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Preface

This paper is the documentation of my thesis that counts a total of 30 study credits. It brings the end of my 2-year master's program in City and Regional Planning at the Faculty of Science and Technology at the University of Stavanger, Norway. The project has been undertaken with great interest and enthusiasm. I experience a great sense of satisfaction to complete the thesis and gain comprehensive knowledge on Solar Photovoltaics(PV) as a renewable urban energy solution and, more importantly, being able to associate my study to a real project at Stavanger Airport. I am fully confident that the learnings from this thesis would prove significant in my future endeavours.

I cannot stay without appreciating the supports and motivations I have received throughout the project.

Firstly, I would like to thank my supervisor, Professor Harald Nils Røstvik, for his outstanding supervision. The insights from Harald helped me to stay on track, and his routine feedbacks enriched my thesis. I also acknowledge the feedback I received from Associate Professors Ari Krisna Mawira Tarigan, Tegg Westbrook, Fabio Alberto and Ana Llopis Alvarez for their valuable feedbacks during Master Thesis Consultation Seminars.

Secondly, my thanks go to Hellik Line Syse from Future Energy Hub and Avinor for their collaboration, which enabled me to associate my thesis to a real project at the airport.

Thirdly, I would like to thank my loving wife, Aakriti Poudel, for her constant support and motivation that encouraged me to keep working even during challenging Covid-19 situations. My special gratitude goes to my parents and sisters, who regularly bestowed love and support.

Finally, I would like to thank all my friends, colleagues, and university staff who directly and indirectly assisted me in completing this thesis.

Stavanger, June 12, 2020

Chandra Prakash Paneru

Abstract

The climate and energy problems are on the rise as the urban population is growing rapidly. The extensive use of fossil fuels and the increasing greenhouse gas (GHG) emissions still awaits collective abatement policies. In this scenario, the need for innovative urban renewable energy solutions is much more crucial than ever.

As Norway envisions to achieve a low carbon society, it mandates abatement measures in all sectors. In the Aviation sector, abatement measures such as renewing of the fleet, electric flights, and use of jet biofuel are potential measures. To achieve 100 per cent electric aviation by 2050, Avinor is exploring innovative local renewable energy solutions at its airports. In the first phase, it plans to install a large-scale PV system of 1000 KWp installed capacity at the pre-regulated open space inside Stavanger airport. With rapid technology advancement and cost reduction, the photovoltaic (PV) system has gained attention as a potential urban energy solution.

The scale of this thesis is to study the planned first phase PV installation through a research methodology that involves site analysis, test rig analysis, spatial calculations, and simulations. The research aims to determine the most sensitive parameters that need to be optimized to maximize the production from planned large scale installation and draw crucial information that would help the stakeholders to draw critical decisions.

Site analysis examines extra design considerations, available area, energy demand, and solar resources at Stavanger airport. Similarly, test rig analysis explores and compares the technical specification and power performance of the PV modules used in the test rig at the airport. Spatial calculations present the calculations on land area requirements, spatial setup possibilities, and land-use efficiency. Test rig-scale simulations present a comparative study of various setup possibilities. Similarly, large-scale simulations present the comparison between different alternatives and help to visualize the system at the actual site environment.

For a large-scale PV installation, tilt angle, azimuth angle, inter-row spacing, module orientation (portrait vs landscape), and the number of modules alongside the bottom of each row are found to be most sensitive. At Stavanger airport, the optimal values for these sensitive parameters are found as a tilt angle of 45°, azimuth angle of 0 ° (due south), interrow spacing of 17.22m, module oriented portrait and two modules alongside the bottom of each row. For 1000 KWp of a solar PV installation, 5665 m^2 of PV generating surface and a total land area of

29615.9 m^2 is required. The installation could avoid 496.7 tonnes of CO_2 emissions annually. The installation cost of the system approximates $1114648.36 with a Levelized Cost of Energy (LCOE) as 0.68 KWh/$. The thesis links the transferability of methodology and results of this research to various urban spaces and to support newer concepts such as Nearly Zero Energy Buildings (NZEBs) and positive energy districts (PEDs). Current PV policies are limiting the diffusion of PV systems in Norway. Therefore, the need for liberal PV policies is realized.

Abbreviations

AC	Alternating Current
DC	Direct Current
GHG	Green House Gas
GIS	Global Information System
HVAC	Heating, ventilation, and air conditioning
ICT	Information and communications technology
KW	Kilowatt
KWh	Kilowatt-hour
MNOK	Million Norwegian kroner
MPPT	Maximum Power Point Tracking
$MTCO_2e$	Million tons of Carbon dioxide equivalence
MW	Megawatt
MWh	Megawatt-hour
NZEB	Nearly Zero Energy Building
O&M	Operation and Maintenance
PED	Positive Energy District
PV	Photovoltaics
USD	United States Dollar

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1 Introduction

1.1 Background

As the use of fossil fuels has demonstrated severe global environmental damage and a fatal threat to all the living species, the world is exploring cleaner renewable energy solutions over fossil fuels. Especially in the urban areas where 68% of the world's population is projected to be residing by 2050(United Nations, 2018), the significance of clean, renewable urban energy solutions is obvious.

Several alternatives to urban renewable energy solutions have already been explored, tested, and implemented. For example, solar and wind power have gained huge popularity. And most interestingly, solar energy has demonstrated vast potential in being an urban energy solution with the rapid development of photovoltaic technology. Small scale installations of solar PV are comparatively easy and have matured over time. However, large scale installations require special considerations in terms of its complexity and uniqueness of each new installation. A comprehensive analysis is necessary to understand the project and the operating conditions. A prior analysis helps to figure out the optimum operating conditions, which would maximize the performance as well as economic benefits. Or in other words, the cost of operations could be lowered, and power output could be increased.

The transport sector, which includes almost all forms of transportation, accounts for c.a 24.48 % (8040 $MTCO_2e$) of the world's total GHG emission as of 2017(IEA, 2020). In Norway, as per 2018, the transport sector is the biggest source of emission, accounting for almost 32% (16.6 MTCO2e) of total GHG emission, and domestic aviation accounted for 2.5 % of total national GHG emission(Miljøstatus, 2020). There are huge emission abatement possibilities within the transport sector. Although electrification within other forms of transportation has already been taking shape, the electrification within the aviation sector is still to be materialized.

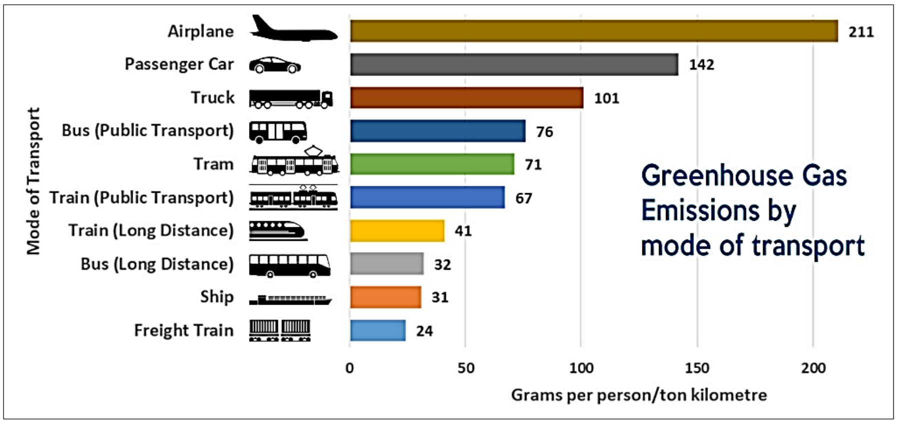


Figure 1: Carbon footprint of various passenger transport modes. (Manaadiar, 2019)

As shown in *Figure 1*, the carbon footprint of aeroplanes is significantly higher than other modes of transportation which is one of the reasons of the growing "flight shame" or "flygskam" for the aviation industry which has generated great unease among the sector as well as among the passengers because the sector uses five million barrels of oil per day which has been expected to account for almost 22% of global GHG emissions by 2050(Papa, 2020). The aviation industry in Norway has also felt the heat and given the fact that the emissions level will keep rising in the absence of abatement measures, as shown in *Figure 2*, the need for greener and sustainable mobility has been realized. In this background, various projects have been conceptualized, which are slowly taking shape.

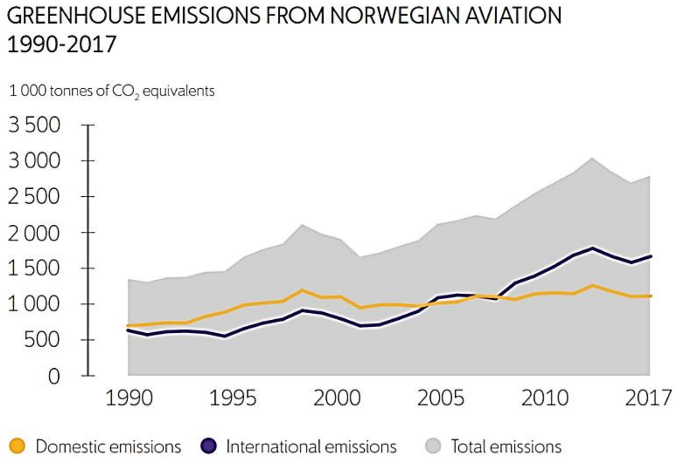


Figure 2: Greenhouse emissions from the Norwegian aviation sector from 1990 to 2017. (Avinor, 2019)

Avinor- the state-owned company is under the obligation of the climate policies in Norway and must align its operations towards collectively achieving the carbon-neutral target by 2050. According to (Avinor, 2019), aircraft handling, taking off and ground transport are the biggest sources of GHG emission that require necessary measures for abatement and 100 per cent reduction demands complete electrification of all the sectors(operation infrastructure- buildings and facilities, air traffic and all other motorized transportation at the Airport). Electric aviation, renewing fleet and using jet biofuel is realized to be potential emission abatement measures in the aviation sector.

With the growing demand for clean energy, there is an increasing quest for newer possibilities to produce energy that could be sustainable. In this aspect, a lot of airports have figured out the possibilities of using a large amount of available land within the Airport for local energy production, which could transform the aviation sector. Currently, several airports around the world have gone fully electric with the help of solar energy. The production does not necessarily come from just solar energy. It could incorporate wind energy as well. However, solar energy has demonstrated its immense potential of being capable of incorporating the existing landscape of the Airport. Several airports have already accomplished the large-scale installation of solar PV to achieve their ambition of powering the Airport with a clean and sustainable energy solution that is produced locally. Large scale installation of PV panels at the Airport is believed to bring the aviation sector closer to the future of 100 % electric aviation.

Stavanger Airport under Avinor's framework aims to be energy-self-sufficient by 2025 and for this purpose requires to produce a large amount of sustainable clean energy using local energy solutions and therefore aims to have a large-scale installation of solar PV of installed capacity up to 1000 KW for the first phase(Avinor, 2019). Avinor is expecting an introduction of hybrid-electric aircraft in its airports by around 2025 and aims to have fully electric aviation by 2050. The choice of solar PV could be understood with the rapidly falling price, advancing technology, and increasing the efficiency of the solar PV modules.

1.2 Selection of the thesis and the relevance in urban planning

The selection of this thesis is made based on personal interest in urban renewable energy solutions and, more particularly, on solar photovoltaics. In this context, ***Future energy hub*** at the University of Stavanger collaborated with Avinor for a potential master thesis. Avinor plans to deploy large scale installation of ground-mounted solar PV inside Stavanger Airport, beginning with a demonstration project of about 1000 KW installed power. In this regard, Avinor expressed an interest to collaborate for a master thesis and offered the data from the test rig that was installed in the Airport since 2016.

The relevance of the thesis with the airport and the large-scale solar installation could be viewed in the larger picture of urban planning. What happens at the Airport also happens in an urban area. For instance, the growth of the urban population increases the road traffic in an urban area and, at the same time, increases the air traffic at the Airport. This growth demands increased infrastructure in both parts. So, there is an obvious correlation between the urban area and the Airport. The Airport also requires the same basic public services and utilities (energy, water, solid & liquid waste management, ICT, and surface transportation) as that of the urban area(Alberto, n.d.). So, the same analogy could be used at the airport like that in the urban area, which is transferable to the urban planning sector. As cities in the past sprawled around the ports and highways, future cities may be planned around the Airport, if not sprawled organically, because of their proximity and greater commercial potential to serve a not only local but global population which could turn a "city airport" to an "airport city" or "aerotropolis"- (Urban Hub, n.d.).For example, the Oslo Airport city project is an ongoing project which aims to be a first energy-positive airport city. With the advancement in technology and energy solutions, niche innovations like the solar roads have surfaced, which could revolutionize the current urban road forms, which would not only be serving for mobility but also generating renewable energy with the use of solar cells. Similar innovation could be analogous at the Airport, where current runways are replaced by solar-powered runways. If the huge area used for runway and taxiway could be used for energy generation, the 100 % urban mobility and 100 % electric aviation will not be far-fetched.

Figure 3: Oslo Airport city project (source: nordicarch)

Further, the findings and methodology of this thesis would not be limited to the open spaces at the Airport. They could be transferred to PV system deployment on various urban landscapes where large scale installation is feasible. Examples of such urban landscapes around Stavanger area includes:

1. **Urban roof spaces**: On residential roofs, small-scale installation is possible. Whereas there are numerous commercial complexes around Stavanger with larger roof spaces where large scale installation of the PV system is possible. The integration of solar PV in such urban roof space aids the idea of achieving nearly zero energy building (NZEB).
2. **Urban solar canopies**: Urban landscape includes large open parking spaces, which could be turned into parking spaces with solar canopies, which would not only serve as the shade for the parking lots but also produce extra electricity for lighting and charging purposes.
3. **Urban agricultural farmlands**: Within the periphery of cities, urban farmlands are common where co-location of the large-scale PV system and crop production is feasible. Ground-mounted PV installation with significant pole heights could be used so that

crops could be produced below the solar arrays, and energy is produced from the solar arrays. According to (Fraunhofer ISE, 2017), the co-production of crop and solar energy increases the land-use efficiency by 60 %, as depicted in *Figure 4*.

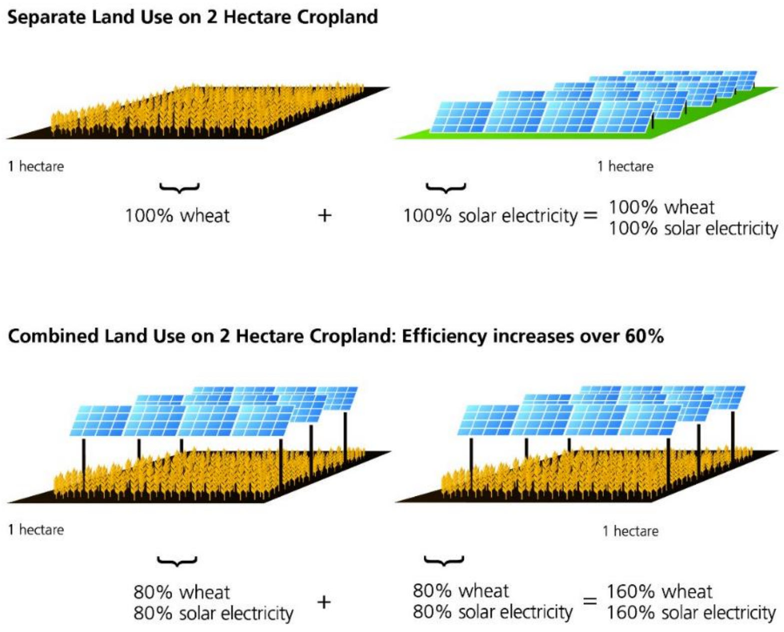


Figure 4: Dual use of agricultural land and the increase in land use efficiency(Fraunhofer ISE, 2017).

4. **Urban water bodies**: In regions like Stavanger, where there are numerous lakes, there is a feasibility of large-scale installation of the floating PV system from where a large amount of renewable energy is possible to be produced.

Figure 5: Examples of Solar PV installation possibilities at various urban landscapes.

The installation possibilities of PV at various urban spaces is not only limited to architectural scale but broadens up to a larger landscape scale which then associates the PV design as a part of energy infrastructure demanded by the modern cities and further relates PV design as a part of sustainable city planning(Scognamiglio & Garde, 2014). The modern cities that envision all new buildings as NZEBs should incorporate various energy generation options not only limited to building's footprint and on-site but also the energy generated offsite(Scognamiglio & Garde, 2014).

The relevance of the thesis could further be viewed in relation to a comparatively newer concept of a positive energy district. A positive energy district is an urban district which produces more energy than it consumes. It plans for renewable energy production through local renewable energy solutions and in integration to a regional energy system that has annual net-zero energy import and annual net zero CO_2 emissions(Urban Europe, n.d.). In this regard, Avinor plans to abate emissions at its airports and achieve fully electric aviation. At Stavanger airport, Avinor plans for a demonstration project which will generate renewable energy locally and together with a consortium and the regional grid known as elnett21 plans to integrate the energy system, which would facilitate for better energy management and optimization. As discussed earlier, the analogy of urban space applies to the Airport. Therefore, Stavanger airport could be viewed as an airport that has envisioned to transform itself as a potential positive energy district. The Airport could only be upgraded as a positive energy district if it could generate more energy per square meter of the area, which could be consumed locally by the buildings and planes more efficiently. The large-scale installation of a solar PV system would increase the energy density at the Airport.

The thesis further highlights the relevance of GIS-based databases and PV related software programs in urban energy and land-use planning. With GIS-based databases, it is possible to exploit solar resource data for the feasibility study, and with PV related software programs it is possible to make potential energy estimates that is useful for sustainable renewable energy planning at the local, regional and national level. GIS-based databases such as PVGIS and SolarGIS have been used to understand the solar radiation intensity and climatic conditions at the site of installation.

Sustainable city and regional planning demands efficient resource and energy management and mandates smart solutions for buildings, transport, and infrastructure(UiS, 2019). Unless urban planners have a better understanding of the technical know-how and how it shapes the society on grounds, there would hardly be a coherence between the policy formulation and the shape of future city envisioned. This thesis aims to present associated technical know-how on the related subject matters raised by the research problem.

1.3 Problem Description

The transition of fossil fuel-driven transportation to emission-free transportation demands extensive electrification, which incorporates electric planes, buses, ships, and ferries and requires huge electricity for instantaneous charging(Enova, n.d.-a). In this regard, a consortium named Elnett21 as shown in *Figure 6* has been formed among regional key players - Avinor, Forus Business Park, Risavika Harbour, Lyse and Smartly to develop and demonstrate the local energy solutions to meet the increasing power demand through local production, storage, and management of energy which could make optimal use of existing grids(Enova, n.d.-a). Enova further mentions that the consortium plans to undertake several demo projects to highlight that local initiatives and regional cooperation can bring solutions to smart energy use and management with increased security of supply and reduced need for grid development.

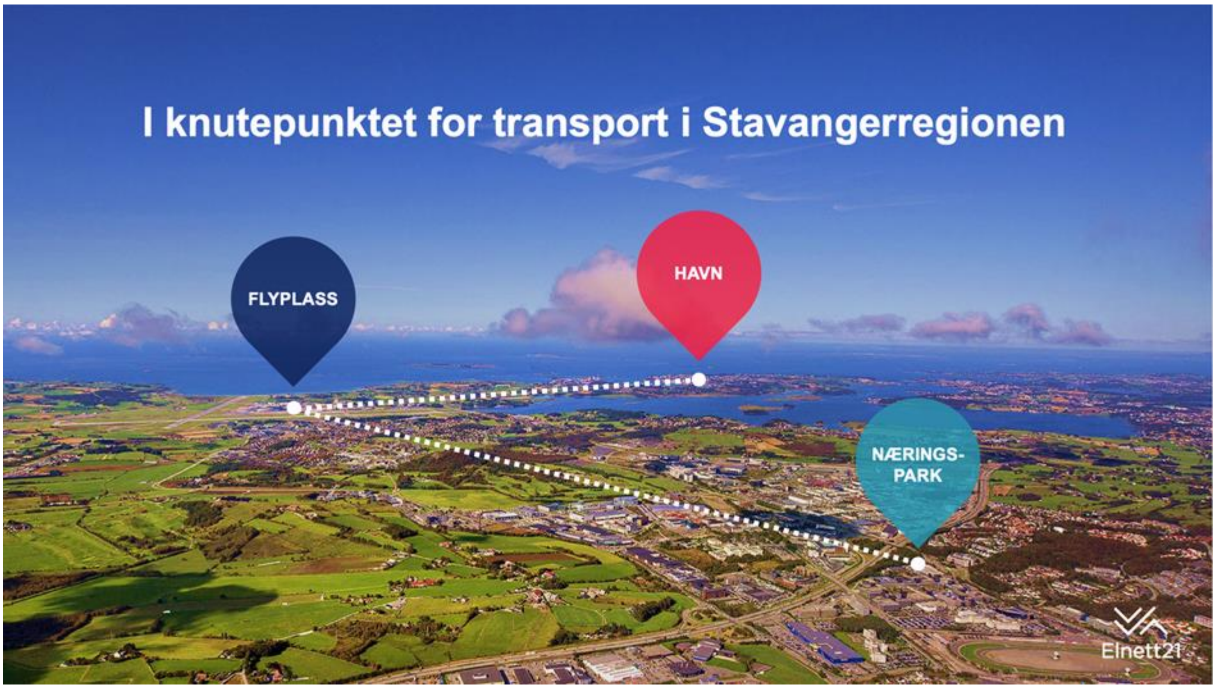


Figure 6:Illustration of future electric transport hubs and the Elnett21(source: www.elnett21.no)

Avinor as one of the partners have been assigned with a work package where it needs to install at first stage **1)** a solar park with a total installed power of 1000 KWp, **2)** two wind turbines of 250 KWp - a total of 500 KWp installed power and **3)** explore for the large scale battery storage possibility at the Sola Airport(Enova, n.d.-a). With this demo project, Avinor wants to gain expertise in establishing micro-networks at its airports, which it believes is a first step for achieving its goal of 100 % electric aviation.

Any new projects inside critical infrastructure such as airports require robust assessment and require extra considerations than at other locations. Wind farms are not new to Norway, whereas large scale solar park inside an airport is unique for Norway. If this installation takes shape, it would be the first of its kind in Norway, which would open a new possibility of replicating the same in other airports of the country. That is why the thesis has its prime interest in the large-scale solar installation. However, the large-scale solar installation at an airport is very challenging and requires a comprehensive study for multi-level decision making. There are no references to look up at in Norway. That is why international case studies must be referred to.

Sola airport has a test rig consisting of 20 PV panels with varying specifications installed inside the Airport that has been in operation for a few years. The test rig is installed to analyze preliminary data. However, the data from the test rig are very limited. So, the thesis would check if the available data from the test rig is enough for the optimization of various parameters for the large-scale solar installation. Which of the parameters could be optimized by exploiting the data from the test rig? First, a literature review is to be made to find out what parameters are to be optimized for large-scale installation and how that can be done. Since the Airport is critical infrastructure, what extra considerations are to be made for such kind of installation in the airside of the Airport. The optimization is expected to mainly optimize the performance and cost such that the performance could be maximized, and costs could be minimized.

1.4 Research Question

What are the site related and most sensitive parameters to optimize a large-scale PV installation at Stavanger Airport?

1.5 Scope and limitations

The study focuses on exploring extra site related parameters and considerations at the Stavanger airport that must be required for large scale installation of a PV system. It aims to determine the most sensitive parameters that need to be optimized for the overall optimization of a large-scale PV system in terms of performance and economy. The thesis attempts to generate information by analysing the test rig at the Airport and utilize the data for the optimization of a planned large-scale installation. The thesis further aims to perform simulation of a large-scale PV system and undertake the financial evaluation. As the potential consequences of the planned installation, the thesis plans to estimate how many tons of annual carbon emission would be reduced (the equivalent of planting how many trees?) after the installation. The usefulness of the simulation in critical decision making and planning is also a part of the study.

The thesis limits its scope to the Avinor's first phase plan of installing 1000 KWp of a solar PV system and takes the predefined plots specified for energy trails on the Stavanger airport's master plan as the potential site of installation. The study limits its scope to the spatial and planning aspects and does not focus on core electrical aspects. Glint & glare analysis is not carried out assuming the modules that would be used will be non-reflective and would pose a non-significant glint and glare hazard. The study is limited to the large scale PV installation at an open area in the Airport and does not account for the solar PV potential in the roofs or at any other spaces but explores the transferability of methodology and findings to all other urban spaces and their solar PV installation potential. The thesis assumes that the risk of complexity and cost associated with trackers is high, and therefore limits its consideration to fixed-tilt PV systems.

The thesis considers the works that have already been undertaken and advances for the prementioned research aims. Earlier works include annual production analysis from test rig and comparison of output for two different PV technologies(polycrystalline vs monocrystalline), five different azimuth angles (due south, due east, due west, due south-east, due south-west) and two different tilt angles (10 ° and 15 °). The thesis refers to the prior work as reference and undertakes comprehensive test rig analysis followed by spatial calculations and analysis to simulate the planned first phase installation. The integration possibility of utility-scale battery is also a part of the study.

1.6 Challenges

The major challenge to undertake the project is undoubtedly the unprecedented case of Coronavirus pandemic, which resulted in total nationwide lockdown. The lockdown was mentally challenging to cope up with, which not only limited the physical access to the university's library and studio but also confined the project to a single laptop screen and a room. This created a lot of difficulties. Regular meetings with Avinor could not materialize as expected. The communications and response were delayed. Another challenge was to learn the technicalities of the solar PV system. The choice and use of various software programs were equally challenging. It demanded a lot of research to select suitable software programs that were good enough to make simulations for large scale PV systems as demanded by this project. Most of the programs were not freely available that limit the access only to the trial version of the program that kept on expiring within a month. Several software programs used in this project were learned from scratch and demanded a significant amount of time to comprehend.

2 Methodology

This section mentions and discusses all the methods and the bases used for information gathering, data collection, calculation, simulation as well as analysis. The sequence of the adaptation of methods provides an insight into the gradual development of the thesis. The selection of the topic, as discussed previously, is highly influenced by the interest in urban renewable energy solutions and, most specifically, solar energy and its immense development potential and integration flexibility to any landscape. The following chart highlights methods that are used sequentially to establish comprehensive knowledge on the subject matter and to undertake the thesis more coherently.

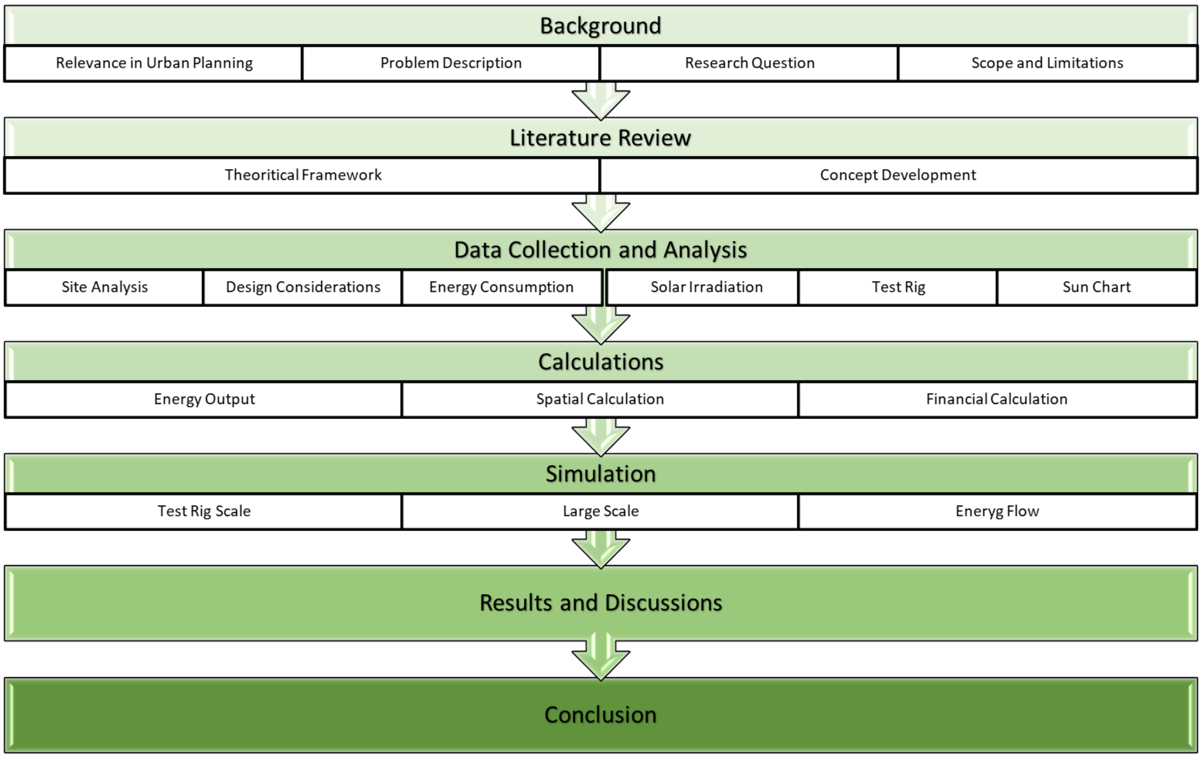


Figure 7: Flow diagram of the methodology adopted for the thesis.

2.1 Literature review

As a preliminary work, a comprehensive literature review has been undertaken to gather associated knowledge about deployment possibilities of solar photovoltaics at Airports. The literature review explores the theoretical, technological as well as economic aspects. The literature review is based on relevant articles, research papers, books, reports, master thesis, and other online databases, which were accessed through google, university's library database as well as others. Combinations of several relevant keywords were used for search purposes. Some of the commonly used keywords include "photovoltaics," "solar energy," "airport,"

"utility-scale," "large-scale," "deployment," "solar irradiation," "design consideration," "optimization," "installation,", "simulation" and others.

2.2 Data Collection and Analysis

Data collection is undertaken to gather site-specific data which includes topographical, meteorological as well as site conditions. Since one of the chapters of the thesis is to analyze the test rig at the Airport, the data associated with the test rig were gathered with significant interest from the optimizer platform called “Tigo” for which the digital access was granted in cooperation with Avinor. The detailed specifications of the types of PV modules that are in use in the test rig have been gathered from the technical datasheets available from the manufacturers' website, which are added in the appendix section for reference.

The solar resource at the site of installation is analyzed based on the meteorological data. For this work, an online database PVGIS is used. Apart from PVGIS, the meteonorm database is also used as some of the software have based their simulation on metronorm. For instance, PVsyst and PVSol have integrated the meteonorm database into their software.

The annual energy consumption data at the Airport were made available by Avinor. The master plan of the Airport was collected from Avinor’s website, which was very helpful for site analysis. The quantitative method is used since most of the information is quantifiable and is presented in the form of data. Qualitative method is used for site assessment as well as other purposes where information is not quantifiable and needs to be discussed. Solar resource and associated data have been extracted from various databases. *Table 1* presents the working principle of the databases used for data extraction.

Table 1: Meteorological databases used and their characteristics

Database	Coverage	Approach	Website
Meteonorm	Global	Interpolation of long term monthly average data from nearby weather stations	https://meteonorm.com/
PV GIS	Europe, Africa, parts of Asia and America.	satellite-based solar radiation data	https://ec.europa.eu/jrc/en/pvgis
Solar GIS	the location between 60N and 45S latitudes	High-resolution data based on satellite observation and meteorological model	https://solargis.com/

2.3 Calculations

Calculations are made on the test rig scale as well as on large-scale installations to understand some of the parameters and the way to optimize them. The data gathered from the test rig were analyzed, and further calculations were made on Microsoft excel to obtain further results. The calculations are mostly comparative calculations to compare the production results of monocrystalline vs polycrystalline modules, similarly, for comparing output at a tilt angle of 10 vs tilt angle of 15 and five different azimuth angles (due south, due south-east, due south-west, due east, due west).

Based on the results from the test rig and the optimum solar data identified, large scale calculations were made to find out a preliminary estimate of the area required for solar PV installation of 1000 KWp of installed power at the site of installation. Further, the sun path for the site is generated, and the solar elevation angle and azimuth correction angle is figured out for the worst solar window at the site of installation for inter-row spacing calculation. The ideal inter-row spacing calculations are made for various alternatives of module orientation and the number of modules alongside each row. By comparing the results of various combinations of parameters, the best alternative is determined. To get a preliminary idea of installation cost, rough financial estimation is undertaken for the best alternative.

2.4 Simulation

After realizing the limitations of the data from the test rig, the simulation was sought after for further observation. In this regard, test rig scale simulations are undertaken for further analysis. Simulation of 20 PV modules at various tracking alternatives is undertaken to see the difference in the annual production. Similarly, the simulation of 20 PV panels at the optimum tilt of 45 and optimum azimuth due south is undertaken to observe the annual production value and compare that with the data from the test rig.

Since one of the objectives of this thesis is to undertake large scale simulation to understand the dynamics of area use, spatial setup, and total energy flow, such simulations are undertaken to compare various scenarios.

There are numerous commercially available software programs for calculation and simulation related to the PV system. Various programs were explored for data extraction, simulation, and analysis purpose. The choice was made based on the availability, desired output, and the flexibility of the software programs for undertaking the required objective. In this prospect, the working principle of the software programs selected is important to understand. *Table 2* summarizes the software programs used, the reason for selection, adaptation of meteorological data, and working principle for each of the simulation software used.

Table 2: List of software programs for simulation and their characteristics

Software	Default Meteorological Database	Reason for selection	Website
PVsyst	Meteonorm 7.1 (1981-2010)	Ability to generate synthetic data to produce a tilt vs azimuth matrix for clear sky irradiance.	https://www.pvsyst.com/
PVSol Premium	Meteonorm 7.1 (1981-2010)	Ability to simulate test rig scale system as well as a large-scale system with 3D visualization.	https://valentin-software.com/en/products/pvsol-premium/
Energy 3D	weather station data	Easy optimization function for various parameters for both small scale as well as large scale systems with 3D visualization	http://energy.concord.org/energy3d/

3 Literature Review

3.1 Deployment of Solar Energy at Airports

Advancement of the solar energy technology, availability of large cleared open space inside the Airport, and high energy consumption and growing energy demand within the airport facilities are the major reasons of growing interest for the deployment of large-scale solar installations at the Airport (FAA, 2018, p. 2). These airport-based installations need to be checked if they are compatible with the aviation services, financial sustainability, as well as national energy policy. Solar PV technology is found to be the most compatible technology which could be easily designed and installed in an existing landscape. For instance, the large open spaces inside the Airport could be utilized for local energy production, which otherwise holds limited value for the aviation operations because of its proximity to the runway and due to underlying land-use restrictions. Large scale installation of solar panels demands substantial capital investment.

That is why the optimization of various parameters is very crucial to minimize the cost of engineering and installation and to maximize the efficiency and production to keep the solar energy an attractive alternative.

Figure 8 shows examples of a few large-scale airside PV installations at the airport around the world.

Figure 8: Examples of Large-scale solar PV installations at the Airport

3.2 Solar Photovoltaics

Most of the literature on Solar energy technology revolves around solar photovoltaics since this renewable energy technology is mature and commercially available and holds a huge potential to be deployed on airports(Kandt & Romero, 2014). The world has witnessed phenomenal advancement of PV technology in recent years that has resulted in rapid cost reductions. Due to this development, several countries around the globe have introduced supportive policies to ease the deployment and utilization of PV technology to increase the share of renewable energy into their total energy mix(Mughal & Jarial, 2018).

Photovoltaic solar cells are made of two layers of crystalline silicon, which are covered with a protective non-reflective glass layer from the top. One of the layers is positively charged, and the other is negatively charged. The photon coming from the sunlight hits the layers of silicon and releases its energy to the atom in the silicon in the form of electrons. The electrons pass through the junction between the layers to generate electric current, as illustrated in *Figure 9* (Simpleray, 2019).

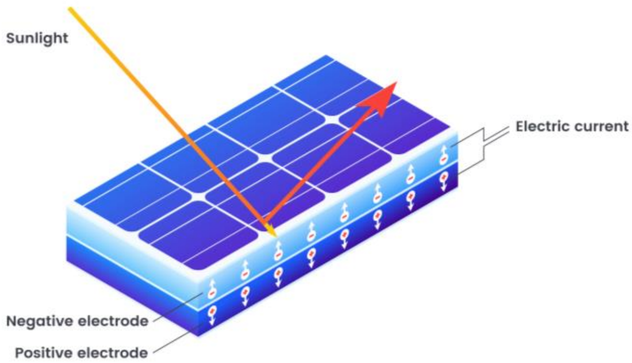


Figure 9: Illustration of how photovoltaic cell works. (Simpleray, 2019)

PV or solar cells are the most basic units. PV module consists of multiple PV cells. A PV panel, also called Solar panel, consists of multiple PV modules that are either fastened to an existing single supporting structure or ground-mounted on a top of a stand. Multiple solar panels are connected in series to form a string which acts as a single generating unit. The illustration below shows the distinction between a cell, module, panel, and an array.

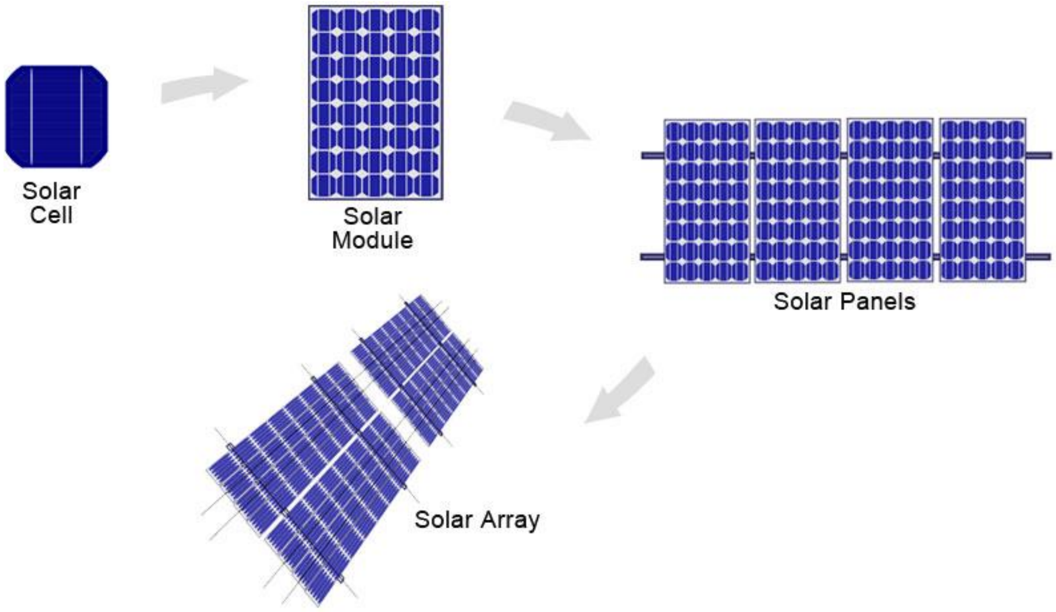


Figure 10: Illustrations of PV Cell, PV Module, PV Panel, and PV array (Builders, n.d.)

The PV array starts producing power once it is exposed to sunlight. However, it requires several interconnected components for conducting, controlling, converting, distributing, and storing the produced energy. *Figure 11* shows a basic configuration of a PV system.

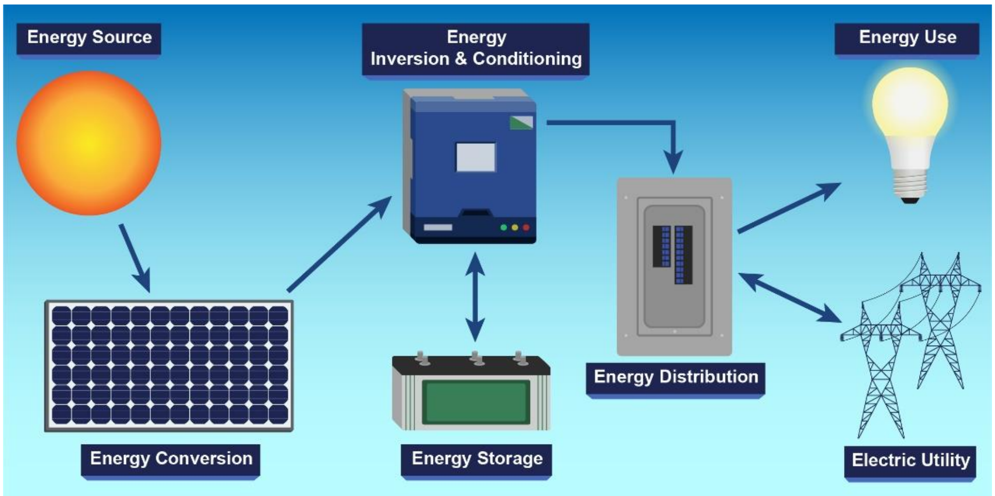


Figure 11: Components in a PV system (FSEC Energy Research Center, 2020)

Electricity is produced in the form of direct current (DC) as the PV panels convert light energy into electrical energy. A PV system consists of major components such as DC-AC power inverter, battery bank, charge controller, a balance of system (BOS) hardware, wirings as well as protection devices, which varies based on the functional requirements of the system. Unlike traditional charge controllers, the MPPT (maximum power point tracking) charge controller increases the efficiency of the solar panels by tracking the ideal maximum power point of a PV array and optimizes the energy output(Photonic Universe, n.d.). Therefore, the use of MPPT charge controllers is preferred. *Table 3* presents some of the major components of a PV system and its functions.

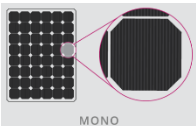
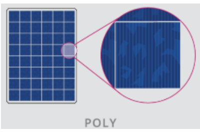
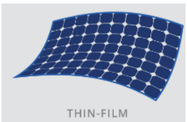
Table 3: *Components of a PV system and their function*

Component	**Function**
DC-AC inverter	Converts DC to AC
Battery bank	Storing power for uninterrupted supply (during the night or for low irradiation situation)
Battery charge controller	Protects battery from overcharging as well as complete drainage.
Wirings	Connects components electrically with each other

3.3 Types of Solar Panels

Table 4 summarises the basic characteristics of the three types of solar panels. The choice of the type of solar panel for installation depends on various factors and system characteristics.

Table 4: Summary of Types of Solar Panels and their characteristics (self-formulated table based on the literature on (energysage, 2020))

Type of Solar Panel:	***Monocrystalline***	***Polycrystalline***	***Thin film***
Panel cells made of:	Silicon Wafers	Silicon Wafers	Variety of Materials: 1.Cadmium telluride (CdTe) 2.Amorphous silicon (a-Si) 3.Copper Indium Gallium Selenide (CIGS)
Manufacturing process	cells are cut from a single, pure crystal of silicon	cells are composed of fragments of silicon crystals that are melted together in a mould before being cut into wafers.	1.A layer of CdTe between transparent conducting layers. 2.composed of non-crystalline silicon. 3. four elements (glass, plastic, aluminium, or steel) placed between two conductive layers
Formation	-wafers assembled into rows and columns - covered with a glass sheet on top and framed together.		Glass layer on the top for protection.
Appearance			
Advantages	High efficiency	Low cost	Lightweight, Portable and flexible
Disadvantages	Higher cost	Lower efficiency	Lowest efficiency

3.4 Performance of Solar PV

The performance of Solar PV mainly depends on geographical, meteorological, and technical conditions at the site of installation. The amount of electricity production depends on the amount of sunshine irradiance as well as environmental factors such as wind, rain, snow, smog, and dust. The sunshine irradiance at a certain location depends upon the position of the sun in the sky, which results in daily as well as seasonal sunshine variations. Solar irradiance is maximum at any location at noon during the summer solstice(FAA, 2018). *Figure 12* shows the solar electricity potential in Norway based on the global irradiation on horizontally mounted as well as optimally inclined PV modules. It can be observed that the numbers are comparatively higher for the optimally inclined PV modules, which indicates that tilt optimization increases the solar potential of PV modules.

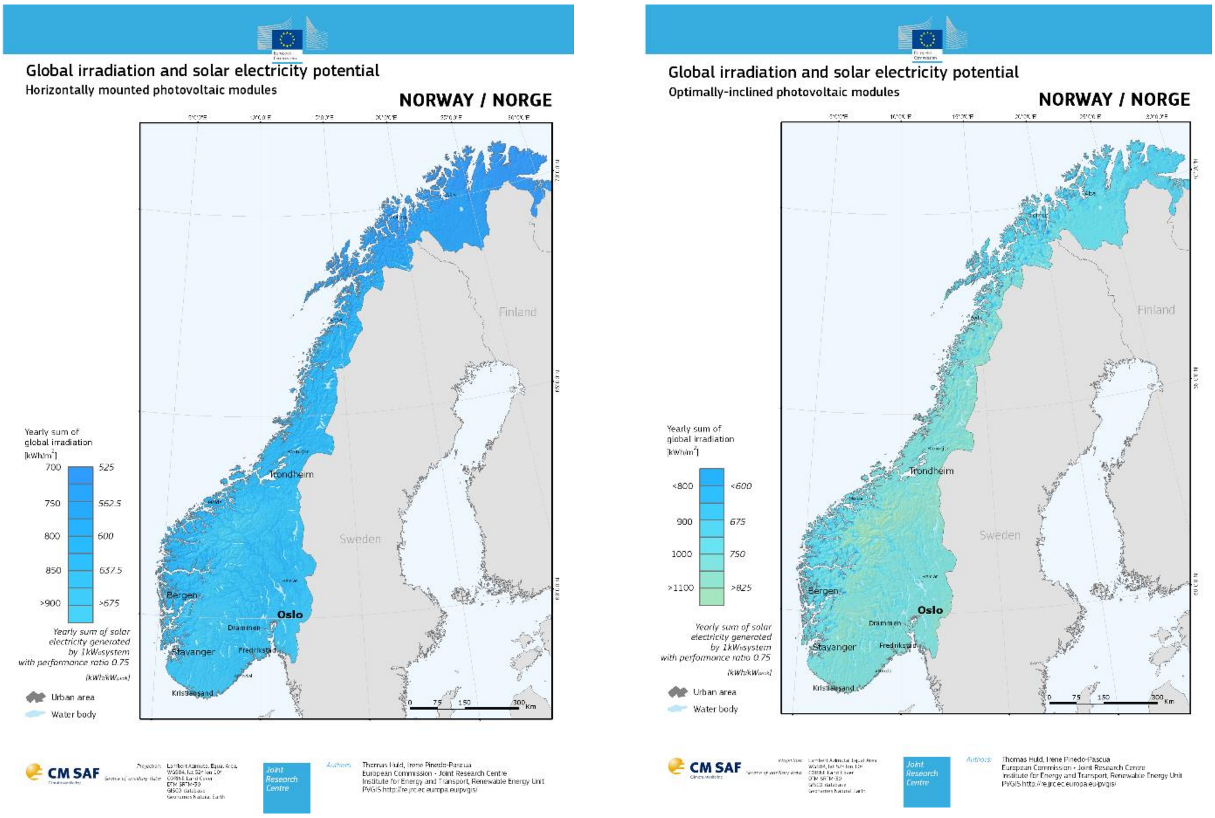


Figure 12: Map of Norway showing global irradiation and solar electricity potential on a horizontally mounted and optimally tilted PV modules (PVGIS, 2019)

The maximum amount of electricity that can be generated from a PV panel, also known as panel capacity, is determined after standardized testing at a laboratory. PV panels of a wide range of production capacity are commercially available. The choice of panel capacity for installation is figured out based on available space and budget. Monthly power produced from a solar panel is calculated as **Power = Rated power of the panel(Watt) X Average Monthly sunshine hours (Hrs) X Average Efficiency loss due to panel heating (%)** (FAA, 2018).

3.5 Solar PV economics

The key to large scale installation of Solar PV lies in the long-term economic benefit. Although the initial investment of solar PV is quite high, the operational and maintenance cost is very low. Further, Solar PV at the Airport is favourable because of the large on-site energy demand and good solar exposure(FAA, 2018, p. 23). This provides certainty over the long-term consumer of the power produced, which helps to widen the payback of initial investment over a longer period.

The Cost-competitiveness of solar PV modules has increased rapidly due to mass production as demanded by growth in large scale installations. As per (SUN, 2019), just in the last decade, there has been more than a fourfold increase in the production capacity of global polysilicon, which is the primary feedstock for solar PV module production whereas the price reduced to \$8.40 in 2019 as compared to \$80 in 2010. *Figure 13* presents the global solar manufacturing capacity versus module price, which shows a sharp decline in the module price and a rapid increase in the production capacity for the last decade (2010 till starting of 2020).

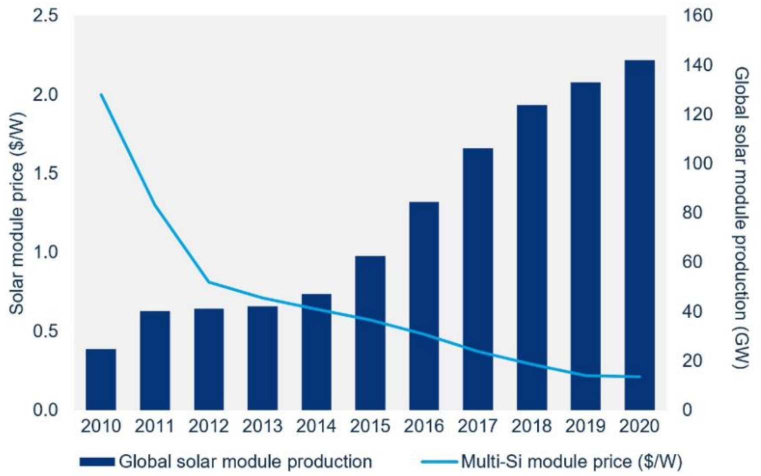


Figure 13: Global solar module production capacity versus Solar module price (SUN, 2019)

Similarly, *Figure 14* presents the breakdown of the installation cost of a utility-scale solar PV system for five of the G20 countries. The breakdown includes hardware cost, installation cost as well as soft cost. As per (Nilsen, 2016), the installation cost of solar PV in Norway is 70 per cent expensive as compared to that of Germany. This is not clear if this applies to large scale PV systems as well, but it is easy to understand that the gap in the price between Germany and Norway is getting narrower every year.

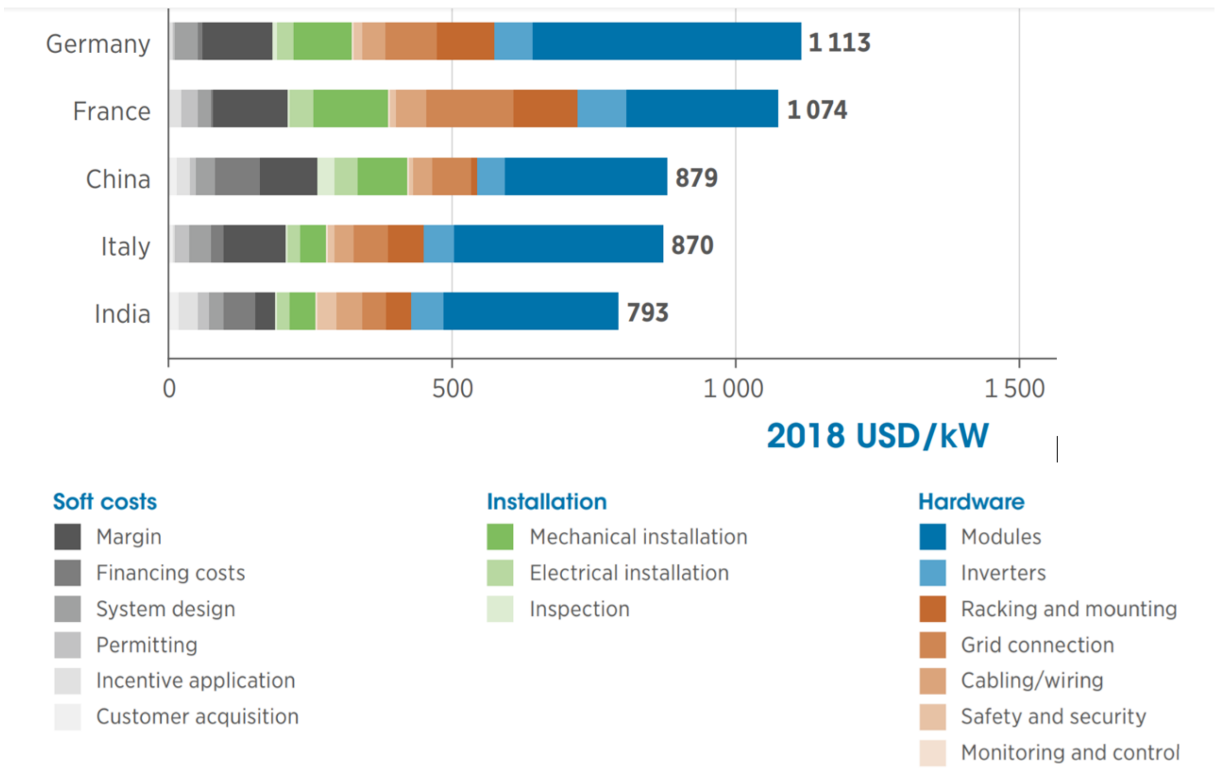


Figure 14: Detailed breakdown of the installation cost of utility-scale solar PV in a few of the G20 countries as per 2018(Irena, 2019a).

3.6 Solar PV policies in Norway

The state-owned enterprise, Enova, aids in the vision of creating a low emission society by financially contributing the projects that are future-oriented and presents energy and climate measures. Enova offers economic grants which are financed through the Energy-fund supported by state budget(Enova, n.d.-b).

Elentt21, as discussed previously, has a total estimated budget of 110 MNOK, of which 40 MNOK is being financed by Enova(Enova, n.d.-b). The planned first stage PV installation as part of Elnett21 is thus indirectly funded by Enova. Enova has also been financially supporting the owners of a small PV system by covering up to 35% of the costs for the projects lower than 15 KWh for building-integrated PV systems with storage(Steigen, 2018).

Under the pro-customer scheme ("*plusskunde-ordningen*"), grid-connected PV systems with maximum feed-in power up to 100 KW are allowed such that the customer is a net consumer of the grid-electricity on an annual basis(Steigen, 2018).

There are no certifications and standards for PV installers in Norway(Unamba, 2016). For a large-scale PV system, the electricity certificate scheme is the only scheme that is by far applicable in terms of financial support. The electricity certificate scheme is market-based, which aims to increase the production of renewable energy. The scheme allocates one certificate for every new megawatt-hour (MWh) of renewable electricity produced(NVE, 2018).

3.7 Meteorological Data and Solar Irradiance

As the amount of power produced by a PV system depends upon the amount of solar irradiation and meteorological parameters of the site, it is very important to have a thorough assessment of these parameters. The solar radiation reaching the earth's surface varies at different locations due to daily as well as seasonal variations and due to other atmospheric conditions, such as clouds, precipitation, snow, pollution, and others.

Horizontal Global Irradiation is the total solar radiation incident on a horizontal surface. It is the sum of direct normal irradiation, diffused horizontal irradiation, and ground-reflected radiation, as illustrated in *Figure 15*.

Meteorological data can be sourced either through databases or from the weather stations. Databases could be accessed online, which provides average radiation data. Some common meteorological databases are Meteonorm, PVGIS, and SolarGIS.

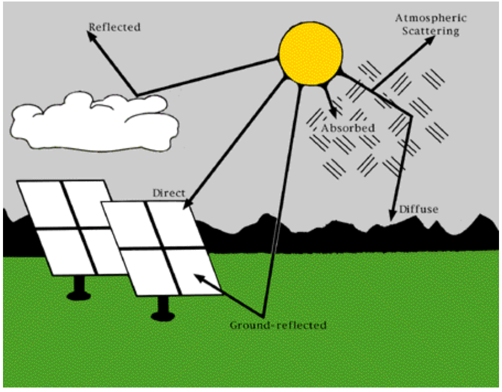


Figure 15: Components of Solar radiation received by PV module. (NREL, n.d.)

3.8 The orientation of the PV Module

The orientation plays a significant role in determining how much solar radiation a PV module receives. The tilt angle (or angle of inclination) and the azimuth angle are the two angles that determine the orientation of the module.

As shown in *Figure 16*, the tilt angle is the angle between the module and the horizontal plane, and the azimuth angle is the angle between the sun and the north.

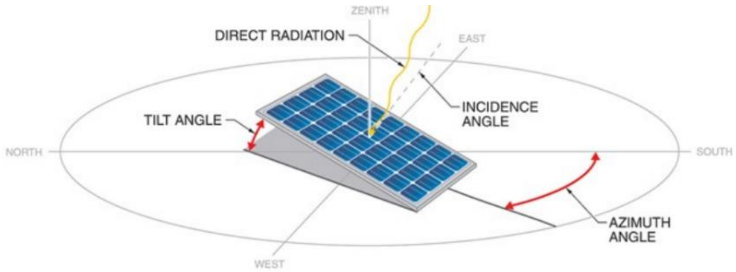


Figure 16: Orientation of a PV module and the associated components. (source: https://slideplayer.com/slide/5297009/)

For extracting maximum solar radiation at a location, a tilt angle and azimuth angle should be optimized. That means the choice of these two parameters should be made such that the PV modules receive maximum possible solar radiation at the intended location of modules installation. Panel output is calculated at different tilt and azimuth angles, and the ones that yield maximum output are then found to be the optimum tilt and azimuth angles.

The azimuth angle of zero means that the solar array is facing south. At +90°, it faces due west; at -90° it faces due east. The compass angle shows 180 for the south, 90 for the east, and 270 for the west.

The **rule of thumb** for the tilt angle is that it should be equal to the latitude of the site of installation with a minimum of 10°-15° of tilt to prevent dust settlement. Whereas, at locations with latitude>30°, a value between 5° and 20° is subtracted from the latitude to determine the tilt angle. Greater the latitude greater will the value to be subtracted(IRENA, n.d.).

Between the latitudes 23 and 90, the PV modules in an array are targeted to the south in the northern hemisphere, and in the southern hemisphere, they are targeted to the north(CivicSolar, 2011).

3.9 Temperature and Wind

The solar radiation hitting the PV produces not only electricity but also heats the module, which increases the temperature of the module. The variation in the ambient temperature also affects the module temperature, which in turn influences the energy output. The cell temperature of the PV is approximated as the ambient temperature plus 25◦C. With the increase of ambient temperature, the energy output decreases. Whereas, cold temperature increases the energy output(Stapleton & Neill, 2012).

Wind provides the cooling effect, which helps to cool down the solar modules. Cooler solar modules have demonstrated higher efficiency, which increases production over time. One degree cooling of solar modules results in a 0.05 per cent increase in efficiency(Solar.com, 2020). Therefore, several PV installations come up with a ventilation system.

3.10 Shading

An ideal solar installation must be free from any kind of shading. However, the shading of the PV modules may occur in various forms, such as shadow from nearby structures such as trees, buildings, or shading caused due to birds or vegetation. Although the shading may be temporary and partial, it reduces the yield of the solar modules. Self-shading or inter-row shading may happen due to array casting shadows on the adjacent arrays, which could reduce the optimal yield of the PV system. Usually, inter-row shading occurs during morning or evening when the irradiation level is low. Therefore, shading analysis is done to determine optimal interrow spacing to minimize shading and, in turn, increase production.

Figure 17: Examples of some shading possibilities in an open land PV installation.

In a module, cells are normally connected in series. In the case of one or more cells being shaded, the output of the module is reduced. The same will occur in the case of the defective or damaged cell.

Hot spot heating will occur when the current produced by unshaded cells is forced to pass through the shaded cell that may lead to damaging of the cell. It is not possible to obtain ideal non-shading conditions all the time. However, use of bypass diodes (one, two or three per module) could provide an alternative path to the current to skip the shaded or damaged cell completely with minimum impact on the power produced and most of the commercially available PV modules come up with these diodes (Stapleton & Neill, 2012).

3.11 The choice of System and Components

The choice of system and components requires technical as well as financial analysis. But the key to such analysis lies in maximizing the performance of the system. The choice of the modules and the inverters from several alternatives of manufacturers, shapes, sizes, and qualities is a challenging task(Bentsen, 2014). The choice of the PV module and inverters are normally made based on the module type, efficiency, tolerance, mechanical strength, weight, price, availability, quality standards, certificates, and guarantee. One special criterion for the choice of inverter is that it should have higher efficiency for a wide range of voltage and current(Stapleton & Neill, 2012).

3.12 Mounting System

The primary role of the mounting system is to secure the position of the PV array and to ensure its safety. The other roles are to facilitate the PV system for optimum solar radiation, ventilation, and overall aesthetics. The choice of mounting system is made based on the location and scale of the installation. For instance, the roof mounting system is used for small scales urban installations such as for homes and businesses. Whereas ground-mounted systems are generally used for residential or commercial properties where **1)** there is large open space and the roof mounting option is not viable and **2)** for large scale installations with huge open space such as solar farms (Stapleton & Neill, 2012).

The mounting system plays the most important role in optimizing the overall PV system as it secures the PV array at optimal orientation and tilt angle for the selected location of installation. In the roof mounting system, modules may be elevated to face the optimum tilt angle and orientation in case the angle and direction of the roof do not correspond to the optimum tilt angle and orientation for maximum yield(Stapleton & Neill, 2012).

Soil tests and other geotechnical analyses are required for a ground-mounted system to ensure stability. The ground-mounted system could be fixed in nature or may be introduced with a tracking system to maximize the contact of PV modules with the sun for increased electricity production.

The introduction of a tracking system comes with the increased complexity of operation and maintenance as it demands a lot of moving parts that are potentially vulnerable to drastic extreme weather conditions. Although the fixed system generates less electricity compared to the tracking system, there is a certainty of a fixed amount of electricity production due to minimal risk of unexpected maintenances(FAA, 2018, p. 20).

Based on the spatial setup of a large-scale PV installation, a ground-mounted system may either be a one-post system, two-post system, or tracker system, as illustrated below.

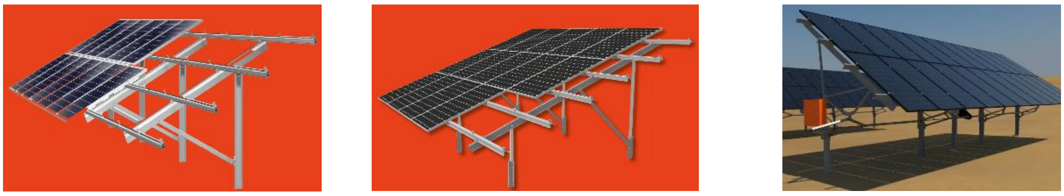
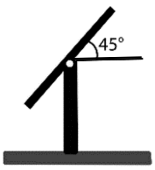


Figure 18: Ground mounted system alternatives: One-post, two-post, and tracker system (source: Mounting Systems GmbH)

3.13 Spatial setup of large-scale PV installation

For a large-scale PV installation, the spatial setup is essential as it incorporates the parameters that should be optimized to optimize the whole system. The following three parameters are the most important ones which determine the spatial setup and, in turn, optimize the total land use.

1. **Tilt Angle**: As the large-scale PV installation consists of hundreds of numbers of same kind of PV modules, all the PV modules are adjusted to the same optimized tilt angle for the site of installation, which creates a visually pleasing ambience.



2. **Orientation of PV modules on a rack**: Modules in a rack may be oriented either in **portrait or landscape** mode. The choice of the module orientation depends on the wiring of the solar cells on a solar module and the shading effect as per the site of installation.

Figure 19: Two orientation alternatives (landscape vs portrait) of solar modules on a rack (simulated image with Energy 3D)

3. **Inter-row spacing**: The inter-row spacing is the distance between adjacent arrays from the centre to centre, which is determined in such a way that the interrow shading is minimized. The interrow spacing depends upon the sun path, tilt angle of the PV modules, mounting structure, and the minimum space requirement for operation and maintenance, which should accommodate a small car or truck to pass through(IRENA, n.d.).

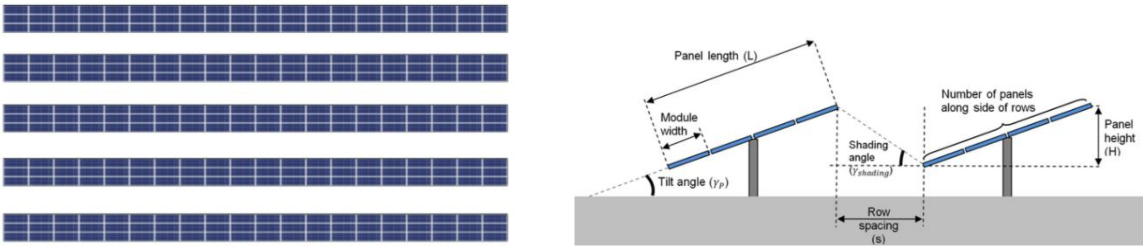


Figure 20: Illustration of several PV arrays and interrow spacing

4. **Number of rows per rack** is the number of modules in any column of a solar rack, which could range from 1 to 6. The optimum number of rows per rack is the one which minimizes the inter-row spacing, yields optimum output, and maximize profit.

Figure 21: Illustration showing four rows in a solar rack (simulated image with Energy 3D)

3.14 Storage and battery technology

The large-scale deployment of solar PV inherits major challenges of daily and seasonal generational fluctuation that is hard to forecast and cope up with the consumption fluctuation. This challenge is addressed by net-metering in the case of a grid-connected system. When production exceeds consumption, the excess energy is sent to the utility grid. In the case of underproduction, energy is fed to the system from the utility grid, and the total cost of the energy is calculated based on the net consumption(energysage, 2019).

Figure 22: 10 MW Clayhill solar PV farm, UK, with 6 MW utility-scale batteries (source:powermag)

For large scale off-grid or microgrid connected PV installation, the utility-scale battery is required to store large amounts of energy. The battery storage increases the flexibility of the system and allows it to make optimal use of fluctuating energy. Lithium-ion (Li-ion) battery technology is the most commercialized type covering almost 90% of installed technology that is used for the utility-scale battery storage system, and the cost of such batteries reduced by 80% from 2010 to 2017. The capacity of the storage system ranges from few MWh to hundreds of MWh(IRENA, 2019b).

3.15 Case Study - Large-scale PV installation at Cochin Airport.

Cochin Airport, India, is one of the fully solar-powered airports. That means the Airport is self-subsistence with locally produced renewable energy to meet its energy demand. However, the fully solar-powered Airport does not mean that aviation is also 100 % electric. The aircraft that arrive and depart at the Airport are fossil fuel operated, making the Airport not completely free from fuel-related carbon emissions. However, Cochin airport is certainly on the right track and is one step closer to eliminate fuel-related emissions. The solar installations at the Airport were done in three phases(B. & George, n.d.).

Phase I: 100 kWp PV installation on the rooftop of Arrival block consisting of 400 panels each of 250 W, 1.6 sq.m of panel area at a tilt angle of 10° facing south.

Phase II: 1 MWp PV installation inside Aircraft Maintenance Hangar facility and adjacent areas consisting of 400 monocrystalline modules of 250 Wp.

Phase III: 12 MWp PV installation in about 45 acres of land that was available near the North West boundary in the area reserved for cargo terminal future expansion. Since this phase of installation is of more interest for our study, it is interesting to observe the technical specifications of the installation, which is shown as below:

Table 5: Technical Specifications of the ground-mounted PV installation system at Cochin International airport[1]

Total installed capacity	12 MWp
Site Coordinates	10.157◦N, 76.383◦E
Type of Solar Module	Poly e Si 260 Wp
Number of PV modules	46150
Mounting Type	Ground Mounted
Land area	c.a 45 acres
Tilt angle	10◦ (fixed tilt)
No of modules per string	1846
No of inverters	10 nos of 1 MW
No of transformers	5 nos of 2 MV A
PV modules warranty	25 years

[1] (Sukumaran & Sudhakar, 2017)

Observations:

- The tilt angle corresponding to latitude has been adopted.
- Polycrystalline panels have been used, which in comparison to monocrystalline, are of low cost and lower efficiency.
- Modules are placed in portrait orientation, and the number of rows per rack is two, as shown in *Figure 23*.
- The inter-row spacing between two rows of PV array is observed to be c.a 2.21 m as measured tentatively on google earth. The inter-row shading is not a prevalent problem in this case since the tilt angle is very low.
- The total investment of the 12 MW solar PV system is reported to have cost 620 million Indian currency (51.7 million Indian rupees per MW)(Kumar, 2015).
- Underneath the ground-mounted PV system, organic farming is introduced, which contributes to almost 60 tonnes of vegetables(mostly low-lying vegetables such as pumpkin) to be sold for airport staff and local market annually(Reuters, 2018).

Figure 23: Spatial Setup of Large-scale PV system at Cochin Airport, India

(source: viralityfacts.com)

Figure 24: Organic farming underneath the solar PV system at Cochin airport.

(source: CIAL website)

4 Data Collection and Analysis

4.1 Site Analysis and Design Consideration

The primary part of the feasibility study of any PV project is the selection of the site of installation. The selection of the site holds great importance because of the meteorological conditions of the site, which determines the energy potential at that site. However, for this thesis, the project site is predefined, which is a pre-regulated open area inside the Stavanger airport. Stavanger Airport (SVG) is an international airport located in Rogaland county, Norway, and lies 11 km south-west of Stavanger city. Stavanger airport is the third busiest airport in Norway and serves both fixed-wing aircraft and helicopter traffic and handles almost 5 million passengers annually(BBC, n.d.).

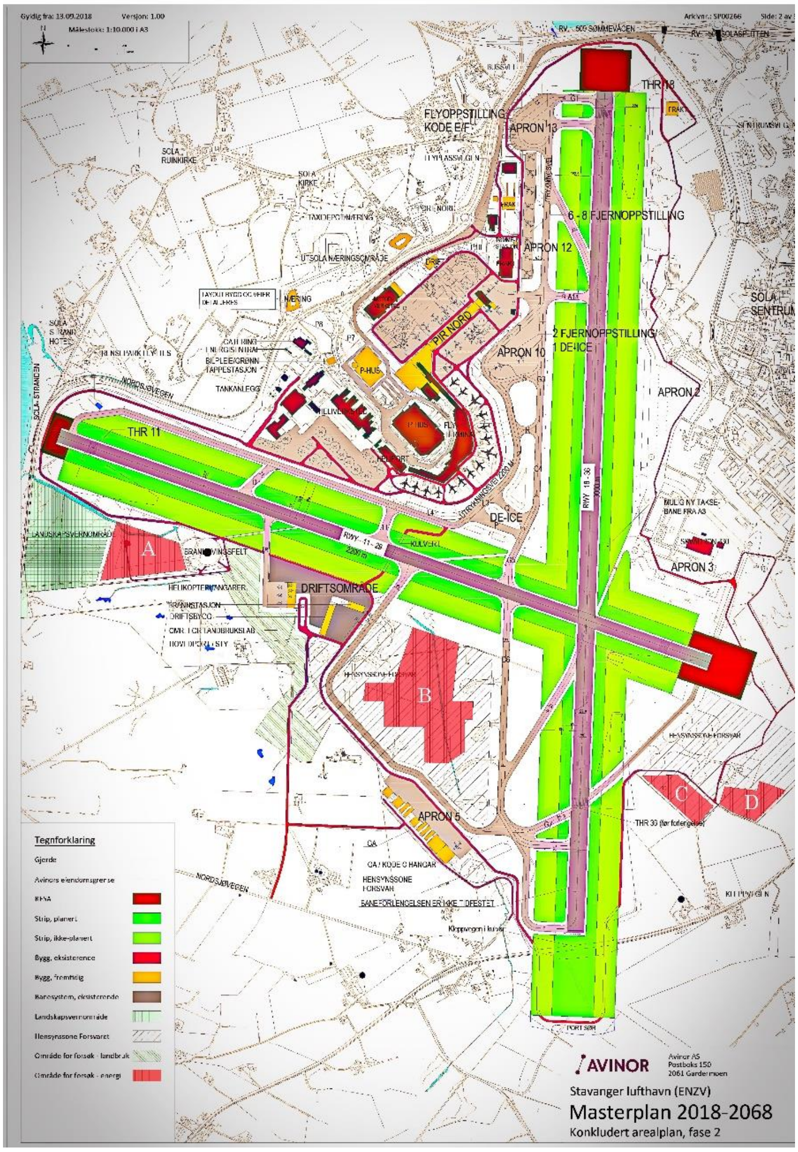


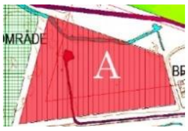
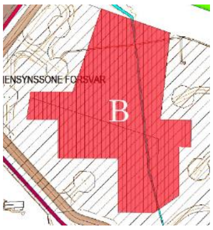
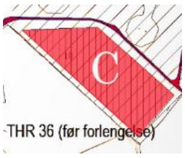
Figure 25: Masterplan for Stavanger Airport (Avinor, 2020)

The long-term Masterplan for Stavanger airport, as shown in *Figure 25*, shows various zones for various activities. The two intersecting runways and the green zones adjoining the runways are the ones that are reserved for safe daily aviation traffic. The plan incorporates four plots as an area designated for potential trail for energy production. As shown in *Figure* 25, areas marked A, B, C, and D are classified under areas for energy trails. The area is pre-regulated, and since it lies entirely inside the airport boundary, the problem of land acquisition does not come into play and does not interfere with any nearby settlement.

Table 6 summaries the nature of each of the red plots and associated estimates of space and the power production potential from each of the four spaces.

Table 6: Information on the four red plots as marked on the Master plan.

(Self-formulated table based on master plan and literature)

Allocated Plots for Potential Energy Generation	***Plot A***	***Plot B***	***Plot C***	***Plot D***
				
Area Designated for	Energy trials	Energy trails or Defence	Energy trails or Defence	Energy trails or Defence
Area	40900 m^2	99032 m^2	19310 m^2	18595 m^2
	10,1 acres	24,47 acres	4,77 acres	4,59 acres
Latitude	58,87	58,87	58,87	58,87
Longitude	5,61	5,62	5,64	5,64
Power Potential[2]	1680 KW	4070 KW	790 KW	760 KW

The preliminary rough estimate shows that the total area of four plots, i.e., c.a. 43 acres could accommodate a total of 7300 KW of installed solar power.

For site analysis, a point coordinate of 58.87°N and 5.62°E is adopted for the Stavanger airport.

The topographical location of the site is very favourable since the terrain is flat and free from any horizon shading such as mountains and free from persistent external shadings such as buildings or trees.

[2] (Mughal & Jarial, 2018) presents rough estimate that a 6 acre of area could accommodate solar installation of approx. 1 MW of power with fixed crystalline silicon solar PV whereas for fixed thin film solar PV the estimate is 1 MW per 7.5 acres of land.

Climatic conditions of the site such as temperature, wind speed, snow, precipitation, ambient temperature, air pollution also need to be considered to understand the site conditions to optimize the design.

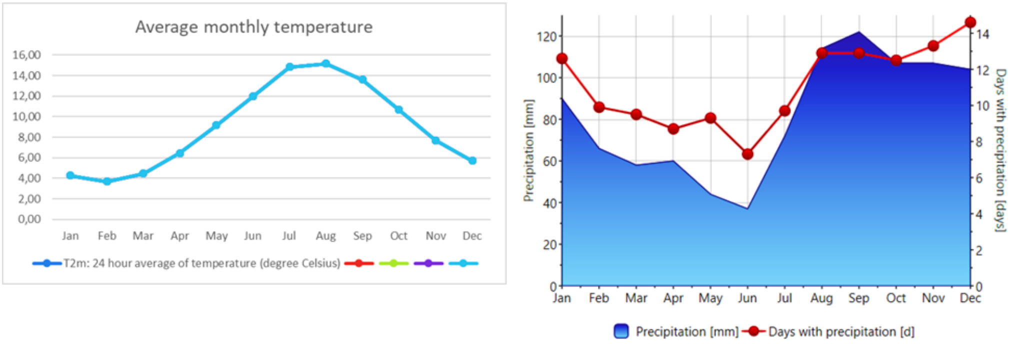


Figure 26: Graphs showing the average monthly temperature and precipitation at Stavanger Airport (source: meteonorm).

The mounting of the PV modules would be open ground-mounted type. However, the most appropriate type of foundation is determined after the overall site analysis. For this project, we assume that the ground conditions such as groundwater level, the load-bearing capacity of the soil, permeability, soil PH, and other conditions for any potential foundation for ground installation are favourable. The site is also favourable in terms of accessibility and water availability that are some of the requirements for cleaning and maintenance. The site is free from the limits of air pollution that could affect any production pattern of the PV installation.

Federal Aviation Authority (FAA, 2018) of the United States have mentioned three preliminary roadblocks for the deployment of solar PV inside an airport.

1. *Reflectivity and glare*
2. *Radar interference*
3. *Physical penetration of airspace*

The reflectivity and glare from the PV panels could pose a potential hazard to aviation safety as it could temporarily or for a longer time cause visibility problems during take-off and landing, which could also cause a disturbance in the air traffic control operations. However, anti-reflective PV panels are commercially available, which could be used to reduce this roadblock. The PV panels at the test rigs at Sola airport have anti-reflective coatings.

The large-scale PV installation could be a source of radar interference, which could cause disturbances to air navigation as well as communication. As a countermeasure to this roadblock, inverters could be equipped with inductor-capacitor (LC) filters to reduce electromagnetic radiation at certain frequencies. Besides, equipment grounding of the PV modules could be specified(Dann & Deline, 2015).

Since the masterplan has allocated areas away from the operation area and the PV installation would not pose a height risk, it seems less likely that the solar installation would face this roadblock. However, other accidental cases should still be taken into consideration.

Since the first phase of the PV-system at Stavanger airport is planned to be open area ground-mounted installation, the thesis would consider ground-mounted installation for further study. However, there still lies possibilities of roof-mounted installation on the administrative buildings as well as canopy mounted on open car parking spaces.

Green space and wildlife: Do large scale PV installation destroy or protect green space?

The large-scale PV installation demands significant infrastructure development, which is likely to pose environmental impacts(Chris Harrison, Huw Lloyd, & Field, 2017). For instance, the otherwise left large green space would be covered by a large number of PV arrays, which may attract birds, and animals (like rabbits and squirrels), which could hardly be prevented by any sort of fencing. And inside the Airport, the site of installation should not be a breeding spot that may stimulate the growth of any sort of birds and animals. Therefore, comprehensive environmental impact analysis, as well as wildlife hazard assessment, should be undertaken for any potential PV deployment at the Airport. The installed PV arrays will shade the green space beneath and likely to change the wind flow over the green space as well as rainfall distribution patterns impacting the soil condition of the whole site(Armstrong, 2014).

The site of installation for large scale installation at Stavanger airport is an open green space covered with grass, as shown in *Figure* 27. The planned PV system would shade most of the area after the installation.

Figure 27: Image showing ground conditions of the green open space at Stavanger Airport with a solar PV panel in place for test purposes. (self-captured image during field visit)

The green space beneath the solar array will only be shaded if the ground-mounted installation is done using poles as supporting structure. But in case of installation, as shown in *Figure 27*, where the area beneath the solar panels is made impermeable, large green space is destroyed.

So, early consideration of these issues helps to plan the mounting alternatives to prevent the loss of green spaces. Innovative practices have been started at some of the solar farms where the height of the mounting is increased so that crops that do not need direct sunlight could be grown beneath the solar arrays increasing the land productivity as well as saving the green space(Chris Harrison et al., 2017).

However, crop production could attract birds and other animals such as rabbits and squirrels, which could pose a hazard to aviation protocols. So, these alternatives at the Airport should be adopted only after comprehensive wildlife hazard assessment and associated control measures.

4.1.1Energy Consumption

The assessment of energy requirements is vital to understand the energy consumption pattern.

As per (Alba & Mañana, 2016), the energy demand at an airport generally comes from the requirements at the terminal building, airfield lighting, radio navigation systems, parking, firefighting, and others whereas the terminal building consumes the highest share of energy, which consists of lighting, HVAC, and ICT systems. The energy requirement is fulfilled through various sources such as electricity, fuels, biomass, and others, with electricity being the dominant source(Alba & Mañana, 2016).

The energy demand at Stavanger airport is supplied through three different energy sources which includes **1)** electric power supplied from Sande traffic station via grid station 210, **2)** thermal heat supplied from the 2MW wood chip plant via local water heating system and **3)** diesel fuel for generator backup for low visibility procedure. The thermal cooling equipment at Stavanger airport includes ventilation units, condensers, and freezers, which are all powered by electric power from the grid(Norconsult AS, 2018).

Since the wood chip plant is self-sufficient to cover the thermal heating demand at the Stavanger airport(Norconsult AS, 2018) and the backup diesel generators could not be ruled out even there is the self-sufficiency of electric power supply, the meter reading of the electric power taken from the grid is more interesting to study the nature of consumption at Stavanger airport.

Figure 28 shows the monthly values of the electric energy consumed at Stavanger airport for years 2014 till 2017. The pattern shows that the consumption is higher during winter, with January being the month of the highest energy consumption. Whereas during summer the consumption is comparatively lower, and the energy is consumed lowest during June. As per the data, the total energy consumed in the year 2016 is equal to **15 860 000** KWh, which will be used for calculations.

Month	2014	2015	2016	2017*
Jan	1,729,000	1,472,000	1,681,000	1,538,000
Feb	1,499,000	1,392,000	1,526,000	1,475,000
Mar	1,443,000	1,366,000	1,432,000	1,502,000
Apr	1,234,000	1,241,000	1,230,000	1,315,000
May	1,176,000	1,246,000	1,173,000	1,213,000
June	1,095,000	1,166,000	1,164,000	1,137,000
July	1,273,000	1,246,000	1,196,000	1,170,000
August	1,205,000	1,295,000	1,178,000	1,192,000
Sep	1,164,000	1,200,000	1,184,000	1,169,000
Oct	1,277,000	1,306,000	1,288,000	1,295,000
Nov	1,265,000	1,359,000	1,435,000	1,428,000
Dec	1,450,000	1,424,000	1,373,000	
Sum	15,810,000	15,713,000	15,860,000	14,535,000

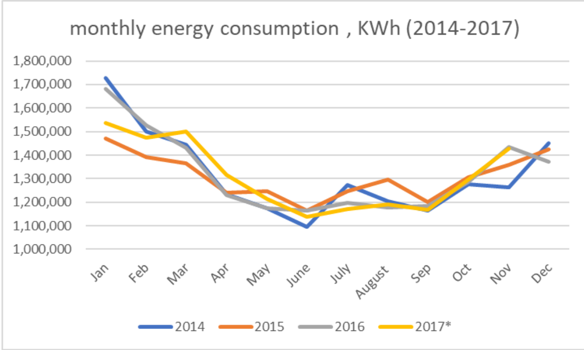


Figure 28: Figures for annual energy consumption(KWh) at Stavanger Airport (Norconsult AS, 2018)

4.1.2Global Irradiation at Stavanger Airport

The solar resource, in terms of global irradiation at Stavanger airport, is extracted from the radiation database – PVGIS-SARAH, which provided monthly data for years 2005 to 2016. Average monthly values are calculated and presented in the table, as shown in *Figure 29*.

Month	H(h)_m	H(i_opt)_m	Hb(n)_m	Kd	T2m:
Jan	8.49	19.42	15.90	0.72	4.28
Feb	22.51	40.46	32.11	0.64	3.68
Mar	61.02	87.37	69.81	0.57	4.46
Apr	109.67	134.29	114.05	0.49	6.45
May	150.33	161.71	139.59	0.48	9.17
Jun	165.70	167.62	149.27	0.47	11.95
Jul	140.01	142.32	104.62	0.57	14.82
Aug	112.80	125.78	91.92	0.58	15.17
Sep	69.97	92.14	68.87	0.59	13.59
Oct	36.66	63.02	52.91	0.57	10.66
Nov	12.33	27.13	22.62	0.67	7.70
Dec	4.72	12.23	10.57	0.75	5.71
Total	**894.22**	**1073.49**			
Average					**8.97**

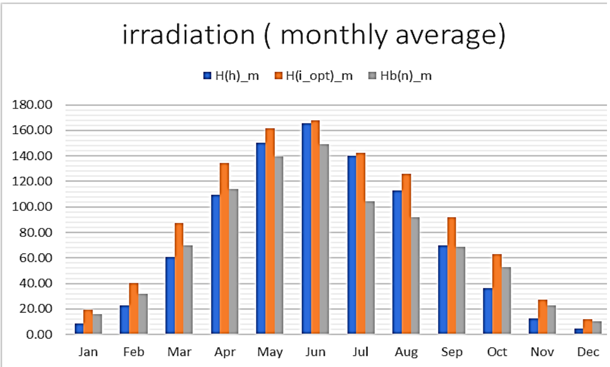


Figure 29: Monthly average solar radiation at Stavanger Airport (self-formulated based on data from PVGIS database)

H(h)_m: Irradiation on horizontal plane (kWh/m2/mo)
H(i_opt)_m: Irradiation on optimally inclined plane (kWh/m2/mo)
Hb(n)_m: Monthly beam (direct) irradiation on a plane always normal to sun rays (kWh/m2/mo)
Kd: Ratio of diffuse to global irradiation (-)
T2m: 24 hour average of temperature (degree Celsius)

It is observed that the lowest solar irradiation occurs during winter. December is the worst month that must be taken into consideration for optimal design. During December, the solar irradiation is observed to be **4,72 KWh/m^2** on a horizontal plane and **12.23 KWh/m^2** on the optimally inclined plane. Since the irradiation levels are higher on the optimally inclined plane, it is essential to figure out what is the orientation of the optimally inclined plane in terms of tilt angle and azimuth angle.

4.1.3Optimum tilt and azimuth angle

As per the rule of thumb, ***Tilt angle against the horizontal = Latitude of the site of PV installation when the latitude ≤ 30°***. For the latitude >30°, the tilt angle usually lies between 5° to 20° less than the latitude. For a reference point coordinate at the site of PV installation at Sola Airport with latitude 58.87 and longitude 5.62 or at GPS coordinates of (58.87°N, 5.62°E); as per rule of thumb; optimum tilt angle lies between 33° and 53°.

Since the site of installation is in the northern hemisphere and between the latitudes of 23 and 90, the optimum azimuth angle as per rule of thumb is due south.

Table 7: Global Clear Sky Irradiances(kWh/m²) on tilted planes at Stavanger Airport (self-formulated matrix based on synthetic data generated by PVsyst)

Azimuth/Tilt	15°	30°	45°	60°	75°	90°	105°	120°
-180°	1097.5	766.0	500.5	360.6	333.3	321.8	318.0	311.5
-165°	1108.8	786.9	531.1	404.3	371.6	353.4	341.6	328.0
-150°	1142.0	849.0	624.3	524.8	478.0	443.3	409.4	378.3
-135°	1195.9	951.0	785.3	695.6	632.4	575.2	515.3	451.2
-120°	1268.5	1092.9	975.5	894.0	817.2	731.5	639.2	541.5
-105°	1354.8	1255.0	1178.8	1105.0	1016.9	908.7	778.9	635.7
-90°	1445.8	1420.5	1386.3	1325.9	1227.2	1082.9	923.2	738.5
-75°	1535.5	1577.9	1582.2	1531.6	1427.1	1265.0	1057.0	826.2
-60°	1618.7	1720.3	1760.4	1725.1	1608.1	1419.9	1178.0	902.8
-45°	1688.6	1842.1	1910.6	1881.7	1759.7	1548.7	1268.6	951.3
-30°	1741.0	1931.1	2018.5	1998.3	1865.2	1635.7	1325.6	970.0
-15°	1772.8	1983.9	2087.1	2067.1	1930.2	1683.3	1352.1	968.6
0°	1783.2	2003.0	2108.9	2087.8	1950.2	1700.4	1357.1	965.3
15°	1772.8	1983.9	2087.1	2067.1	1930.2	1683.3	1352.1	968.6
30°	1741.0	1931.1	2018.5	1998.3	1865.2	1635.7	1325.6	970.0
45°	1688.6	1842.1	1910.6	1881.7	1759.7	1548.7	1268.6	951.3
60°	1618.7	1720.3	1760.4	1725.1	1608.2	1419.9	1178.0	902.8
75°	1535.5	1577.9	1582.2	1531.6	1427.1	1265.0	1057.0	826.2
90°	1445.8	1420.5	1386.3	1325.8	1227.2	1082.9	923.2	738.4
105°	1354.8	1255.0	1178.8	1105.0	1016.9	908.7	778.9	635.6
120°	1268.5	1092.9	975.5	894.0	817.2	731.5	639.2	541.5
135°	1195.9	951.0	785.3	695.6	632.3	575.2	515.3	451.2
150°	1142.0	849.0	624.2	524.8	477.9	443.3	409.4	378.3
165°	1108.8	786.9	531.1	404.3	371.6	353.4	341.6	328.0

PVsyst software with the use of meteonorm data (1999-2010), it is possible to extract synthetic data for global clear sky irradiances on a tilted plane for all 365 days for the year 2019. The data is generated for various combinations of tilt and azimuth angle. Total yearly values were calculated for each combination by adding the daily values. A matrix table is formulated to check the overall data, as shown in *Table 7*. As per the table, maximum irradiance occurs at 0

° azimuth angle (due south) and 45° tilt angle. PVsyst considers the following parameter for the synthetic data generation, where albedo is the measure of the diffuse reflection of solar radiation.

At Sola Airport, (Lat. 58.89° N, long. 5.64° E, alt. 0 m)			
Albedo = 0.20			
Atmospheric pressure =		1.013	Bar
Atmospheric temperature =		15.040	°C
Air density =		1.225	kg/m3

4.2 Test Rig Analysis

Test rigs are normally installed to generate the preliminary data for a feasibility study or for research purpose of gathering information or of validating some assumptions which help to make significant decisions for large scale installations.

In 2016, 20 solar modules - 10 monocrystalline types and ten polycrystalline types, were installed at Stavanger Airport as a test facility to observe the performance of two-panel types and the influence of various tilt angles and azimuth angles on the total production of those types(Norconsult AS, 2018).

The real-time monitoring of the test rig is done through Tigo's SMART website, which allows module-level online monitoring to check the performance of each module and to track their production. The platform also suggests maintenance actions and alerts for keeping the system at maximum efficiency(Tigo, 2020). *Figure 30* shows the physical layout of the test rig.

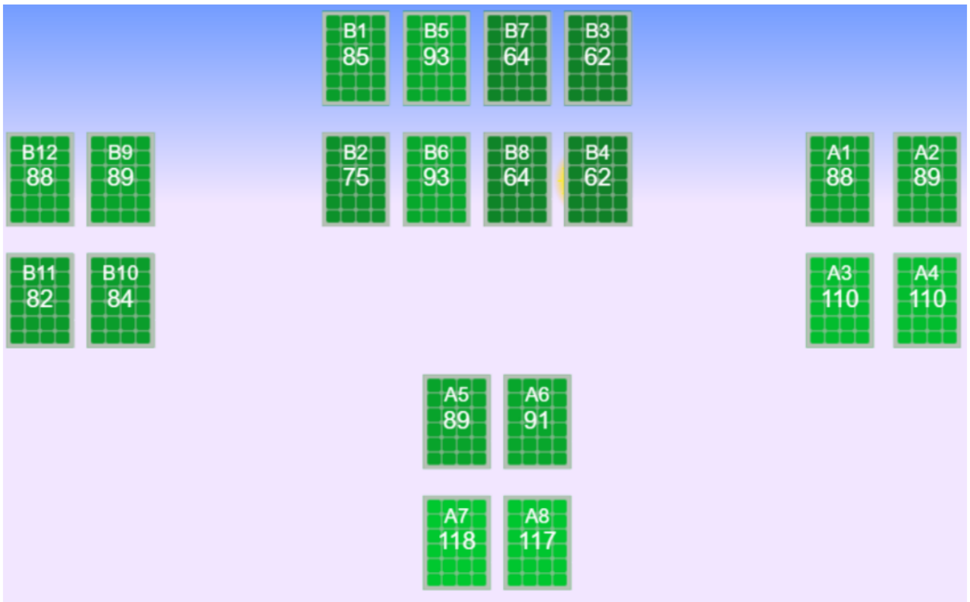


Figure 30: Physical Layout of PV modules, as shown in the Tigo platform.

4.2.1Technical Specification of Test Rig

Table 8: Specification of the components used in the test rig at Stavanger airport

<table>
<tr><th colspan="5">Modules</th></tr>
<tr><th>Model</th><th>Manufacturer</th><th>Maximum Power</th><th colspan="2">Count</th></tr>
<tr><td>PolySol 265 CS4</td><td>IBC</td><td>265 W</td><td colspan="2">10</td></tr>
<tr><td>MonoSol 285 ZX4</td><td>IBC</td><td>285 W</td><td colspan="2">10</td></tr>
<tr><th colspan="5">Inverter</th></tr>
<tr><td>PRIMO 4.6-1</td><td>Fronius</td><td>4800 W</td><td colspan="2">1</td></tr>
<tr><td colspan="5"></td></tr>
<tr><th>Panel No.</th><th>Panel Type</th><th>Orientation</th><th>Azimuth Angle</th><th>Angle from the roof surface</th></tr>
<tr><td>13,14</td><td rowspan="5">Monocrystalline</td><td>East</td><td>-90</td><td>10</td></tr>
<tr><td>9,10</td><td>West</td><td>90</td><td>10</td></tr>
<tr><td>1,2</td><td>South-East</td><td>-45</td><td>15</td></tr>
<tr><td>20,17</td><td>South-West</td><td>45</td><td>15</td></tr>
<tr><td>5,6</td><td>South</td><td>0</td><td>15</td></tr>
<tr><td>11,12</td><td rowspan="5">Polycrystalline</td><td>East</td><td>-90</td><td>10</td></tr>
<tr><td>15,16</td><td>West</td><td>90</td><td>10</td></tr>
<tr><td>3,4</td><td>South-East</td><td>-45</td><td>15</td></tr>
<tr><td>19,18</td><td>South-West</td><td>45</td><td>15</td></tr>
<tr><td>7,8</td><td>South</td><td>0</td><td>15</td></tr>
</table>

Panel Specification:

Table 9: Specification of the panel types used for test rig (from panel's technical datasheet)

Panel Type	MonoSol 285Zx	PolySol 265CS4
Length, m	1,639	1,640
Breadth, m	0,983	0,992
Thickness, m	0,040	0,040
Weight, kg	18,5	19,5
Load Capacity, Pascal (KN/m^2)	5400	5400
Front sheet	3 mm, Low iron PV glass with anti-reflective coating	3 mm, Low iron PV glass with anti-reflective coating

4.2.2Power production from the test rig

The power production data is available for all the solar modules of the test rig for analysis. Since the test rig consists of inverter, which has two inbuilt MPPT (maximum power point tracking) charge controllers, the efficiency of the panels is high. Due to this reason, the output from the test rig seems to be comparatively higher than the values that are observed on traditional charge controllers. *Figure 31* shows the total power produced form the test rig for the year 2017 and 2018.

Total Energy(KWh)	2017	2018
Jan	56,133	36,718
Feb	132,894	154,008
Mar	291,992	344,046
Apr	578,105	456,961
May	677,995	801,035
Jun	639,054	841,829
Jul	650,968	888,156
Aug	528,475	545,068
Sep	354,495	351,029
Oct	165,549	177,054
Nov	64,969	70,68
Dec	23,105	34,17
Yearly Sum =	4163,73	4700,75

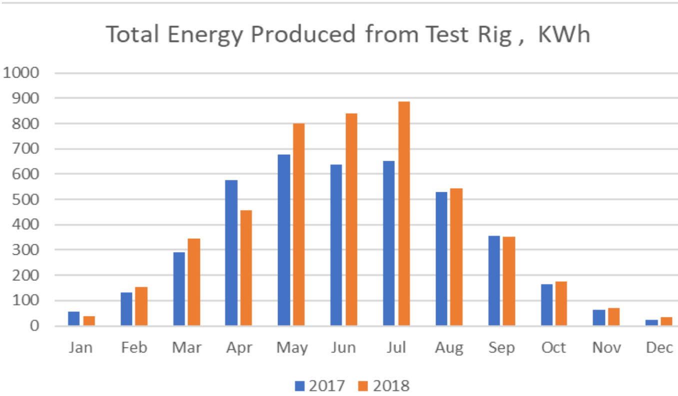
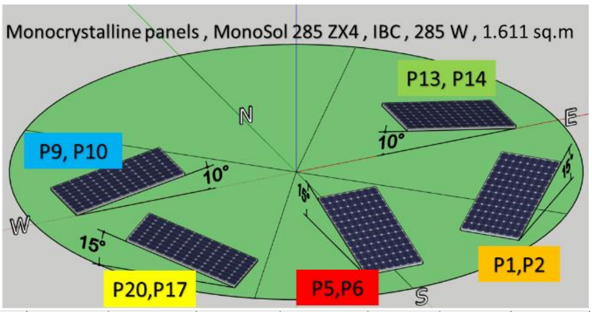
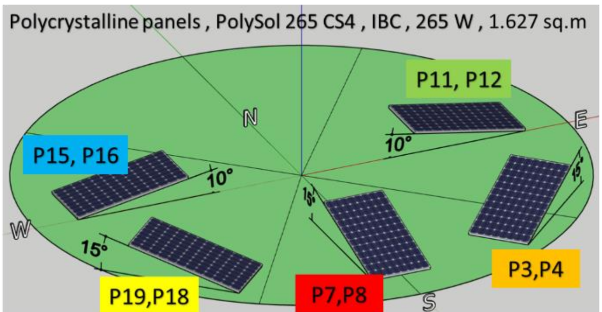


Figure 31: Figures showing total energy produced for the test rig. (self-made based on data from Tigo online platform)

The production is higher during summer and lowers during winter whereas the consumption at the Airport is maximum during winter and minimum during summer, which indicates that there is the opposite nature of production and consumption. To address this problem, a grid-connected PV system is preferred where net metering feeds in lagging amount of energy when



S.N	2018 (Wh)	2018 (KWh)	Panel No.	Rating (KWp)	Area , m2	Kwh/m2	KWh/KWp
A1	260535	260.54	P1	0.285	1.61	161.72	914.16
A2	262739	262.74	P2	0.285	1.61	163.09	921.89
A5	273612	273.61	P5	0.285	1.61	169.84	960.04
A6	273760	273.76	P6	0.285	1.61	169.93	960.56
B1	215368	215.37	P9	0.285	1.61	133.69	755.68
B2	208548	208.55	P10	0.285	1.61	129.45	731.75
B5	208113	208.11	P13	0.285	1.61	129.18	730.22
B6	200697	200.70	P14	0.285	1.61	124.58	704.20
B9	247638	247.64	P17	0.285	1.61	153.72	868.91
B12	247508	247.51	P20	0.285	1.61	153.64	868.45
Avg.						148.88	841.59



S.N.	2018 (Wh)	2018 (KWh)	Panel No.	Rating (KWp)	Area , m2	Kwh/m2	KWh/KWp
A3	215241	215.24	P3	0.265	1.63	132.29	812.230
A4	217237	217.24	P4	0.265	1.63	133.52	819.762
A7	270446	270.45	P7	0.265	1.63	166.22	1020.551
A8	268494	268.49	P8	0.265	1.63	165.02	1013.185
B3	209691	209.69	P11	0.265	1.63	128.88	791.287
B4	212278	212.28	P12	0.265	1.63	130.47	801.049
B7	216068	216.07	P15	0.265	1.63	132.80	815.351
B8	212076	212.08	P16	0.265	1.63	130.35	800.287
B10	240167	240.17	P18	0.265	1.63	147.61	906.291
B11	240538	240.54	P19	0.265	1.63	147.84	907.691
Avg.						141.50	868.77

Figure 32: Visual illustration of panel specification adopted at the test rig together with associated calculation for various alternatives. (simulation using SketchUp, Calculation based on data from Tigo platform)

there is not enough production in the system and takes out extra energy when the production surpasses the consumption. *Figure 32* presents a visual illustration of panel specification adopted at the test rig together with associated calculations for various alternatives. The production data for the year 2018 has been adopted for calculations and comparison purposes.

Finding from the calculations:

1. The rating of the monocrystalline panel used is 285 W, and that of the polycrystalline panel used is 265 W. So, the comparison can only be made based on annual specific panel yield.
2. Annual specific yield (annual output/generating panel area), KWh/m^2, is higher for monocrystalline panels.
3. For both types, the output is highest for the panels facing south (azimuth 0) followed by the panels facing south-east (-45), south-west (45). The panels facing east (-90) and west demonstrated the lowest output. This shows that the optimum azimuth angle is due south (0). However, the panels at the test rig at due south are tilted just on a single tilt angle of 15 degrees; the test rig lacks data for comparison of various values of tilt angle to check which tilt angle gives the maximum output.
4. The output values are optimized values, which are the result of inbuilt MPPTs on the inverter. That is why, besides solar resource and PV type, the use of MPPTs should also be considered for output optimization.

4.3 Sun path

Since the installation is going to be done in open land with no nearby trees and other obstruction, there will be no external shading on the PV modules. Unlike in rolling or hilly terrain, there is no horizon shading to be considered for open land installation in a large flat land.

For Stavanger airport, based on the nature of the plots, there will be no horizon shading. But there will be inter-row shading that needs to be optimized. Theoretically, the worst-case scenario is taken for the calculation of ideal inter-row spacing. The worst case is the shortest day of the year, which is December 21, and the solar window is taken between 10 am to 2 pm. Using the sun path for Stavanger airport, as shown in *Figure 33*, the solar elevation angle and azimuth correction angle is determined, which is found to be 4° and 27.4°, respectively. These values would help to determine the ideal inter-row spacing to understand and analyse interrow shading, which is one of the sensitive parameters in large scale installation.

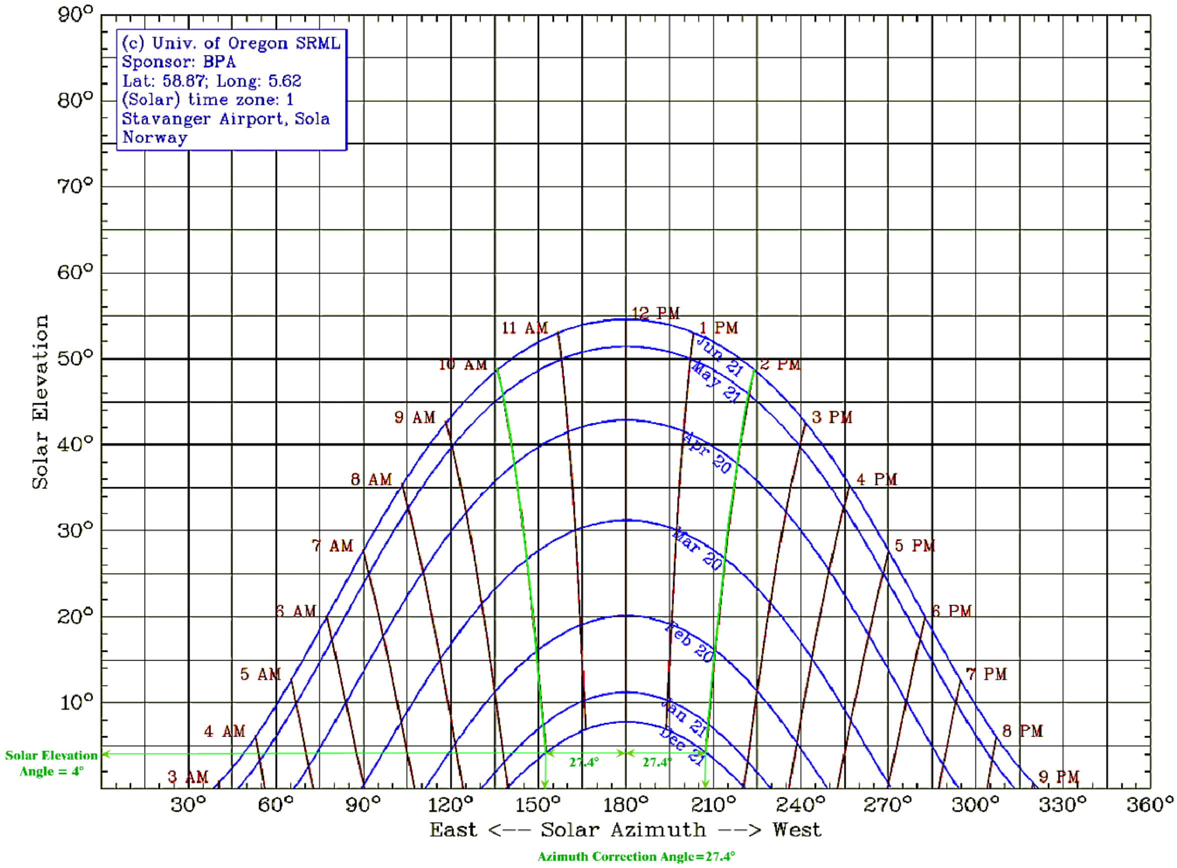


Figure 33: Sun path for Stavanger Airport and the worst solar window consideration

How much area is required for 1000 KWp of solar PV installation at Stavanger Airport?

The area calculation gives the total area of the solar generating surface as well as the total land area of the installation. The area of the solar generating surface is the total surface area of the PV modules that generates electricity. However, the total land area of the PV installation is the total area coverage of the whole system, which includes not only the solar arrays but also the spacing between the rows, area for inverters, batteries, or any other associated components. The following calculation gives an example of area calculation.

Let us assume the monocrystalline module that is used in the test rig is to be used for the large-scale installation.

- *In that case, Power rating of each PV module, Pm = 285 Wp*
- *Length=1,639 m, Breadth= 0,983 m*
- *Area of module, Am = 1.611 m^2*
- *Go= G_{STC} = Global irradiance for which Pm is defined (under standard testing conditions, STC) = 1000 W/m^2*
- *Optimum Azimuth = Due south (0 degree)*
- *Optimum Tilt angle = 45 degree*
- *Optimum clear sky irradiance on tilted plane, H = 2108,9 KWh/m2*
- *P_{nom} = 1000 KWp = nominal peak solar power generation (at STC)*

- *Solar Module Efficiency,* η_M *= 17,69 %*
- A_G*= Total area of solar generation*
- A_L*= Land area required for solar installation*
- L_f *= Land Factor to avoid interrow shading in large scale installation*

$$A_G = n_m * A_m = (P_{nom} / Pm) * A_m$$
$$= (1000000/285) * 1{,}611$$
$$= 5652{,}63\ m^2$$

$$A_L = L_f * 5652{,}63\ m^2$$

Land factor could range between 2 and 6, which gives a rough estimate that for 1000 KWp of land mounted solar installation, the land area required ranges between (11300 m^2 to 33900 m^2)

<u>Ideal Inter row spacing Calculation</u>

The significance of inter-row spacing calculation is to limit the inter-row shading. The space between the rows also determines the total land area for the PV system. The number of modules along the rows and the module orientation (portrait vs landscape) also determines the inter-row spacing. The inter-row spacing also depends on the seasons. When the altitude of the sun is high above in summer, the inter-row spacing becomes less significant. However, the problem is more prevalent when the sun is at low altitudes during winter, and the PV output is low.

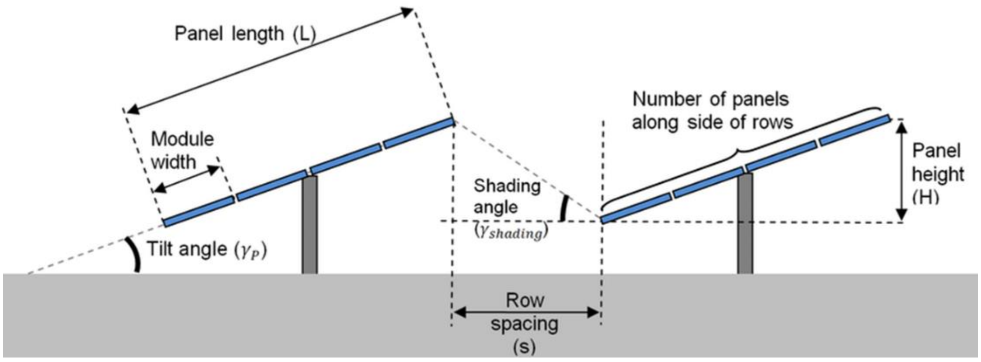


Figure 34: Illustration showing spatial setup parameters (Saint-Drenan & Barbier, 2019)

<u>Calculation Example:</u>

We have,

Tilt angle, $\boldsymbol{\gamma_p}$ *= 45°*

Module Width = 0,983m (landscape); 1,639m (portrait)

Panel Length, **L***= Module Width * No. of Panels alongside of rows*

Taking 10 am to 2 pm on December 21 as the worst solar window,

Solar Elevation Angle at 10 am (or shading angle), $\gamma_{shading}$ *= 4°*

Azimuth Correction Angle = 27.4°

Then,

*Panel Height = Panel length * Sin (Tilt angle)*

*Row spacing, **s** = Panel height / Tan (Solar Elevation Angle)*

*Minimum Module Row spacing = Row spacing * Cos (Azimuth Correction Angle)*

Based on the above formulae, the following tables are generated for 1 to 6 numbers of modules alongside each row.

<u>If modules are oriented in landscape,</u>

No of modules	Panel Length(L), m	Panel height(H), m	Inter row spacing(S), m	Minimum Inter Row Spacing,m
1	0.983	0.695	9.940	8.825
2	1.966	1.390	19.880	17.650
3	2.949	2.085	29.82	26.48
4	3.93	2.78	39.76	35.30
5	4.92	3.48	49.70	44.13
6	5.90	4.17	59.64	52.95

<u>If modules are oriented in portrait,</u>

No of modules	Panel Length(L), m	Panel height(H), m	Inter row spacing(S), m	Minimum Inter Row Spacing,m
1	1.6390	1.1589	16.5737	14.7144
2	3.2780	2.3179	33.1475	29.4288
3	4.9170	3.4768	49.7212	44.1432
4	6.5560	4.6358	66.2949	58.8576
5	8.1950	5.7947	82.8686	73.5721
6	9.8340	6.9537	99.4424	88.2865

Findings:

- Portrait orientation requires larger inter-row spacing.
- The ideal interrow spacing seems to be too large for practical cases. For a site with no concern for land limitation, the ideal inter-row spacing could be adopted. But this would decrease the land-use efficiency. However, at the locations with land limitations, partial shading may be tolerated to decrease the inter-row spacing and compensate for the land limitation and increase land-use efficiency.
- The selection of portrait vs landscape orientation is also made based on the placement of the bypass diodes, which in case of shading, would allow the produced current to pass through the shaded part. The selection is made based on the alternative, which allows more current to pass through the shaded cells and leads to minimum interrow shading.
- Cell strings of IBC MonoSol panels are perpendicular to the short side, as shown in *Figure 35*.

Figure 35: Illustration of cell string in IBC Monosol panel. (source: PVSol)

5 Simulation and Data Analysis

The analysis based on the data from the test rig is found to be limited. To broaden the analysis and to understand the overall nature of the alternative conditions, simulation on two different scales (test rig scale and large scale) were undertaken to compare various alternatives as well as scenarios to figure out the optimum alternative further.

5.1 Test Rig Scale Simulation

5.1.1 Energy 3D simulation

With the use of energy 3D software program, the simulation was done for various alternatives to make annual energy output comparison. The results are compared to test rig conditions, fixed-tilt, and three different tracking systems. Energy 3D calculations are based on the weather station data. For comparison purposes, the closest weather data available on the software database is adopted, which is Bergen with coordinates and altitude as: (60.39°N, 5.32°E; altitude 40m). The solar module properties used for the simulation is, as shown in *Figure 36*. Since the same module as used in the test rig is not available in the database of the software, a custom model that has almost similar properties is chosen.

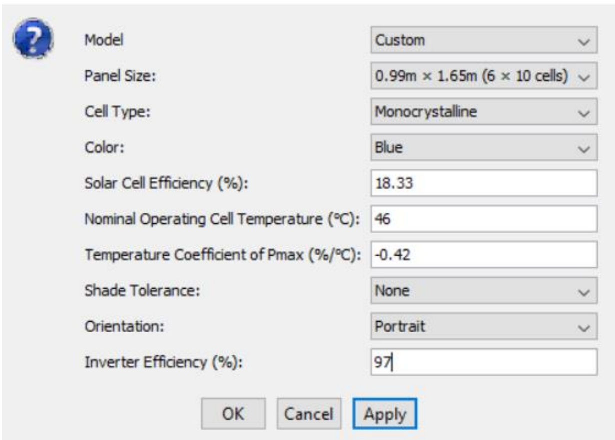
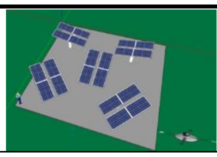
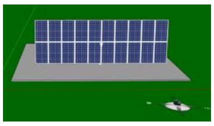
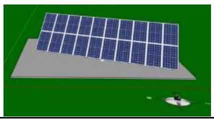
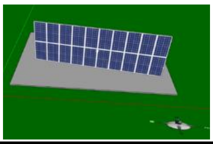


Figure 36: Solar Panel properties used for the simulation (energy 3D)

Results of the five different simulation cases are presented in *Table 8*:

Table 8: Simulation results of various system possibilities with 20 PV modules using Energy 3D

Sim No	***System Type***	***Tilt angle***	***Azimuth***	***Average annual Output, KWh***	***3D Illustration***
1	Fixed Tilt	Same as in test rig	same as in test rig	2573,15	

2	Fixed Tilt	45°	due south	3062,31	
3	Horizontal single-axis tracker	Follows tracking	due south	3411,22	
4	vertical single-axis tracker	45°	Follows tracking	4244,43	
5	Azimuth Double axis tracker	Follows tracking	Follows tracking	4588,82	

Findings:

- The output values are based on the generating surface area of the PV modules and not based on the rated power and any MPPTs on the connection.
- The use of a tracker increases output. Vertical axis tracker produces more compared to horizontal axis tracker, whereas azimuth double axis tracker produces significantly higher compared to the single-axis tracking system.
- However, the cost and complexity of the tracking system associated with the operation and maintenance in a location with extreme weather is a subject of consideration.

5.1.2PVSol simulation:

Twenty monocrystalline PV panels, each of rated power 280 Wp and PV generator surface of 32.2 m^2, were simulated for the total annual production in two different setups ***1***. Test rig conditions, **2**. Calculated optimum tilt and azimuth condition) to make comparisons with the actual test rig results.

1. **Simulation of 20 PV panels (Test rig conditions)**

3D model of 20 PV panels was made in the PVSol software to create a test rig environment and to analyze the output. The specifications of the model are kept the same as in the test rig at Stavanger airport. The climate data: Stavanger/Sola (1986-2005) is based on the default meteorological database of the software, which is meteonorm. The total generator surface area for 20 PV modules is 32,2 m^2.

Table 10: Five different orientations with corresponding tilt and number of panels

No. of Modules	Tilt angle	Azimuth Due
4	15 °	South
4	15 °	South East
4	15 °	South West
4	10 °	East
4	10 °	West

The 3D illustration of the model for simulation is as shown in *Figure 37*.

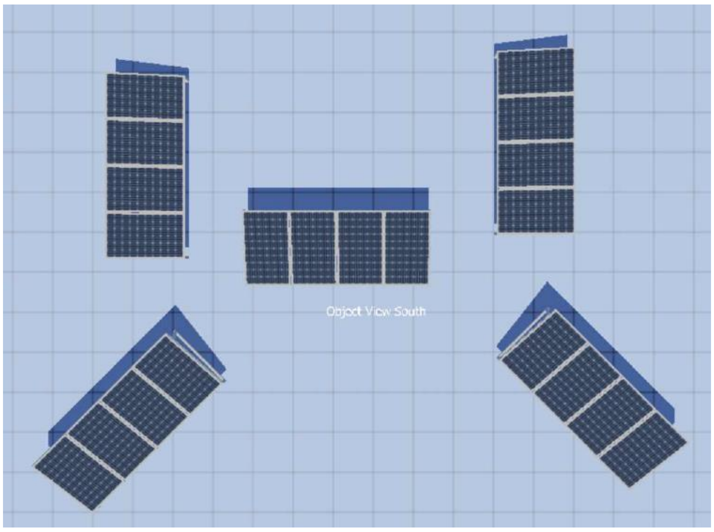


Figure 37: 3D modelling of the test rig setup in PVSol for simulation purposes.

Simulation for yearly production is undertaken, and the results obtained are presented in *Table 11*.

Table 11: Simulation Results of the test rig similar setup

PV Generator Power (AC grid)	4288 KWh
Spec. Annual Yield	765.66 Kwh/KWp
Performance Ratio (PR)	85.6 %
CO2 Emissions avoided	2570 kg / year

- Total annual production from actual test rig at Stavanger Airport for the year 2017 and 2018 were 4163,73 KWh and 4700,75 KWh, respectively. Whereas the annual production from the test rig set up as simulated in PVSol is 4288 KWh, which seems to be on a similar level. This means the PVSol simulation could provide close enough results if not accurate.

2. **Simulation of 20 PV panels (Calculated optimum tilt angle: 45 ° and optimum azimuth: due south)**

A 3D model is set up for 20 PV panels at the optimum conditions of tilt and azimuth at Stavanger airport, as determined earlier in previous chapters. The specification of the model for simulation is as presented by *Table 12*, the 3D illustration of the model is as shown in *Figure 38*, and the simulation results are presented in *Table 13*.

Table 12: Specification of the model with optimum tilt and azimuth for simulation

PV Modules	20 x IBC Monosol 280 ZX
Manufacturer	IBC Solar AG
Tilt Angle	45°
Azimuth Angle	0° (Due South)
Installation Type	Mounted – Open Space
PV Generator Surface	32.2 m^2

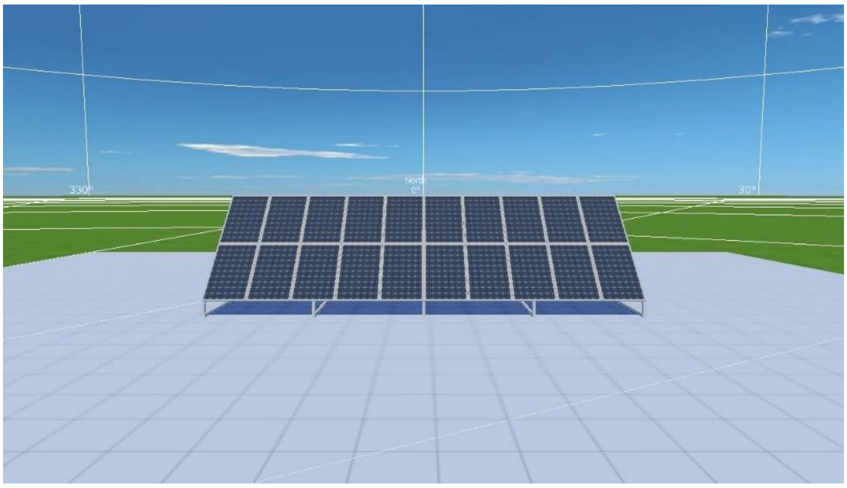


Figure 38: 3D illustration of the model for simulation (PVSol)

Table 13:Simulation results of the setup with optimum tilt and azimuth

PV Generator Power (AC grid)	4750 kWh
Spec. Annual Yield	848.19 kWh/kWp
Performance Ratio (PR)	85.9 %
CO_2 Emissions avoided	2847 kg/ year

Comparing the production from a setup similar to test rig, which is 4288 kWh and the production from the setup with optimum tilt and azimuth, which is 4750, it is validated that at optimum tilt and azimuth, the production increases significantly.

5.2 Large-scale simulation of a solar installation of 1000 kWp

The full-scale simulations for a PV system of 1000 kW installed power will be made to compare the results and determine the most favourable conditions. For this purpose, it is necessary to define the parameters that would be set constant and the parameters that would be varied for simulation. The parameters that have already been determined to be optimal would be set as constant parameters whereas the parameters that still need to be optimized would be taken as variable parameters. *Table 14* and *Table 15* presents the specifications that are adopted for the large-scale simulation.

Specifications:

Table 14: Constant Parameters for large scale simulation

PV system	Grid Connected with battery
Calculated Optimal Tilt	45 °
Calculated Azimuth Angle	0 ° (Due South)
Model of Module used	IBC Monosol 285 ZX
Installation Type	Ground Mounted – open space
Design Solar Elevation Angle and Time	7.68°, December 21 12:00, Sola Airport
Shading Tolerance	Partial

Table 15: Variables for large scale simulation

Orientation of Modules	Portrait vs Landscape
No of modules alongside a row	1 to 6

For comparison purposes, several large-scale simulations have been performed. Two orientation alternatives and six different alternatives of module numbers alongside each row have been adopted, as defined in *Table 15*.

Simulations were undertaken for all the combinations of variables. *Table 16* presents the results for portrait module orientation and five alternatives of module numbers alongside each row.

Similarly, *Table 17* presents the simulation results for landscape orientation and six alternatives of module numbers alongside each row.

The result of the simulation as shown in *Table 16* and *Table 17* gives the fundamental information about the PV system such as annual energy output, specific annual yield, performance ratio, PV generating surface area, total land area coverage, a total number of modules required, shading loss as well as total carbon emissions avoided annually, which are critical information that helps in deciding the best alternative and further project planning.

Table 16: Simulation Results for different modules number alongside the bottom of each PV row with portrait orientation

Variables	Units					
Orientation				**Portrait**		
No of modules alongside each row		**1**	**2**	**3**	**4**	**5**
Interrow spacing	***m***	8.597	17.222	25.845	34.469	43.092
Simulation Results						
Total No of Modules		3514	3514	3510	3520	3510
PV Generator Output	***kWp***	1001.49	1001.49	1000.35	1003.2	1000.35
PV Generator Surface	***m²***	5661.5	5661.5	5655.1	5671.2	5655.1
Total Land coverage	***m²***	32021.4	29615.9	28058.5	32021.4	24206.7
Global Radiation at the Module	***kWh/m²***	996	996	996	996	996
PV Generator Energy (AC grid)	***kWh/Year***	825469	828096	827343	829973	827,343
Spec. Annual Yield	***kWh/kWp***	824.2	826.86	827.05	827.3	820.75
Performance Ratio (PR)	***%***	82.7	83	83	83	83
Total CO2 emissions avoided	***kg / year***	495127	496703	496250	497829	496250
Shading Loss	***%/year***	1.2	0.9	1	1	1

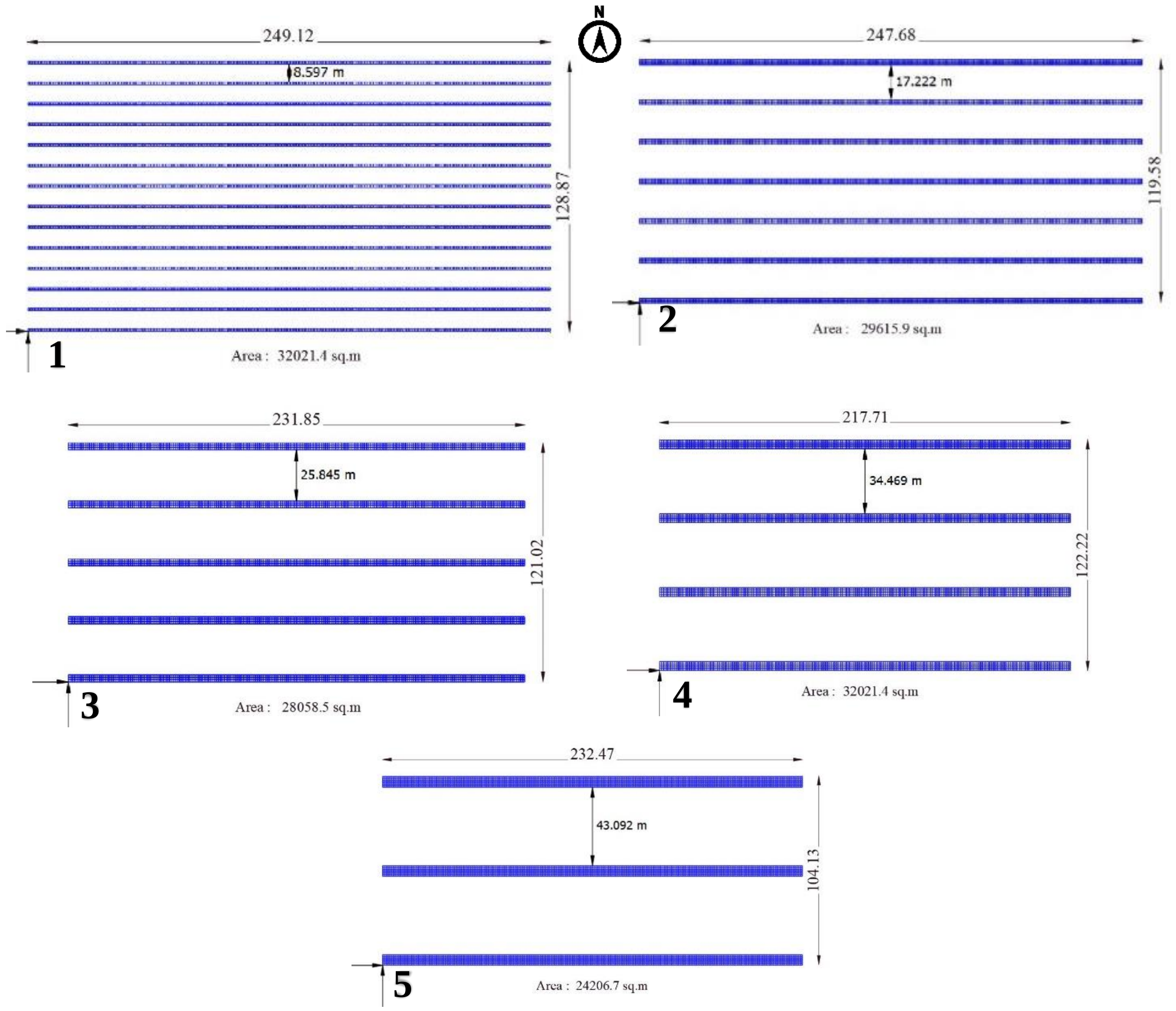


Figure 39: Illustration showing top views of five different alternative installations with their land area coverage, as presented by Table 16

Table 17:Simulation Results for different modules number alongside the bottom of each PV row with landscape orientation

Variables	**Units**						
Orientation		**Landscape**					
No of modules alongside each row		**1**	**2**	**3**	**4**	**5**	**6**
Interrow spacing	***m***	5.156	10.339	15.522	20.704	25.887	31.07
Simulation Results							
Total No of Modules		3519	3528	3528	3528	3525	3528
PV Generator Output	***kWp***	1002.92	1005.48	1005.48	1005.48	1004.62	1005.48
PV Generator Surface	***m²***	5669.6	5684.1	5684.1	5684.1	5679.3	5684.1
Total Land Coverage	***m²***	32873.6	31695.3	30263.4	29366.1	28291.9	26658.2
Global Radiation at the Module	***kWh/m²***	996	996	996	996	996	996
PV Generator Energy (AC grid)	***kWh/Year***	833609	830821	830821	829912.1	824153	829912
Spec. Annual Yield	***kWh/kWp***	831.19	826.29	826.29	825.4	820.4	825.4
Performance Ratio (PR)	***%***	83.4	82.9	82.9	82.8	82.3	82.8
Total CO2 emissions avoided	***kg / year***	500009	498337	498337	497792	494338	497792
Shading Loss	***%/year***	1.2	0.9	0.9	1	1	1

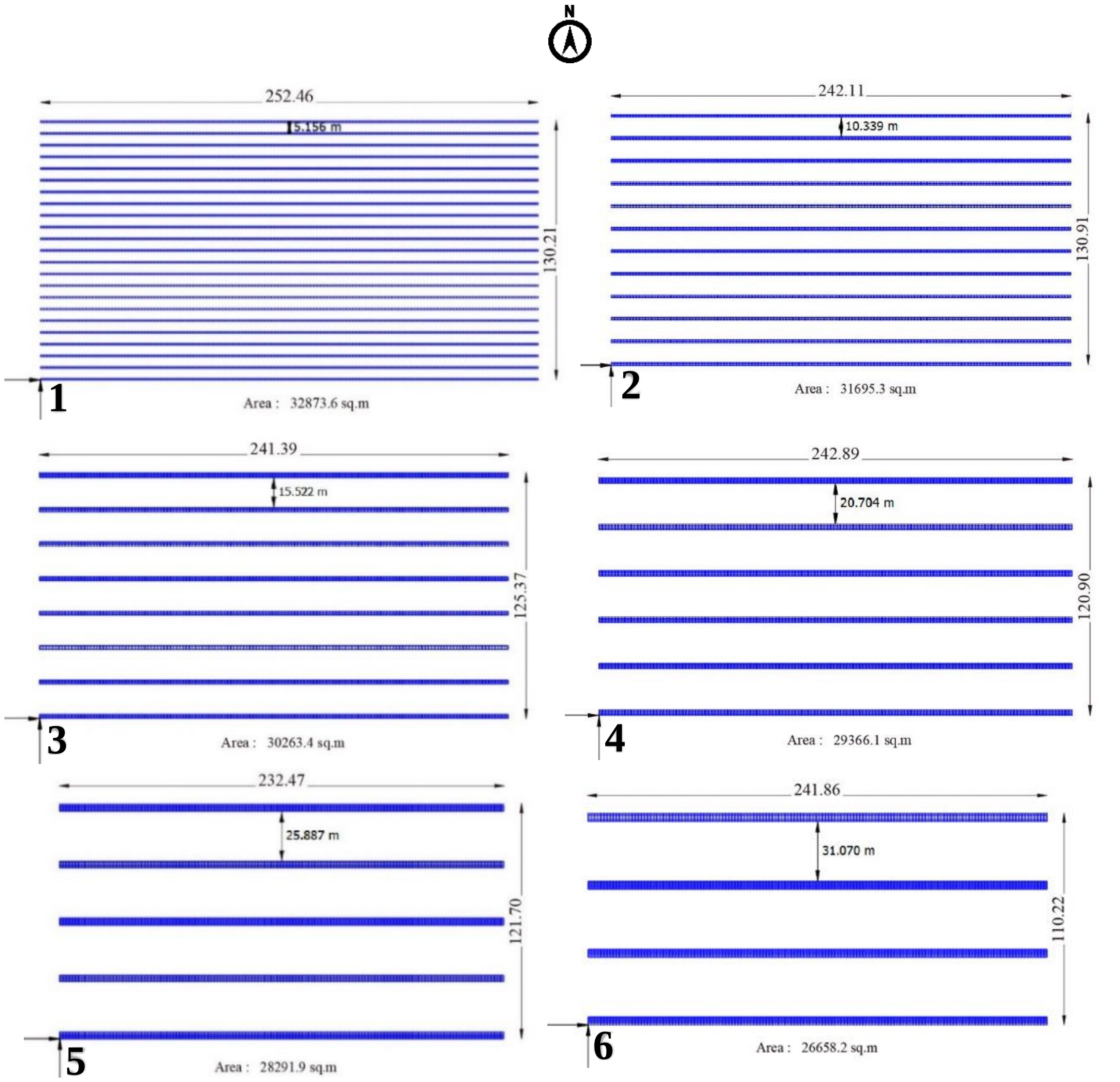


Figure 40: Illustration showing top views of five different alternative installations with their land area coverage, as presented by Table 17

After comparing the results for all the alternatives in *Table 16* and *Table 17*, the best alternative is to be figured out. The alternative with minimum **shading loss** will result in the highest output. As three alternatives, **P2, L2,** and **L3** have the lowest shading loss, each with **0.9 %**. The initials **P** or **L** is the abbreviation for **portrait** or **landscape** orientation and the number 2 and 3 indicates the number of modules alongside of each row of PV array.

To find the best alternative out of three preselected alternatives, the second criterion that could be used for comparison is the **annual specific yield** (**KWh/KWp**). Annual yield for the alternatives **P2, L2, and L3** is observed to be **826.86, 826.29, and 826.29**, respectively. Since alternative **P2** has the highest annual specific yield, it would be the optimum alternative that would yield maximum annual energy.

P2 AS BEST ALTERNATIVE

After determining P2 as the best alternative, it is interesting to see the 3D modelling of the PV system at the site of installation at the airport, as shown in *Figure 41*. It can be observed that the **interrow spacing** is **17.222m,** and there are **7 rows** of PV arrays with total modules number of **3514** totalling installed PV power of **1001.49 KWp** and annual energy production of **828096 KWh.**

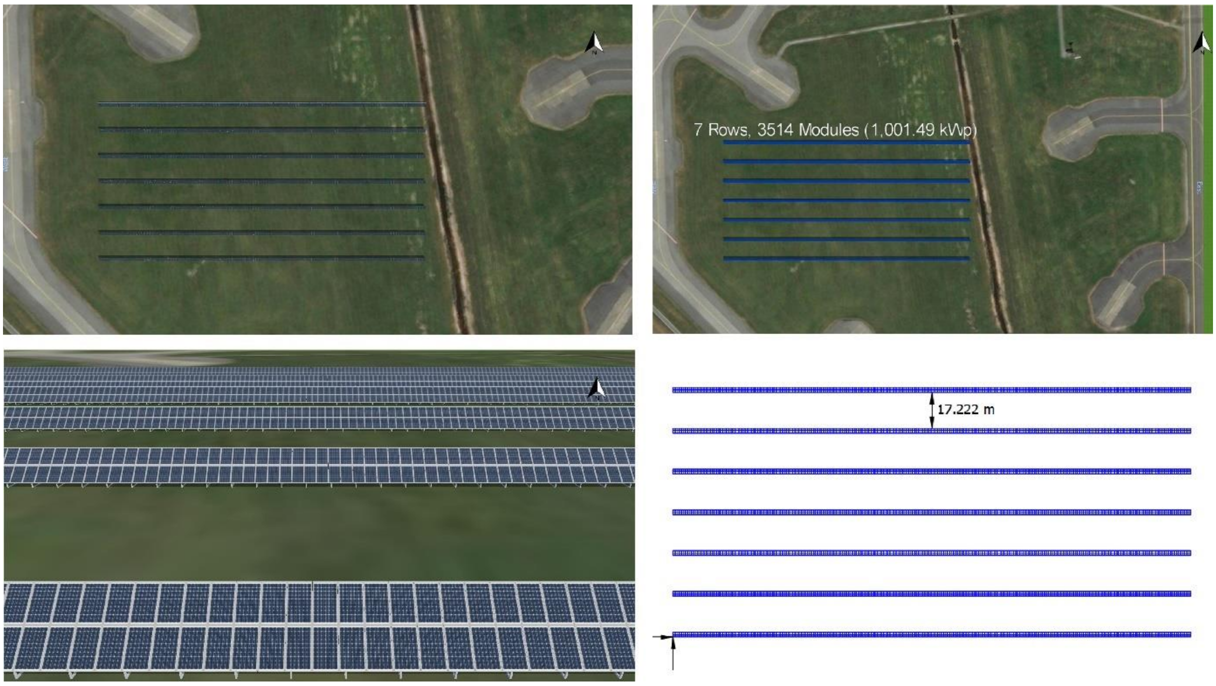


Figure 41: 3D modelling of P2 as the best alternative (PVSol Simulation)

Energy Flow Graph:

The energy flow diagram shows how the energy demand would be met after the installation of a PV system. For average annual energy demand of **15 860 000** KWh at Stavanger airport, *Figure 42* shows the energy flow where **825,096** KWh of energy is supplied by the PV system annually, of which **15,247,726** KWh is supplied from the grid. This means that the level of **self-sufficiency** of the PV system is **3.9** %.

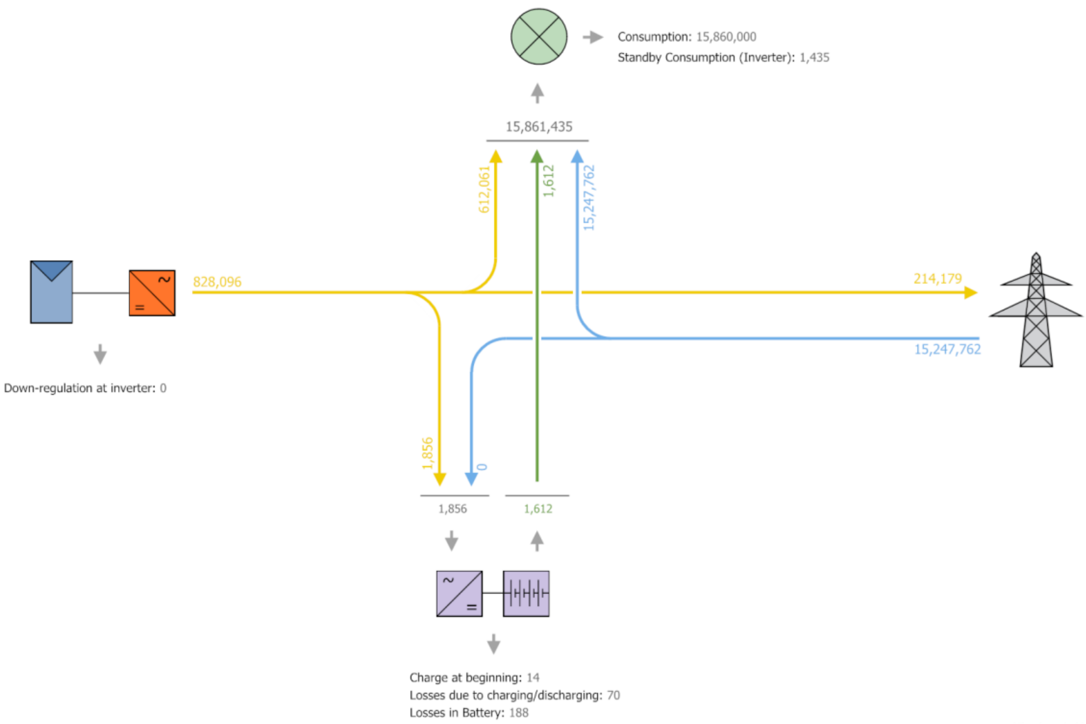


Figure 42: Energy flow diagram for the best alternative P2 to understand the self-sufficiency of the Airport. (simulated using PVSol)

The flow diagram shows how the battery system could be adopted together in connection with the PV system and the grid connection. Here in this simulated case, the battery system stores 1856 KWh of energy annually, and all of that is supplied by the PV system. The battery size could be increased drastically since the technology advancement in battery storage possibilities has demonstrated the commercial availability of utility-scale.

5.3 Economic Evaluation

For utility-scale PV system (Irena, 2019a, p. 49) has presented an illustration of cost breakdown for the installation of the PV system in G20 countries for the year 2018. Out of the 20 countries, Germany has been selected as a reference country to determine further the cost estimate for Norway as (Nilsen, 2016) has mentioned that the installation cost of solar PV is 70 % higher in Norway compared to Germany. Although this gap in price is narrowing down, two extreme cases were taken as two scenarios for rough cost estimation.

Table 18 presents the rough estimate of the installation cost for the PV system of 1001.49 KWp (for **P2** as the best alternative). Two cost scenarios have been presented. ***Scenario 1*** assumes that the PV installation cost in Norway is the same as that in Germany. Whereas ***Scenario 2*** assumes that the installation costs are 70% higher in Norway compared to Germany.

Table 18: Rough Cost estimate of the selected PV system as per 2018

		PV system of 1001.49 KWp	
		Scenario 1	***Scenario 2***
		cost same as in Germany	cost 70 % expensive than in Germany
Cost Breakdown	**Cost (USD/KW)**[3]	**USD**	**USD**
PV module	473.77	474475.92	806609.06
Inverter	70.95	71055.72	120794.72
Racking and Mounting	102.85	103003.25	175105.52
Grid Connection	86.31	86438.60	146945.62
Cabling and Wiring	42.83	42893.82	72919.49
Safety, Security, Monitoring, and Control	20.48	20510.52	34867.88
Mechanical Installation	102.15	102302.20	173913.75
Electrical Installation	40.4	40460.20	68782.33
Soft Costs	173.25	173508.14	294963.84
Total	1112.99	**1114648.36**	**1894902.20**
O&M (per yr.)	47 [4]	47070.03	47070.03

Scenario 1 is more likely for large scale installation. Scenario 2, where PV installation in Norway is 70 % expensive, may only be valid for small scale and roof-mounted installations. In the case of large-scale installation, as Avinor has planned, it is more likely that the installation cost could be negotiated to a similar level as that of Germany. So, for the LCOE (Levelized Cost of energy) calculation, the results of *Scenario 1* will be adopted.

LCOE value for the project would be useful in a financial comparison of the energy produced from the planned PV system with the cost of energy from alternative sources. LCOE value also helps in analyzing the financial feasibility as well as the profitability of the project.

To carry out LCOE calculations, some of the parameters should be assumed, as presented in *Table 19.*

[3] (Irena, 2019a)

[4] (ScottMadden, 2010)

Table 19: Assumptions for economic evaluation

Parameter	**Unit**	**Value**	**Explanation**	**Reference**
Project Duration	years	25	Warranty period of the PV modules is adopted, i.e., 25 years	**(Taylor & So, 2015)**
Discount Rate	%	7	Assumed not to vary during the whole project duration. Ranges between 3 % and 10 % as assumed by IEA Average of 7 % is adopted, which represents the market rate in the unstructured market.	**(Taylor & So, 2015)**
O & M cost annual growth rate	%	2	2 % annual growth rate of O & M cost assumed.	

<u>LCOE Calculations:</u>

Initial Investment Cost (I) = $1114648.36

Fuel Cost (F) = 0

Operation and Maintenance Cost (M) = $ 47070.03

Annual Energy Output (E)= 828096 KWh

Levelized cost of energy is given by the ratio of the net present value of total costs over the lifetime by the net present value of total electricity produced over the lifetime.

i.e.

$$\text{LCOE} = \frac{\text{Net Present Value of Total Costs Over Lifetime}}{\text{Net Present Value of Total Electricity Produced over lifetime}}$$

$$\text{LCOE} = \frac{\Sigma[(I_t + M_t + F_t)\ /\ (1+r)^t]}{\Sigma[(\mathrm{E}_t/(1+\mathrm{r})^t]}$$

$$= \frac{6079685.38}{8876364.12}$$ (results from calculations performed in excel sheet – appendix 3)

$=$ 0.68 $/KWh

The calculation shows that the NPV (Net present value) of the total costs of the PV system over its lifetime is $ 6079685.38, and the net present value of total electricity produced over its lifetime is 8876364.12 KWh. And the Levelized cost of the energy produced from the PV system is 0.68 $/KWh.

6 Results

6.1 Extra Considerations at Airport:

- The area of designated plots for energy trials adds up to a total of c.a. 43 acres, and as per literature, this area could accommodate up to 7300 KW of Solar PV installation. The designated plots are away from the physical airspace operation zone.
- As per (Jensen, 2018), the PV installations may increase the fire risk in the electrical system.
- A picture, as shown in *Figure 43,* emerged after the Corona crisis, which halted all the aviation activities, and planes are seen to have parked very near to plot B, where the first phase of installation is planned. A comprehensive hazard study should be conducted for unprecedented cases like this one to understand the implications of aircraft being parked near the PV installations and vice versa.

Figure 43: All the planes seen parking near block B at Stavanger airport during the Covid-19 crisis. (source: Stavanger Aftenblad)

- Site of installation lying inside the Airport is free from any land acquisition problem as well as does not pose interference to external settlement as well as physical airspace.
- Topography is favourable because of the location being free from horizon shading as well as persistent external shadings. The site is favourable for accessibility as well as water availability for cleaning and maintenance works.
- Ground conditions of the site are favourable for the ground mounting system.
- The preliminary roadblocks to deploying large scale PV at Airport, as pointed by (FAA, 2018), for instance, glint and glare and radar interference, could be reduced by countermeasures such as the use of anti-reflective PV modules and use of inductor-

capacitor filters respectively. However, the effectiveness of such measures may require a comprehensive study.

- Large scale installation at open space at Airport will decrease the green space and could stimulate birds, rabbits, squirrels, and other wildlife movements posing a hazard to aviation protocol. The choice of the mounting structure that does not involve extensive concrete works limits the extent of damage to the green space. The increase of the mounting height within the permissible limits opens the possibilities of dual production of energy as well as crop. But the practice of such co-production could further stimulate the movements of birds and wildlife. So, a comprehensive wildlife hazard assessment, as well as environmental impact assessment, is necessary.
- Annual energy consumption at the airport is used to be 15 860 000 KWh, which is meter reading of the electrical power supplied from the grid to the airport. However, there are thermal heating, thermal cooling, as well as fuel demand as well. If all the demand is to be met by electrical energy produced from local renewable solutions, it is better to add all the energy demand in the equivalence of electrical energy.

6.2 Optimization of most sensitive parameters:

- Several parameters have been identified, which could affect the overall energy output of a Solar PV system, as discussed in previous chapters. However, tilt angle, azimuth angle, inter-row spacing, module orientation (landscape vs portrait), and the number of rows per rack are the most sensitive parameters.
- Optimization of the tilt angle and azimuth angle ensures that the PV modules receive the highest possible irradiation. At Stavanger airport, a tilt angle of 45 ° and azimuth angle due south (0 °) is found to be optimum. However, the optimum values have been determined with the help of synthetic data for clear sky irradiation at Stavanger airport. With software PVsyst it is only possible to achieve data for different alternatives of tilt and azimuth with a step interval of 15 °. This indicates that the tilt and azimuth could be more optimized with a methodology that could produce data of irradiance for a matrix of tilt and azimuth with small step interval, for instance, a step interval as low as 1 °.
- Inter-row spacing is the space between two adjacent arrays. At a place with a higher latitude of 58.83 ° and having an optimum tilt of 45 ° interrow spacing is one of the sensitive parameters affecting the output of the PV system. The higher tilt produces larger shadows and thus increases the interrow shading. Ideal interrow shading has been registered using calculations. The optimum interrow spacing for a system could be calculated only after the orientation of modules (portrait vs landscape) and the number of rows per rack.

6.3 Analysis of Test Rig

- Test rig analysis helped to gather and validate some important data. Newer real-time monitoring applications have made it possible to track the test rig performance very easily, even with smartphones.
- After observing the annual output for individual panels of the test rig at Stavanger airport, module oriented due south is found to have produced the highest annual energy. This observation is found to be valid for both module types – monocrystalline and polycrystalline.
- The monocrystalline (285 Wp) and polycrystalline (265 Wp) modules used in the test rig were of different ratings. So, the specific yield calculation was made to compare the performance of these two different types of modules. It is observed that the annual specific yield (which is the ratio of annual energy produced to the rated power of the modules, kWh/KWp) is higher for polycrystalline panels (1020.5 KWh/KWp vs 960.04 KWh/KWp)
- The modules due south at the test rig are tilted at 15°. But the optimum tilt at Stavanger airport is discovered to be 45°. So, test rig conditions were simulated to compare the production data at the optimum tilt. The table below summarizes the observations from the test rig as well as from test-rig scale simulation for a single monocrystalline module as used in the test rig.

MonoSol 285	Tilt Angle	Azimuth Angle	Annual Output, KWh
Test Rig	15 °	0 ° (Due south)	**169**
Simulated	45 °	0 ° (Due south)	**237.5**

- Similarly, the simulation of the test rig similar setup with 20 panels demonstrated annual output of 4288 KWh, and the simulation of similar panels in optimum tilt condition of 45 ° demonstrated total annual output of 4750 KWh.
- Simulation of test rig similar setup with two different software programs resulted in different results, as shown in the table below.

Software	Tilt Angle	Azimuth Angle	Annual Output, KWh
Energy 3D	Same as test rig		**2573,15**
PVSol	Same as a test rig		**4288**

- The difference is due to the introduction of maximum power point trackers(MPPT) in the software PVSol but not in Energy 3D. MPPTs helps to optimize the power production from the modules by receiving the maximum solar energy at any time and thereby increasing energy efficiency.

- The test rig helped to compare the performance of the PV module for various tilts, various orientation, and modules types and modules with different power ratings. Further, the test rig observation helped to validate the optimum tilt as 45° and optimum azimuth as 0° (due south), which were determined earlier with the help of synthetic data in the form of the tilt-azimuth matrix.
- The simulation of 20 PV modules using energy 3D software for a fixed tilt and tracking system showed the following results.

	Tilt Angle	**Azimuth Angle**	**Annual Output, KWh**
Fixed Tilt	45 °	0° (Due south)	**3062,31**
Horizontal single-axis tracker	Follows tracking	0° (Due south)	**3411,22**
Vertical Single Axis tracker	45 °	Follows tracking	**4244.43**
Azimuth Double axis tracker	Follows tracking	Follows tracking	**4588,82**

- The tracking system increases the output. But it comes with the increased complexity of operation and maintenance and is more likely to have higher out of operation days in comparison to the fixed-tilt system. So, the introduction of the tracking system requires comprehensive performance analysis before introducing it for a large-scale PV system.
- The results and analysis from the test rig formed a solid basis for spatial calculation for large scale PV systems which helped further for parameter setting for large scale simulation.

6.4 Spatial Calculation

- Sun chart for Stavanger airport helped to understand the seasonal sun path diagram. The worst solar window of 10 am to 2 pm on December 21 was assumed, and thus corresponding solar elevation and azimuth correction angles were observed to be 4° and 27.4°, respectively. These values were useful for calculating ideal inter-row spacing.
- After spatial calculation, it is found that 5653,63 m^2 of the PV generating surface is required for 1000 KWp of solar installation. Simulation results validated the area requirement as obtained by the calculation. The best alternative P2 as per simulation requires 5661.5 m^2 of generating surface for 1001.49 KWp solar installation.
- Ideal inter-row spacing is larger at places with a higher optimum tilt angle, which makes it difficult to eliminate the inter-row shading fully. Since the shadows during morning and evening are larger, partial tolerance of shading is the practical way of minimizing inter-row spacing to compensate for the land limitation as well as increase land efficiency.

- The module that comes with bypass diodes should be considered because bypass diodes allow the current to pass even from the shaded cells in case of shading.

6.5 Simulation and Optimization of Large-Scale PV installation

- MonoSol panels used for simulation are of 285 W rated power with a surface area of 1.61 m^2. Panels with higher ratings and higher efficiency are now commercially available. With the use of more efficient panels of higher efficiency, land coverage could be reduced without increasing surface area or without decreasing total annual energy output.
- Among several alternatives, the alternative P2 is observed to be an optimum one. Alternative P2 is the one with a portrait orientation of PV modules and a total of two modules along the bottom of each rack.
- Alternative P2 has an inter-row spacing of 17.222 m, total rows 7, the total number of modules 3514, and total installed solar power of 1001.49 KWp.
- The alternative P2 requires a total generating surface area of 5665.1 m^2 and the total land area coverage of 29615.9 $m^{2,}$ which corresponds to the land factor of 5.22. The shading loss per year amounts to 0.9% of total production. Similarly, the total annual energy production equals to 29615.9 KWh, with a performance ratio of 83 and a specific annual yield of 826.86 KWh/KWp.
- After the installation of P2, 496703 kg of CO_2 emissions could be avoided.
- To sequester **1 tonne of CO_2**, c.a 15 trees should be planted(carbonneutral, 2017). And to remove 496703 kg or 496.703 tonnes of CO_2 emissions, c.a. **7456 trees** should be planted.
- There is a possibility of a utility-scale battery storage system at Stavanger airport, which could be changed entirely from the PV system. The flow diagram shows how the battery integration scenario would work.
- The rough financial estimate shows that the installation cost for alternative P2 is c.a **$1114648.36**, Avinor can achieve scenario one by negotiating the cost for its planned large-scale installation in Norway to the cost level similar to that of Germany.
- The calculation shows that the NPV (Net present value) of total costs of the PV system over its lifetime is $ 6079685.38 and the net present value of total electricity produced over its lifetime is 8876364.12 KWh. The Levelized Cost of energy for the alternative P2 is calculated as **0.68** KWh/$, which enables to compare the energy cost of the PV installation with the energy cost from alternative methods.

7 Discussions

Most of the site related parameters are found to be favourable. However, some of them were assumed to be favourable without adequate analysis to limit the scope of the thesis. Further research should be required to understand the actual favorability of assumed factors.

These most sensitive parameters were determined with the methodology which analyses optimum output based on the spatial setup. However, some electrical parameters such as the use of an online tracking platform, the use of MPPT solar charge controllers, and the use of modules with bypass diodes have demonstrated increased energy output from the PV system. Thus, further research is recommended that puts weight on output maximization based on electrical parameters as well as the choice of electrical components.

The solar resource analysis, test rig analysis, sun chart, spatial calculations, and simulations are valuable to identify the parameters and their optimum values. The values were determined by analyzing the solar radiation vs tilt-azimuth matrix and further by comparing the large-scale simulation results of various potential alternatives. The financial evaluation presents rough estimates of total installation cost, O&M cost, and LCOE. These estimates are calculated based on literature data, thus may not fully signify the real scenario. Therefore, comprehensive cost estimation is recommended in further research.

The methodology and results of this thesis are transferable partly if not fully to PV installations at several urban spaces and various scales. However, there are no policies, standards, and certifications in Norway regarding a large-scale PV system. Even for small scales, the support system is very limited. The current limited policy allows grid-connected PV systems up to 100 KW only if the customer meets the requirement of being a net consumer of the grid-electricity on an annual basis. Such a policy limits the ambition of achieving positive energy districts where the production is required to be more than the consumption. Such policies even contradict with the national vision of achieving a low carbon society. Therefore, it is recommended that the policymakers should come up with the energy policies for local, regional as well as the national level that would liberalize the deployment of large scale PV systems to tap the vast solar resource which thereby would supplement the energy and climate targets as well as sustainable development goals.

8 Conclusion

To address the research question: "**What are the site related and most sensitive parameters to optimize a large-scale PV installation at Stavanger Airport?**", the thesis arrived at various key results that offer critical information for the proposed large-scale PV installation.

Availability and sufficiency of land, physical airspace operation zone, PV-system induced increased fire hazard, wildlife hazard, environmental impact, glint and glare hazard, radar interference, topographical and meteorological conditions, shading profile, accessibility, water availability, impact on green space and permissible mounting height are the site related parameters that need to be explored to optimize a large scale PV installation at Stavanger Airport.

Similarly, tilt angle, azimuth angle, interrow spacing, module orientation, and the number of modules alongside each row are found to be the most sensitive parameters to optimize a large-scale PV installation at Stavanger airport. The optimum values of most sensitive parameters for the planned first stage installation are found as tilt angle of 45°, azimuth angle of 0 ° (due south), inter-row spacing of 17.22m, module-oriented portrait and two modules alongside the bottom of each row.

Site Related Parameters:

Availability and sufficiency of land, physical airspace operation zone, PV-system induced increased fire hazard, wildlife hazard, environmental impact, glint and glare hazard, radar interference, topographical and meteorological conditions, shading profile, accessibility, water availability, impact on green space and permissible mounting height.

Most Sensitive Parameters:

tilt angle, azimuth angle, interrow spacing, module orientation, and the number of modules alongside each row.

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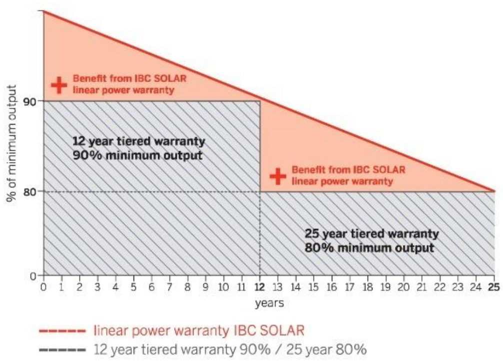
Appendix 1: Technical Data of IBC Polysol 265 CS4

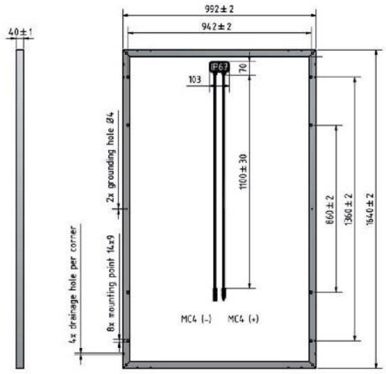
TECHNICAL DATA

IBC PolySol	260 CS4	265 CS4
Article number	2203800017	2203800018
Electrical data (STC):		
STC Power Pmax (Wp)	260	265
STC Nominal Voltage Umpp (V)	31.1	31.4
STC Nominal Current Impp (A)	8.37	8.44
STC Open Circuit Voltage Uoc (V)	38.1	38.6
STC Short Circuit Current Isc (A)	8.98	9.03
Module Efficiency (%)	15.9	16.2
Power Tolerance (Wp)	−0/+5	−0/+5
Electrical data (NOCT):		
800 W/m² NOCT AM 1.5 Power Pmax (Wp)	196.53	199.83
800 W/m² NOCT AM 1.5 Nominal Voltage Umpp (V)	29.42	29.56
800 W/m² NOCT AM 1.5 Open Circuit Voltage Uoc (V)	35.86	35.98
800 W/m² NOCT AM 1.5 Short Circuit Current Isc (A)	7.38	7.48
Relative Efficiency Reduction at 200 W/m² (%)	2.81	2.83
Temperature coefficient:		
NOCT (°C)	46	46
Tempcoeff Isc (%/°C)	+0.044	+0.044
Tempcoeff Voc (mV/°C)	−120.78	−122.36
Tempcoeff Pmpp (%/°C)	−0.423	−0.423

Operating conditions:	
Max. System Voltage (V)	1000
Application Class	A
Reverse Current Ir (A)	20
Current value string fuse (A)	15
Fuse protection from parallel strings	4
Mechanical properties:	
Dimensions (L × W × H in mm)	1640 × 992 × 40
Weight (kg)	19.5
Load capacity (Pa)[2]	5400
Front sheet (mm)	3.2 (low-iron photovoltaic glass and anti-reflective coating)
Frame	anodized aluminium, sturdy hollow-chamber frame
Cells	6 × 10 polycrystalline silicon cells
Connection type	MC4 (IP65)
Warranties and certification:	
Product warranty	10 years[1]
Power warranty	25 years, linear
Certification	IEC 61215, IEC 61730-1/-2 ISO 9001, ISO 14001, OHSAS 18001
Packaging information:	
Number of modules per pallet	26
Number of pallets per 40' container	28
Number of pallets per lorry	30
Dimensions incl. pallet (L × W × H in mm)	1695 × 1135 × 1150
Gross weight incl. pallet (kg)	535.5
Stackability per pallet	3-fold

25 year linear power warranty by IBC SOLAR





Presented by:

[1] The warranty presupposes installation in accordance with the valid installation instructions.
Standard test conditions: 1000 W/m² irradiation with a spectral distribution of AM 1.5 and a cell temperature of 25 °C. 800 W/m², NOCT. Information according to EN 60904-3 (STC).
All values according to DIN EN 50380. The precise conditions and content can be taken from the respectively valid version of the product and power warranty, which you obtain from your IBC Premium Partner. Subject to errors and modifications.

[2] Tested according to IEC 61215 for snow loads up to 5400Pa (5.4 kN/m²).

As of: 2016-02-22

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Appendix 2: Technical Data of IBC MonoSol 285 ZX

TECHNICAL DATA

IBC MonoSol	280 ZX	285 ZX	290 ZX
Article number	2004100019	2004100010	2004100011

Electrical data (STC):			
STC Power Pmax (Wp)	280	285	290
STC Nominal Voltage Umpp (V)	32.9	31.2	31.5
STC Nominal Current Impp (A)	8.51	9.14	9.21
STC Open Circuit Voltage Uoc (V)	39.1	40.2	40.6
STC Short Circuit Current Isc (A)	9.02	9.74	9.76
Module Efficiency (%)	17.4	17.69	18.0
Power Tolerance (Wp)	−0/+5	−0/+5	−0/+5

Electrical data (NOCT):			
800 W/m² NOCT AM 1.5 Power Pmax (Wp)	206.1	215.91	219.7
800 W/m² NOCT AM 1.5 Nominal Voltage Umpp (V)	31.41	29.49	29.94
800 W/m² NOCT AM 1.5 Open Circuit Voltage Uoc (V)	36.95	39.74	40.12
800 W/m² NOCT AM 1.5 Short Circuit Current Isc (A)	7.29	7.87	7.89
Relative Efficiency Reduction at 200 W/m² (%)	2.50	2.50	2.50

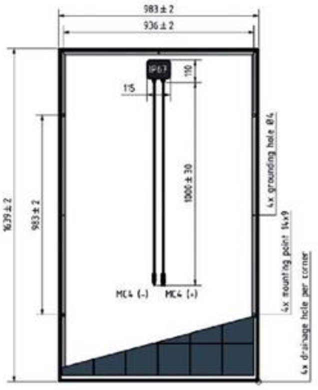
Temperature coefficient:			
NOCT (°C)	46	46	46
Tempcoeff Isc (%/°C)	+0.05	+0.05	+0.05
Tempcoeff Voc (mV/°C)	−117.3	−120	−122
Tempcoeff Pmpp (%/°C)	−0.42	−0.42	−0.42

Operating conditions:	
Max. System Voltage (V)	1000
Application Class	A
Reverse Current Ir (A)	15
Current value string fuse (A)	15
Fuse protection from parallel strings	3

Mechanical properties:	
Dimensions (L × W × H in mm)	1639 × 983 × 40
Weight (kg)	18.5
Load capacity (Pa)[2]	5400
Front sheet (mm)	3.2 (low-iron photovoltaic glass and anti-reflective coating)
Frame	anodized aluminium, sturdy hollow-chamber frame
Cells	6 × 10 monocrystalline silicon cells
Connection type	MC4 (IP65)

Warranties and certification:	
Product warranty	10 years[1]
Power warranty	25 years[1]
Certification	IEC 61215, IEC 61730-1/-2, ISO 9001, ISO 14001, OHSAS 18001

Packaging information:	
Number of modules per pallet	26
Number of pallets per 40' container	28
Number of pallets per lorry	30
Dimensions incl. pallet (L × W × H in mm)	1700 × 1100 × 1170
Gross weight incl. pallet (kg)	482
Stackability per pallet	2-fold



Modules from 285 Wp are equipped with an additional crossbar on the rear side.

Presented by:

[1] The warranty presupposes installation in accordance with the valid installation instructions.
Standard test conditions: 1000 W/m² irradiation with a spectral distribution of AM 1.5 and a cell temperature of 25 °C. 800 W/m², NOCT. Information according to EN 60904-3 (STC).
All values according to DIN EN 50380. The precise conditions and content can be taken from the respectively valid version of the product and power warranty, which you obtain from your IBC Premium Partner. Subject to errors and modifications.

[2] Tested according to IEC 61215 for snow loads up to 5400 Pa (5.4 kN/m²).

As of: 2015-11-06

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Appendix 3: Excel Calculation for LCOE (Levelized Cost of Energy)

year	O & M Costs	Fuel Costs	Discount Factor	Present Value of Costs		Yearly Output , KWh	Present Value of Outputs
				1114648.36			0
1			0.93				
2	47070.03		0.86	41112.79		828096	723291.12
3	56484.036	0	0.79	46107.80		828096	675973.01
4	67780.8432	0	0.74	51709.68		828096	631750.47
5	81337.01184	0	0.68	57992.17		828096	590421.00
6	97604.41421	0	0.63	65037.94		828096	551795.33
7	117125.297	0	0.58	72939.75		828096	515696.57
8	140550.3565	0	0.54	81801.59		828096	481959.41
9	168660.4278	0	0.50	91740.10		828096	450429.36
10	202392.5133	0	0.46	102886.09		828096	420962.02
11	242871.016	0	0.43	115386.27		828096	393422.44
12	291445.2192	0	0.40	129405.16		828096	367684.53
13	349734.263	0	0.37	145127.29		828096	343630.40
14	419681.1156	0	0.34	162759.57		828096	321149.91
15	503617.3387	0	0.32	182534.10		828096	300140.10
16	604340.8064	0	0.29	204711.14		828096	280504.77
17	725208.9677	0	0.27	229582.59		828096	262153.99
18	870250.7613	0	0.25	257475.80		828096	245003.73
19	1044300.914	0	0.23	288757.90		828096	228975.44
20	1253161.096	0	0.21	323840.64		828096	213995.74
21	1503793.315	0	0.20	363185.77		828096	199996.02
22	1804551.979	0	0.18	407311.14		828096	186912.17
23	2165462.374	0	0.17	456797.54		828096	174684.27
24	2598554.849	0	0.16	512296.31		828096	163256.33
25	3118265.819	0	0.15	574537.91		828096	152576.01
			NPV of Total Costs, $	6079685.38		NPV of Total Costs ; KWh	8876364.12
LCOE	0.68	$/KWh					