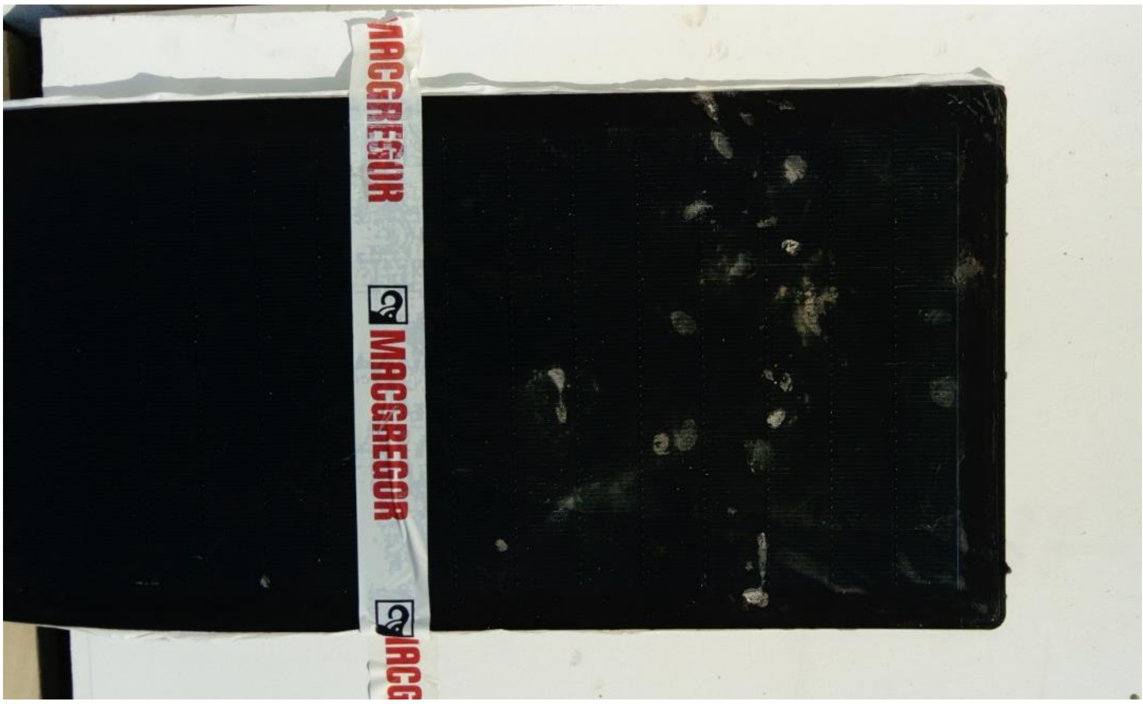
where

m	mass of the falling object
v	velocity of the falling object

Table 8. Sample sizes and impact forces in the test zones

Test area	Sample rocks	Repeats	Impact force
Zone 1	4 pieces, 50-200 grams	5	50 J
Zone 2	2 pieces ~1 kg	3	180 J
Zone 3	4,2 kg	3	370 J

The impact force and the test procedure are presented in Table 8 . Using the same equation, it can be calculated that in the standardized hail test, which Flex-02 has passed, the impact force was 2 J. So, the impact forces were significantly higher than what the module is certified for. The module was inspected visually, and it was clear that all the impacted zones were severely damaged (Picture 11). The protective barrier plastic was broken, and the module was clearly dented on the impact locations. The plywood bed absorbed a bigger portion of the impact energy than a steel deck of a ship would and that made the damage milder, especially on the zone 3, where the sample rock size was larger.



Picture 11. The damaged module on the plywood bed

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7.3.4 Measurements after the impact testing

The module was tested on the same test bench after the impact test on 29th September 2017. The sky was cloudless, solar irradiance was 548 W/m^2, air temperature was 12 C° and relative humidity was 76 %. The peak power and IV-curve measurement was performed with the same equipment as the earlier test. The measured peak power at STC was 76,6 Wp which is 30 % lower than the initial value. The internal series resistance was 90 % higher than the initial value. The IV-curve is presented in Figure 12 and the detailed report is in Appendix 2.

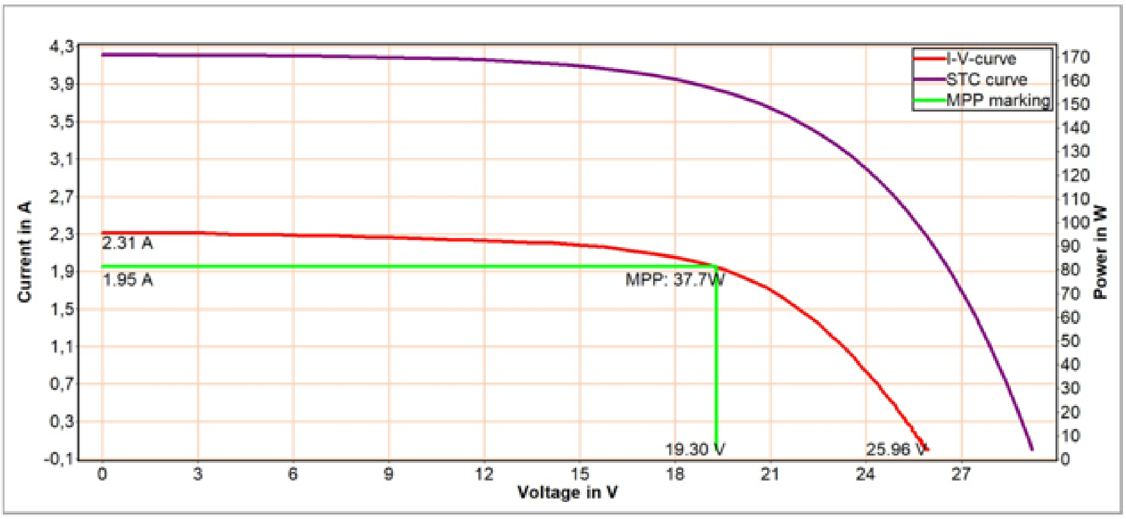
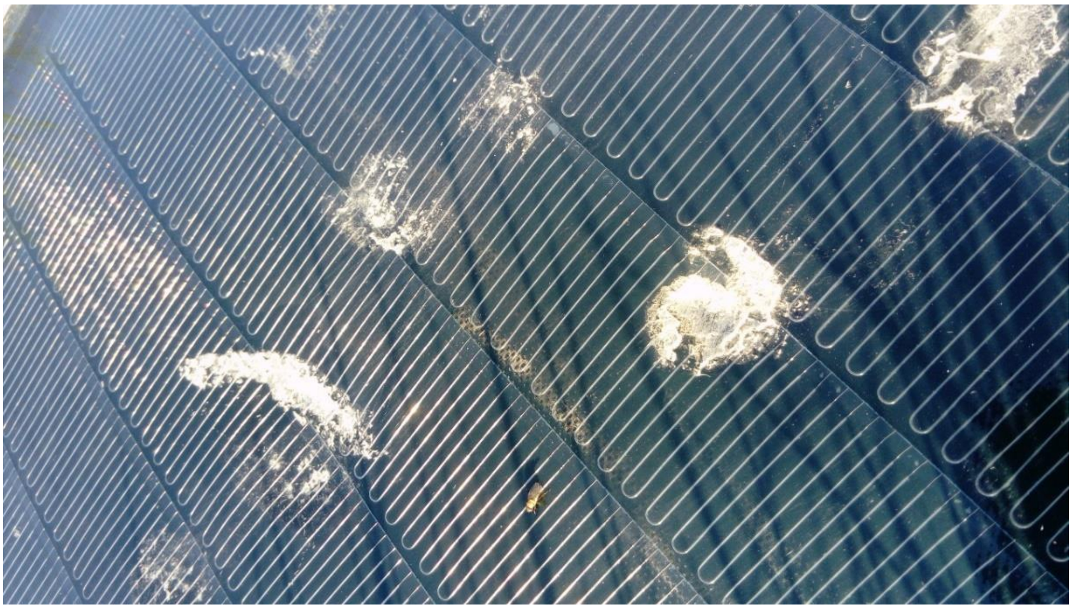


Figure 12. The test module's IV-curve after the impact test

7.4 Results

The impact test left physical damage to the module that was clearly visible to the naked eye (Picture 12). The barrier plastic was broken, and the structural steel layer was dented on the impact spots. The performance measurements showed that the module lost 30 % of its peak power due to the impacts. The impact zone covered 50 % of the module which means that the defected area was still generating energy despite the impacts.

The protective barrier plastic was broken in several spots exposing the cell to corrosion. Even though the module is still functional and has most of its nominal power left after the test, the corrosion would keep decaying the cell. Without further studies it is impossible to say how long the test module would be functional and generating energy. This test shows that even though Flex-02 can resist minor impacts, it cannot take direct impacts from falling cargo without major physical and functional damage. If the impacts of this kind cannot be avoided, modules need to be placed in protected areas like under open cargo panels.



Picture 12. The broken barrier plastic and other damage

8 CONCLUSION

8.1 Discussion

The objectives of this thesis were to evaluate PV potential at ships, to study utilizing solar energy with MacRack and to test if MiaSolé Flex-02 is suitable for cargo ship environment. All these objectives were fulfilled and provided results were meaningful to draw conclusions and outline subjects for future research.

Solar energy potential on ships

Studying the PV potential at ships focused mainly around the NASA SSE irradiation data. The subject is wide, and this study was just a preliminary and general view to it. The gathered irradiation data shows that the available irradiation provides good preconditions for PV production. The average annual irradiation on the modelled route is about the same as in Portugal. It is uncertain how well the satellite data used corresponds the irradiation on actual circumstances, but it was evaluated to be accurate enough for the purposes of this thesis. In general, although PV will probably never be the main energy source for large vessels, it can have a significant role as additional power source helping to reduce the fuel consumption and emissions. The interesting future research topics include on-site irradiation measurements, validating the satellite data and analyzing the consumption and appliances on ships for creating new application models.

Powering MacRack with PV

Utilizing PV with MacRack was studied by modelling five different scenarios. The modelling result did not turn out the way they were anticipated and only one of the scenarios was anywhere near to be financially feasible. The main reason for this was that the current MacRack setup demands high power and 3-phase power which did not make smaller scenarios technologically possible without significant overcapacity that could not be utilized. The results show that powering MacRack with PV is technologically possible but to reach financial feasibility, additional research is needed. Due to MacRack’s low energy use, other electrical appliances should be connected to the same grid to get the capacity use close to 100 %. One possible topic is to study if it would be possible to connect MacRack to a high voltage DC-microgrid via a DC-bus of the VFDs.

Impact testing MiaSolé CIGS module

The MiaSolé Flex-02 impact test was very limited. Test conditions imitated the operation environment on the deck of a bulk carrier's but weren't a perfect reflection of reality. The stones were used to imitate the falling cargo, but, the cargo is usually coal or iron ore which has slightly different physical qualities. The drop height was set based on practical reasons and was extreme in comparison with typical vessel loading and unloading operations. The plywood bed used as a surface for the module absorbed the energy of the impacts in a different way than a thick steel deck would absorb. Despite these limitations on test setup, the result was clear. Although MiaSolé Flex-02 is rugged and can endure smaller impacts and didn't break completely from the test impacts either, it cannot take the constant impacts of falling cargo and needs to be protected from those impacts. It isn't the ideal PV module for bulk carrier environment and the search and development for a more rugged module should be continued. In the mean while Flex-02 should be further tested in the field environment.

8.2 Future research

While making this thesis and analyzing the results, several possible topics for future research were raised. These topics are described below.

Finding the best ways to utilize PV on different ship types

Different vessels are very different regarding to their electricity consumption, electricity consumption profile, electrical appliances, routes and the area possible for PV installations. When the operating environment is well-known, the PV systems can be optimized to specific applications like propulsion power, feeding the electrical appliances or minimizing the emissions and environmental impact on ports.

Gathering actual irradiation data onboard

The lack of on-site irradiation measurements rises the need for further research. Measuring and logging solar irradiation on ships could provide valuable data for future studies and for making more accurate yield and cost calculations for onboard PV systems. By comparing the measured values with the corresponding satellite data, the uncertainty of the satellite dataset could be validated. When the uncertainty is known the data can be utilized better.

On-site measurements can be conducted using an affordable solar irradiance logger device. One option is Pordis 140B Solar Variability Datalogger (Picture 13). It is specifically designed for this kind of long-time measurements. It is IP67 certified and to designed to operate in extreme temperatures. It is battery-operated and equipped with wireless communications, so the installation is completely cordless. The logger’s solar cell is used to augment the battery and if the device is connected to the internet, the measurements can keep going even years without actions needed onboard. (Pordis, 2016.) For optimal results, these measurements should be carried out on several vessels at the same time, on different routes and for a long period of time.

Picture 13. Two Pordis 140B Solar Variability Dataloggers (Pordis 2016)

Evaluating the accuracy of satellite irradiation data

When there is enough actual measured onboard irradiation data, it can be compared with corresponding NASA SSE data to evaluate the accuracy of satellite data. If the accuracy of satellite-based data is found to be accurate enough for designing on board PV-systems, the data should be made more easily available. One way of doing this would be to create a software tool for gathering irradiation profiles for different routes, areas and time periods. The data is freely available, and NASA is sharing the API key with developers, so the tool described should be quite straightforward to develop

Field testing PV in the MacRack test bench

To gather information about how the specified system setups and selected components function under real-life conditions extensive field testing is needed. The field tests can be conducted by building a test setup at the test bench in China. The main component setup for field testing was specified in the part 6.7. The tests can be conducted under many different natural sunlight conditions testing different peak loads and load patterns. If these tests look promising, the testing can be continued in real life environment on the deck of a bulk carrier.

Connecting MacRack to a DC-microgrid

The scenarios in this test created a 3-phase AC-grid and connected MacRack in it. This thesis didn’t study the possibility of using a DC-grid. This could theoretically be done by connecting the MacRack to the DC grid via the DC-bus of the VFDs. A DC grid would get rid of the unnecessary DC-AC and AC-DC -conversion. This kind of setup could possibly be more cost effective.

Field testing MiaSolé Flex-02

PV manufacturers should answer the rising need for developing even more rugged modules. In the meanwhile, MiaSolé Flex-02 or similar promising rugged modules should be field-tested in real-life environment on a bulk carrier. The objective of this test would be to confirm the assumptions that Flex-02 would sustain all the other elements onboard besides the heavy impacts and to test if other issues rise. It would also be interesting to study how different levels of damage to module's water barrier plastic layer affect the decay during longer period due corrosion caused by moisture and salt.

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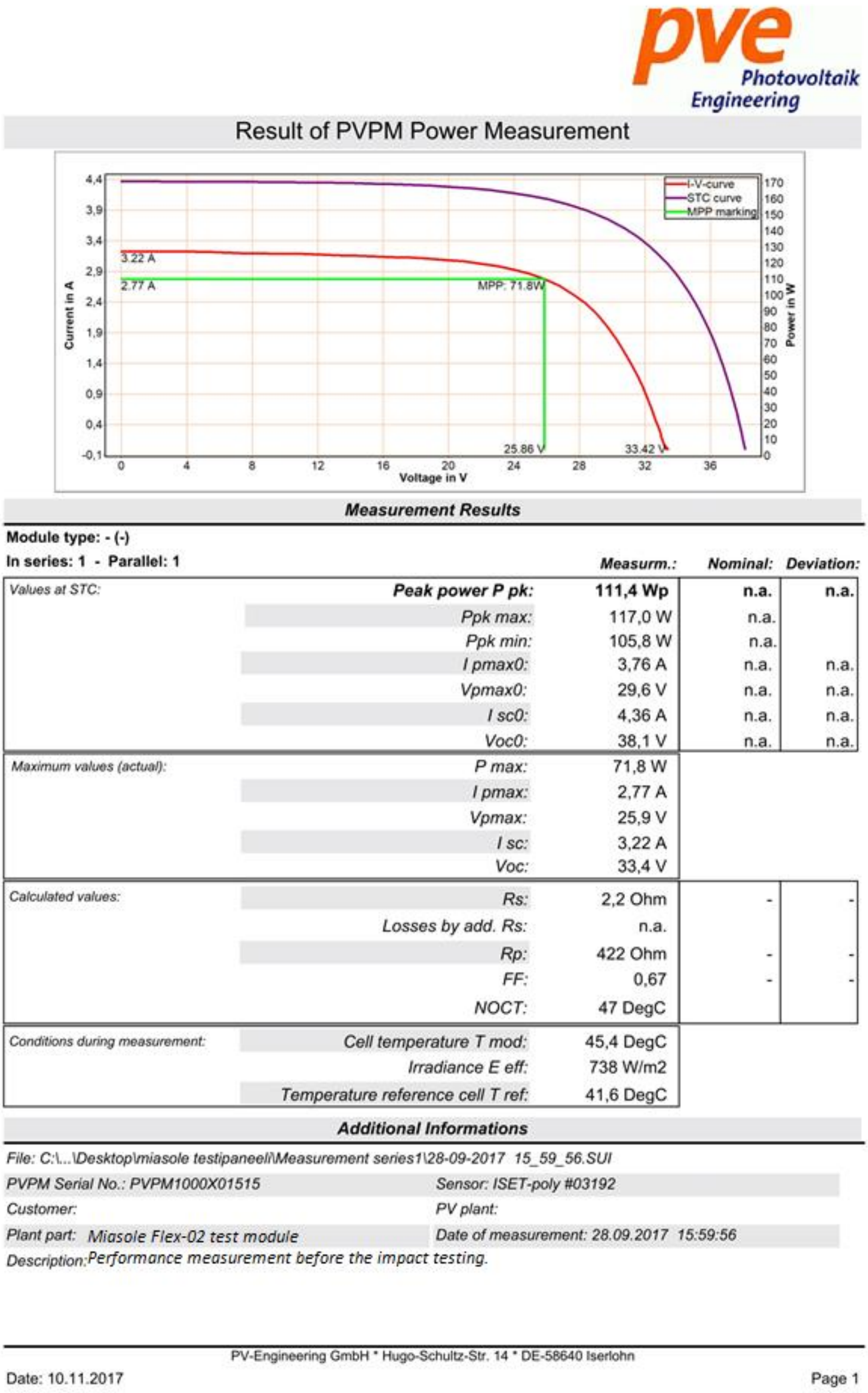
Appendix 1



Result of PVPM Power Measurement

Measurement Results

Module type: - (-)

In series: 1 - Parallel: 1

		Measurm.:	*Nominal:*	*Deviation:*
Values at STC:	***Peak power P pk:***	**111,4 Wp**	**n.a.**	**n.a.**
	Ppk max:	117,0 W	n.a.	
	Ppk min:	105,8 W	n.a.	
	I pmax0:	3,76 A	n.a.	n.a.
	Vpmax0:	29,6 V	n.a.	n.a.
	I sc0:	4,36 A	n.a.	n.a.
	Voc0:	38,1 V	n.a.	n.a.
Maximum values (actual):	*P max:*	71,8 W		
	I pmax:	2,77 A		
	Vpmax:	25,9 V		
	I sc:	3,22 A		
	Voc:	33,4 V		
Calculated values:	*Rs:*	2,2 Ohm	-	-
	Losses by add. Rs:	n.a.		
	Rp:	422 Ohm	-	-
	FF:	0,67	-	-
	NOCT:	47 DegC		
Conditions during measurement:	*Cell temperature T mod:*	45,4 DegC		
	Irradiance E eff:	738 W/m2		
	Temperature reference cell T ref:	41,6 DegC		

Additional Informations

File: C:\...\Desktop\miasole testipaneeli\Measurement series1\28-09-2017 15_59_56.SUI

PVPM Serial No.: PVPM1000X01515	*Sensor: ISET-poly #03192*
Customer:	*PV plant:*
Plant part: Miasole Flex-02 test module	*Date of measurement: 28.09.2017 15:59:56*

Description: *Performance measurement before the impact testing.*

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Date: 10.11.2017

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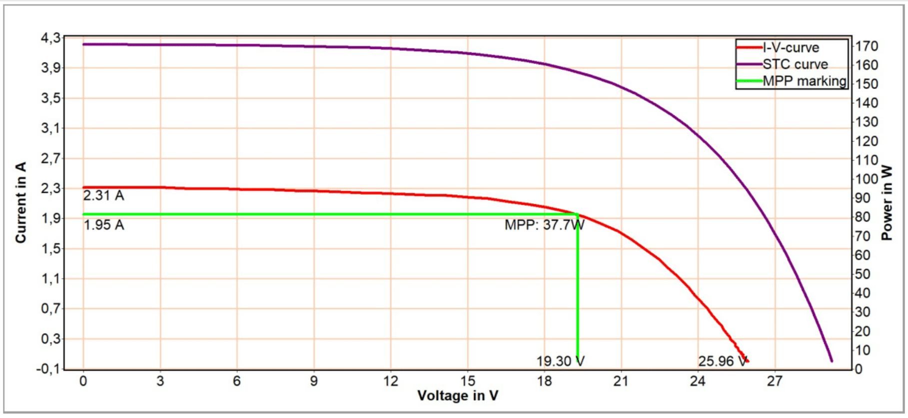
Appendix 2

Result of PVPM Power Measurement



Measurement Results

Module type: Flex-02N 110N (MiaSole)

In series: 1 - Parallel: 1

		Measurm.:	*Nominal:*	*Deviation:*
Values at STC:	***Peak power P pk:***	**76,6 Wp**	**110,0 W**	**-30,3 %**
	Ppk max:	80,5 W	n.a.	
	Ppk min:	72,8 W	n.a.	
	I pmax0:	3,56 A	3,81 A	-6,5 %
	Vpmax0:	21,5 V	28,9 V	-25,6 %
	I sc0:	4,21 A	4,50 A	-6,4 %
	Voc0:	29,2 V	37,1 V	-21,2 %
Maximum values (actual):	*P max:*	37,7 W		
	I pmax:	1,95 A		
	Vpmax:	19,3 V		
	I sc:	2,31 A		
	Voc:	26,0 V		
Calculated values:	*Rs:*	3,9 Ohm	2,1 Ohm	90,2 %
	Losses by add. Rs:	-24 W		
	Rp:	434 Ohm	259 Ohm	67,6 %
	FF:	0,63	0,66	-4,7 %
	NOCT:	31 DegC		
Conditions during measurement:	*Cell temperature T mod:*	27,4 DegC		
	Irradiance E eff:	548 W/m2		
	Temperature reference cell T ref:	28,3 DegC		

Additional Informations

File: C:\...\Measurement series1\Measurement series1\29-09-2017 17_00_08.SUI

PVPM Serial No.: PVPM1000X01515	*Sensor: ISET-poly #03192*
Customer:	*PV plant:*
Plant part: *MiaSole Flex-02 Test module*	*Date of measurement: 29.09.2017 17:00:08*

Description: Performance measurement after the impact testing.

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Date: 10.11.2017

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Appendix 3: Powering MacRack with PV (Confidential)

The contents of this appendix are confidential.