NTNU
Norwegian University of
Science and Technology

Tracking Technologies for Solar Photovoltaics

Proposal for a Solar PV Farm in Tasmania and Opportunities for Norway

Anja Jones Gudbrandsen

Master of Science in Mechanical Engineering
Submission date: June 2018
Supervisor: Bjørn Haugen, MTP
Co-supervisor: Ivar Marthinusen, MTP

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

Table of Contents

List of Figures

List of Tables

PREFACE

This Master´s Thesis was written in spring, 2018 and concludes a five year Master's degree in Mechanical Engineering at the Norwegian University of Science and Technology (NTNU). The research was performed in cooperation with DNV GL´s Energy Department in Australia.

The thesis evaluates the performance of three types of tracking technology used in large scale solar PV farms. The study combined both power output and spot price in the analysis to capture the variation in performance and income during the day for the three systems. The analysis was performed for Wesley Vale Solar Farm, a recently approved solar PV farm in Tasmania, Australia, and the results obtained were further used for assessing opportunities for Norway. Australian industry experience, with real production data facilitated for an overall establishment of the arrays´ technical performance, risk profile and financial benefits for the farm in question.

The strong interest and potential for solar PV, globally as well as for Australia and Norway, motivated for researching this technology. A previous internship working with floating offshore wind power (DNV GL, WIN WIN) and a course in renewable energy at the University of New South Wales increased my desire to contribute to the further development of sustainable solutions.

Oslo, 23rd June, 2018

Anja Jones Gudbrandsen

Anja Jones Gudbrandsen

ACKNOWLEDGEMENTS

Firstly, I would like to express my gratitude to my contacts at DNV GL´s Renewable Advisory Department at Høvik, the Business Assurance and Maritime Department in Sydney as well as the Energy Department in Melbourne. DNV GL in Sydney provided me with office space and facilitated many inspiring discussions, particularly with Alex Argyros, Senior Engineer. Especially, I wish to thank Graham Slack, Country Manager in Australia, for his continuous recommendations and sharing his insight into the solar industry. Moreover, I would like to thank Elyse Wise, Project Manager for the Wesley Vale Solar Farm, and Daniel Gilbert, Solar Asset Manager at Epuron, for their assistance throughout the research. Many thanks also to my supervisors at NTNU, Bjørn Haugen and Ivar Marthinusen who followed my progress despite the time difference.

The thesis relies on experience from the Australian solar industry, achieved through private communication with market participants from the entire value chain. The unique assistance received is greatly appreciated and I wish to thank PwC, Rystad Energy, First Solar, Jinko Solar, NEXTracker, Array Technologies, Signal Energy, AGL, Impact Investment Group, DIF, University of New South Wales and AEMO. Moreover, Norwegian industry participants including Statkraft, Multiconsult, Equinor, Scatec Solar, Trønder Energi, Powel, FUSen and ASKO have provided valuable guidance.

I would also like to thank Xait for providing their document automation and collaboration software, XaitPorter, as well as user support setting up the template for the thesis. Finally, the support provided through communication with PVsyst was greatly appreciated.

.

ABSTRACT

This Master's Thesis assesses the suitability of three large scale solar PV tracking technologies for a range of conditions; subtropical, temperate and cold weather climates. Systems evaluated include Fixed Tilt (FT), Single Axis Tracking (SAT) and Dual Axis Tracking (DAT). The importance of establishing the project objectives is emphasized; is it peak power, grid utilization, annual electricity generated or seasonal production that should be optimized? Similarly, understanding site specific characteristics is critical for system selection. The relationship between solar irradiance, ambient temperature, power demand and electricity spot price throughout the year is discussed, as is the importance of understanding how the solar irradiance can vary from predominantly direct to diffuse during the year thus affecting the choice of tracking system.

Traditional project analysis focuses on solar irradiance and weather data when quantifying the efficiency, with fixed electricity prices for the economics. This thesis aims to utilizes real and simulated performance data in combination with actual electricity spot prices to establish both the energy output and financial benefits of the different systems. The methodology presented also incorporates an uncertainty analysis to highlight the risk profiles for the technologies, thereby assisting system selection.

The methodology was first applied for the operating Gatton Solar Research Facility (subtropical, Queensland). Gains in energy output of 20% and 25% for SAT and DAT over FT were achieved, whilst the gain in income was 36% and 40% respectively, emphasizing the importance of daily spot price variations. The results, together with simulations in PVsyst, were used to make recommendations for a new farm in Tasmania (temperate). Thereafter, the findings were transferred to Norway to illustrate solar PV's potential even in a high latitude and cold weather climate.

The advantage of combining solar PV with other energy sources, such as hydro, is discussed together with the potential benefits for including limited battery storage for stabilizing output and exploiting typical over-production at midday. Opportunities for learning from large scale farms in Australia are highlighted in order to benefit from their experience when implementing new technology. The importance of using qualified partners throughout all phases of the project is emphasized.

The research was mainly performed in Australia, where the thriving solar PV industry is only limited by access to the grid and securing a power purchase agreement. A network was established covering the entire value chain from equipment suppliers, EPC contractors, farm owners, certifying institutions, consultancy companies and academia. This was complemented by a similar network in Norway.

This thesis thus provides an unbiased evaluation of tracking systems and their potential, focusing on both technical and economic performance.

SAMMENDRAG

Denne masteroppgaven evaluerer tre teknologier brukt for storskala solcelleanlegg (PV). Systemene som vurderes er statiske anlegg og anlegg hvor panelene roterer om enten en eller to akser. Disse refereres til som FT (Fixed Tilt), SAT (Single Axis Tracking) og DAT (Dual Axis Tracking). Systemene blir vurdert under forskjellige klimaforhold; subtropisk-, temperert- og kaldere klima. Intensjonen, og hva som skal optimaliseres i solcelleanlegget, er av essensiell betydning; kapasitet, utnyttelse av elektrisitetsnettet eller årlig/sesongbasert produksjon. Videre er særtrekk ved anleggets plassering avgjørende for systemvalg. Forholdet mellom solinnstråling, temperatur, etterspørsel etter energi og spotpris på elektrisitet gjennom året diskuteres. Analysen viser betydningen av variasjonen mellom direkte og diffus solinnstråling.

Tradisjonell prosjektanalyse fokuserer på solinnstråling og værdata for kvantifisering av effektiviteten, med faste elektrisitetspriser brukt for å vurdere lønnsomheten. For å belyse både energiproduksjonen og de økonomiske fordelene ved de ulike storskala teknologiene, er det benyttet reelle samt simulerte produksjonsdata i kombinasjon med faktiske spotpriser. For å bistå ved valg av PV system inneholder den anvendte metoden en risikoanalyse av de ovenfor tre nevnte teknologiene.

Metoden ble først utført for Gatton Solar Research Facility, et eksisterende PV anlegg i Queensland med subtropisk klima. Energiproduksjonen for SAT og DAT økte med henholdsvis 20% og 25% i forhold til FT, mens inntektsøkning var henholdsvis 36% og 40%. Dette fremhever betydningen av daglige variasjoner i spotprisene og PV systemenes evne til å produsere i samsvar med etterspørsel. Resultatene, sammen med simuleringer i PVsyst, ble benyttet for å gi anbefalinger til et nytt anlegg i Tasmania (temperert klima). Videre funn ble benyttet til å undersøke økt utnyttelse av solenergi i Norge.

Solcelleanlegg i kombinasjon med andre energikilder som vannkraft diskuteres, samt benyttelse av batteri for å stabilisere tilbudet og lagre overproduksjon av kraft. Muligheter for å bruke erfaringer fra Australia ved implementering av ny teknologi, samt betydningen av å benytte kvalifiserte aktører gjennom alle faser av prosjektet, er fremhevet.

Oppgaven ble hovedsakelig utført i Australia, hvor den voksende solenergiindustrien største utfordring er tilgang til elektrisitetsnettet og kjøpere av kraften. I utarbeidelsen av analysen ble kontakter gjennom hele verdikjeden etablert; leverandører, investorer, installasjons-, sertifiserings- og konsulentselskaper samt akademia. Dette ble komplementert av et lignende nettverk i Norge.

Denne oppgaven tar for seg nye, objektive betraktninger for evaluering av storskala teknologier og deres potensiale, med fokus på både teknisk og økonomisk ytelse.

ACRONYMS

@RISK	Commercial Monte Carlo analysis software
AC	Alternating Current
ACF	Annual Capacity Factor
A$/W	Australian Dollars per Watt
AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
BIPV	Building Integrated Photovoltaic
BOM	Australian Government Bureau of Meteorology
BOS	Balance of System
Capex	Capital Expenditure
DAT	Dual Axis Tracking
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
ENSO	El Niño Southern Oscillation
EPC	Engineering, Procurement and Construction
FT	Fixed Tilt
GCR	Ground Covering Ratio
GHI	Global Horizontal Irradiance
GSRF	Gatton Solar Research Facility
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LGC	Large Scale Generation Certificate
ML	Machine Learning
MWac	Mega Watt Alternating Current

MWdc	Mega Watt Direct Current
NEM	Australian National Energy Market
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NSW	New South Wales
NTNU	Norwegian University of Science and Technology
O&M	Operating and Maintenance
Opex	Operational expenditure
PPA	Power Purchase Agreement
PV	Photovoltaics
PVsyst	Commercial software for simulating solar PV array performance
QLD	Queensland
RRP	Recommended Retail Price
SAT	Single Axis Tracking
TAS	Tasmania
VLOOKUP	Function in Microsoft Excel for synchronizing data sets
WVSF	Wesley Vale Solar Farm

NOMENCLATURE

Greek symbols

γ_s Elevation or altitude angle

α_p Azimuth angle of the panel

α_s Azimuth angle of the sun

γ_p Tilt angle of the panel

δ Declination angle

θ Zenith angle

β Annual degradation rate

Roman symbols

d Discount rate

E_t Energy generated in year "t"

I_t Investment in year "t"

M_t Operations and maintenance in year "t"

n Expected lifetime of the system

1 INTRODUCTION

1.1 Motivation

According to DNV GL's Energy Transformation Outlook, solar PV will account for over 35% of the global electricity production by 2050, being the primary source of electricity [1]. This is equivalent to what onshore and offshore wind is predicted to generate combined at that time. Moreover, it will be rivalling oil as an energy supplier. Based on installed capacity, it is the fastest growing energy source in the world, and was the renewable source invested the most in during 2017 [2]. In several regions, large scale PV is already the cheapest form of electricity generation and the least expensive renewable energy solution in several additional locations. Major PV installations have also been constructed in locations with relatively low solar irradiance, and growth is expected to occur in all regions through the next decades. Despite a more electrified and cleaner world being achievable, the current carbon emissions are not aligned with the Paris climate goals and comprehensive actions must be taken [3]. Power generation is transforming from a top-down centralised structure to a more interactive, decentralised and fragmented system influenced by prosumers [4]. The rapid growth of renewable energy creates a highly diversified energy mix, resulting in a marketplace with opportunities. Alternative business models that recognise technological advances are needed.

Improving performance and further cost reductions drives the PV deployment. Efficiency improvements, economies of scale, streamlining of the development processes, financing mechanisms, market competition as well as storage and demand management are contributing factors. The costs of solar energy are decreasing more rapidly than expected and it is anticipated to become widely competitive by the mid 2020's [3]. Large scale solar PV system costs were reduced by almost 30% from 2016 to 2017 in the US [5].

While further improvement of the efficiency of the solar modules has proven to be challenging, tracking technologies can increase output generation by 10% to 50% [6]. Analogous to a sunflower, solar PV arrays installed with tracking systems follow the path of the sun to improve their energy harvesting [7]. As the sun changes its position throughout the day and its path varies with the seasons, increased energy yield is achievable by rotating and orientating the panels accordingly. Trackers are mechanical devices with more advanced mounting of solar PV arrays compared to the static fixed tilt (FT) options. They are distinguished between single axis tracking (SAT) and dual axis tracking (DAT). While SAT follows the sun throughout the day, DAT additionally adjusts for seasonal variations and thereby captures maximum direct solar irradiance. Generally, both efficiency and costs increase with the complexity of tracking solutions, while reliability declines. However, in accordance with design innovation and a competitive market, tracking costs are decreasing and their quality and reliability improving. Historically, FT has been employed, however, SAT is currently dominating the large scale PV market [5]. It must be emphasized that the ideal array solution is determined by the project environment and goals, influenced by latitude, solar irradiance, weather, site conditions as well as available area and grid capacity [8].

An expanding deployment of solar PV farms, higher electricity prices and increasing environmental awareness creates incentives for further investigation of large scale solar PV array technologies. Along with the trend of increased electricity generated from solar PV, the potential gains through higher energy yield become crucial. However, there is a lack of published work assessing the PV arrays' performance in accordance with income from the spot price electricity market (i.e. considering daily and annual variations). A mechanical success is not sufficient, understanding the key cost drivers is crucial for maximizing project value. Moreover, it was found that reports are often biased whether they be from equipment suppliers, management consultancy companies or the Universities themselves. Thus, an independent analysis evaluating the array technologies' overall feasibility from a project developers perspective was performed. The research was performed in Australia, a country with a thriving large scale solar market. Experience and research results from Australia are further utilized to provide guidance for Norway, the country of the university publishing this Master's Thesis.

The Australian energy market is characterized by increasing wholesale electricity prices, political uncertainty regarding renewable energy targets and a strong pipeline of larger solar projects [8]. Despite Australia having the highest average solar radiation per square metre of any continent, along with some of the highest per capita uptake of residential rooftop solar, large scale solar developments have lagged behind the rest of the world [9]. The country's relatively late start with large scale solar, has been compensated for by a rapid development in the market for renewables and the entrance of international participants. The sunniest parts of the grid are now full and over 3.3 GW of cumulative large scale solar capacity is expected to be operational by 2019, with a further 17 GW of proposed projects awaiting approval (Appendix A) [8,10]. The National Energy Guarantee focuses on the delivery of reliable and affordable electricity whilst meeting emission commitments [11]. Due to the sun being an intermittent energy source, including energy storage to increase the system's reliability is becoming crucial to achieve access to grid connection and project approval [8]. Ongoing and potential solar farms are gradually including storage solutions such as batteries or pumped hydro, or being installed in combination with wind farms. Large grid connected solar projects receive subsidies in the form of Large scale Generation Certificates (LGC). However, as the supply is exceeding demand, their value is declining [8]. Generated power is either sold at the spot price electricity market or through a Power Purchase Agreement (PPA). Due to the volatility in the spot price in response to electricity supply and demand, utility providers and retailers often enter into hedging contracts to manage their risk and achieve price certainty [12]. PPAs are typically desirable, however, along with the highly competitive solar market, such agreements are now difficult to obtain and their value has decreased significantly.

Norway is characterized by less solar irradiance, lower electricity prices and over 95% electricity generated from hydro. Despite the limited incentives for investing in solar PV, an increasing interest and demand for PV deployment is now occurring.

1.2 Objective

The thesis will evaluate the potential of three array technologies, namely FT, SAT and DAT for Wesley Vale Solar Farm (WVSF), a recently approved solar PV project in Tasmania, Australia. Technical performance of the arrays will be analysed by using the simulation software PVsyst. The economic viability and key cost drivers are identified and discussed by calculating the Levelized Cost of Electricity (LCOE) and performing uncertainty analysis in @RISK. Furthermore, by identifying trends in electricity demand, commercial potential is assessed. Geographical characteristics of higher latitude locations will be determined by a continuous comparison of the WVSF (41°S) with a solar PV farm located closer to the equator, namely the Gatton Solar Research Facility (GSRF, 27°S) in Queensland, Australia. As this farm includes FT, SAT and DAT with associated real electricity generation data, it will also provide validation of the simulated electricity output predicted for WVSF. Based on technical performance and economic viability, an optimal array solution for the WVSF will be proposed.

The technical and economic performance of FT, SAT and DAT will be analysed for WVSF by addressing the following research questions:

- Which factors influence the technical suitability and the commercial potential of the different array technologies?
- How does the array technologies perform with regards to efficiency, daily and annual variations, latitude, solar irradiance and ambient temperature?
- Which values for capital and operational expenditure can be expected for the array technologies along with resulting LCOE and payback time?
- How does the fluctuating spot price on the electricity market affect the arrays' financial performance?
- How does the arrays' production profile compare with daily electricity price trends motivate investment in storage technologies such as batteries?
- What are the key cost drivers of the different array technologies?

Moreover, WVSF can be considered to have similar conditions to Norway with regards to a higher latitude and colder climate. An extrapolation of the results for WVSF will be used to evaluate the potential for large scale solar PV investment for Norway.

1.3 Research Cases

The two cases studied can be argued to represent a higher latitude, colder climate location, and a lower latitude, warmer climate location. WVSF in Tasmania (TAS) is in a temperate climate zone (41°S) and GSRF in Queensland (QLD) is subtropical (27°S). While Queensland, being closer to equator, is exposed to less seasonal variation, a greater difference is experienced in Tasmania with its longer days during summer and shorter days during winter. Despite Norway being located at a considerably higher latitude (Oslo 60°N), results obtained from Tasmania are utilized for further evaluation of large scale solar PV in Norway. The sites' location along with associated solar irradiance is indicated in Fig. 1.1 .The annual global horizontal irradiation is around 1900 kWh/m_2, 1500 kWh/m^2 and 1000 kWh/m_2 for GSRF, WVSF and Oslo, respectively.

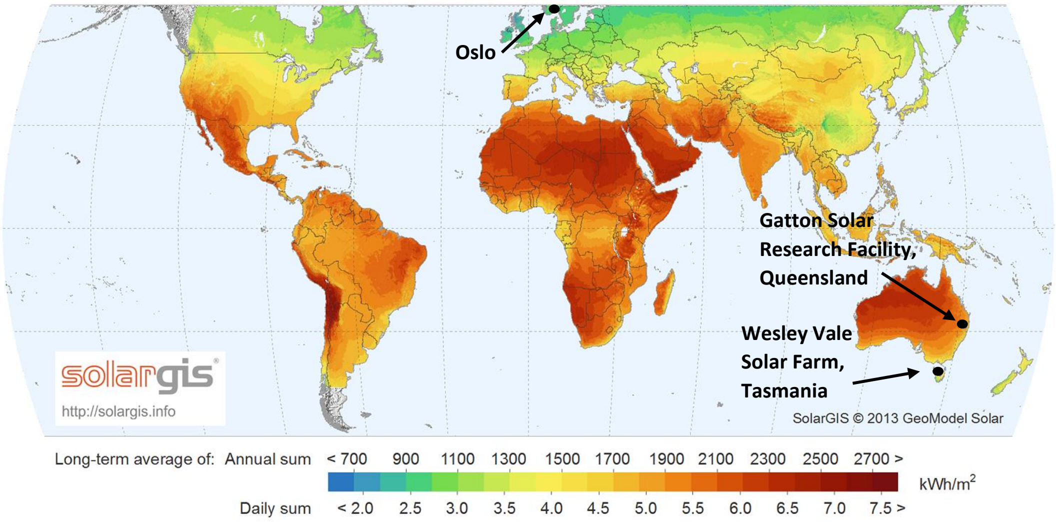


Fig. 1.1. Irradiance and location of Oslo, GSRF and WVSF [13]

Wesley Vale Solar Farm

Feasibility analysis was performed for the 12.5 MWac Wesley Vale Solar Farm, which recently received development approval [14]. A colder climate, less competition, more land and grid capacity available motivates investment in Tasmania [8]. WVSF is the second large scale solar farm to be approved in the state, the first one being a 5 MWac project. WVSF is located on the sunny northern coast of Tasmania. The land being flat and clear along with having good access to the existing road network and adjacent substation, makes it an ideal site. It will be connected through a 22 kilovolt power line to the adjacent Wesley Vale substation. It occupies an area of approximately 35 hectares. The farm will contribute to diversify the state´s energy mix alongside its hydroelectric backbone.The project's site topography is indicated in Fig. 1.2. The project is assumed to receive subsidies in the form of LGCs, which, due to policy changes, have a projected value of A$80/MWh until 2020 and an unknown value beyond this point [8]. The analysis is performed for two cases; without and with subsidies.

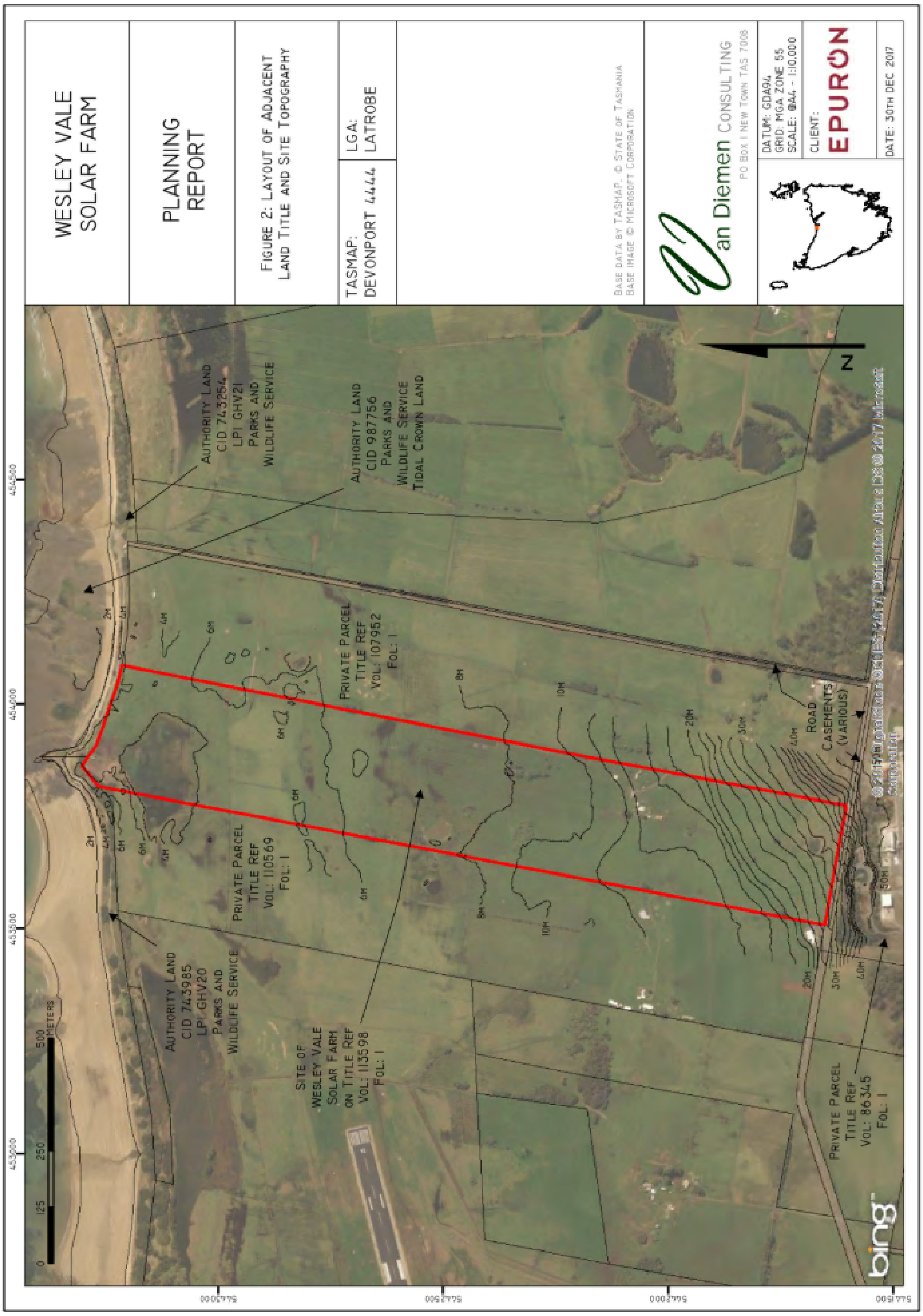


Fig. 1.2. Wesley Vale Solar Farm [15]

Gatton Solar Research Facility

Located to the west of Brisbane in Queensland, Gatton Solar Research Facility provided real generation data and cost estimates for their installed FT, SAT and DAT arrays as well as numerous publications. The full-scale testing facility was opened in Q1 2015 and comprises of the three types of array, each with identical type and number of panels and inverter (630 kWac). More precisely, three identical arrays with FT were installed, located at the top part of the farm, with the SAT array to the right and the DAT array below, as Fig. 1.3 illustrates.

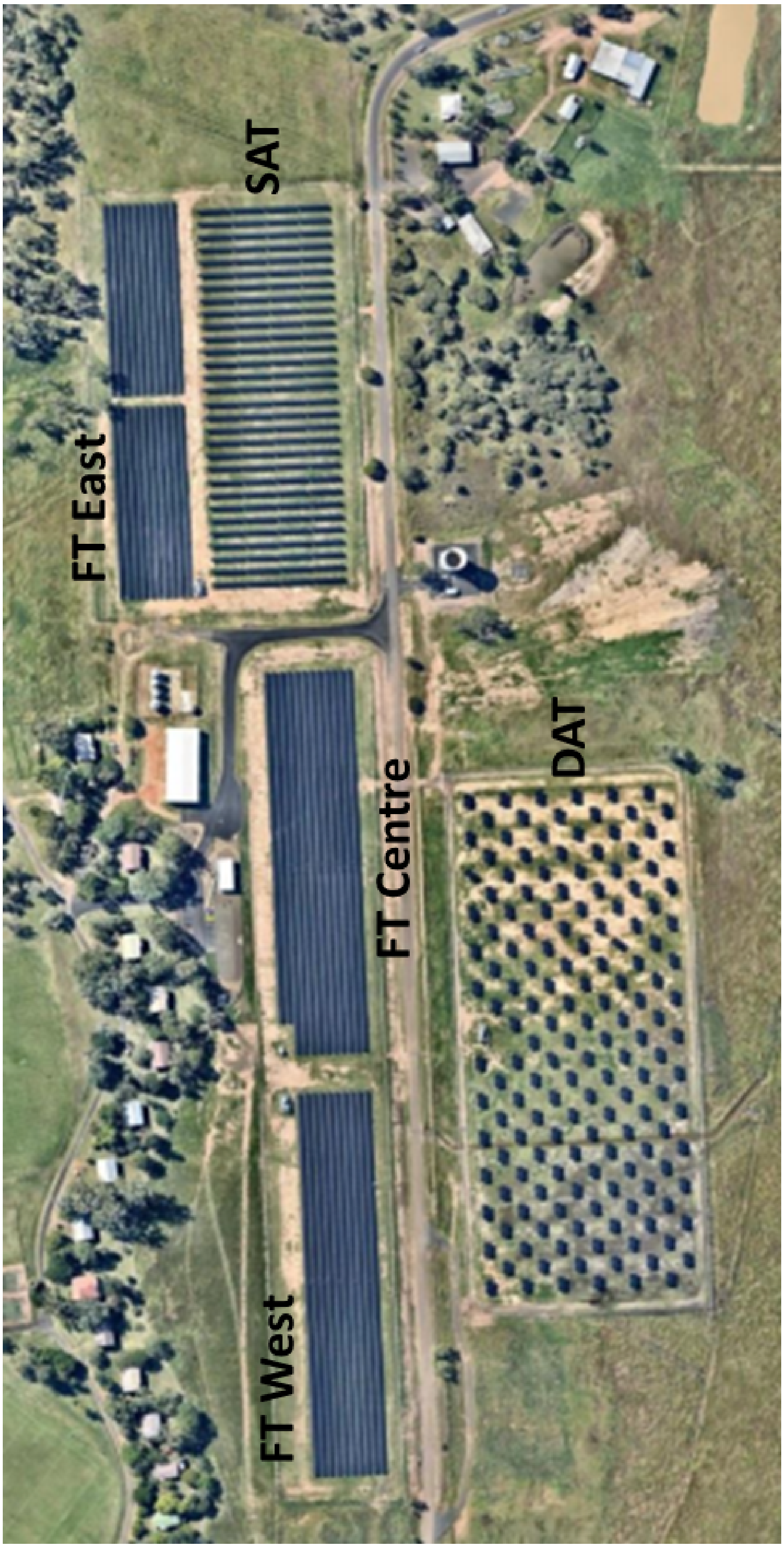


Fig. 1.3. FT, SAT and DAT arrays at GSRF [16]

Technical details for WVSF and GSRF are contained in Appendix B.

1.4 Caveats

As the thesis relies on experience from the Australian large scale solar market, which is highly competitive and relatively new, available data was limited. Especially, faults, failures and operating costs were rarely revealed. Additionally, issues not yet encountered may occur due to the solar farms' long operating lifetime. Due to confidentiality considerations, information received through private communication with industry participants has been made anonymous.

With the purpose of comparing the three array technologies' performance, factors of similar influence are typically excluded to maintain the focus on the objective. This thesis does not discuss the PV cells performance. The numerous assumptions made throughout the analysis along with the limited data the conclusions are based upon should be emphasized. The thesis is performed in a manner which shall provide assistance for a project developer.

Solar farms in Australia are typically controlled by a time clock which is programmed to make the panels follow the sun, harvesting the direct light. In cloudier regions, sensors may be included to move the panels to a horizontal position during overcast weather to optimize collection of the diffuse light. This thesis studies the first (time clock) solution.

In contrast to the real generation data from GSRF, the simulated results for WVSF and Oslo exclude non productive time and therefore are likely to provide optimistic estimations. Moreover, WVSF and Oslo are simulated using a larger tracking range for SAT than is actually used at GSRF, thereby underestimating the potential performance of SAT at the GSRF location. Anticipated downtime factors are included for the economic analysis of WVSF, while the difference in tracking range is considered to be negligible.

Australian dollars is the currency used, unless stated otherwise.

The terms radiation, irradiation and irradiance are commonly used interchangeably in the literature. In this report, irradiance is typically used to indicate the intensity of the solar resource at the locations in question. Moreover, the terms array and tracking system are used interchangeably.

1.5 Thesis Outline

Chapter 1 provides an introduction to the thesis including motivation, thesis objective and problem statement, background of the cases studied and caveats.

The general concept of a large scale, grid connected solar PV system is explained in chapter 2. First, the essential system components and their function are described. Thereafter, common performance measurements for a solar farm are defined. Lastly, faults and failures are discussed and related to Australian industry experience.

An understanding of the fundamentals of solar energy is provided in Chapter 3. The theory of solar radiation is described first. Then the apparent motion of the sun is explained, including its daily and seasonally variation in position. Lastly, the effects of the orientation of PV panels are discussed.

In chapter 4, the three array technologies are explained followed by a thorough discussion of factors influencing the suitability of their employment. Solar irradiance, latitude, weather, site conditions, investment strategy and market environment are aspects further considered.

The approach utilized for undertaking the performance analysis is described in chapter 5. After a review of the market participants assisting throughout the research, the simulation software and economic model are presented. The arrays' technical performance is assessed by utilizing the simulation software PVsyst, and the approach for employing the relevant features is described. Thereafter, the method for calculating the levelized cost of electricity is reviewed along with the Monte Carlo simulation for evaluating the arrays' associated uncertainty. GSRF, with its real data is continuously used for comparison and guidance when evaluating WVSF. An overall evaluation of the arrays' performance for WVSF is presented, resulting in a suggestion for the optimal array solution. Finally, considerations for large scale solar PV in Norway are discussed.

Results are presented and discussed in chapter 6. First the arrays' technical performance on a yearly and daily basis are evaluated. Next, the effects of diffuse irradiance and temperature are discussed. Thereafter, potential income from selling electricity at the spot market is evaluated. Moreover, trends in electricity price and demand are assessed and key cost drivers are discussed. Then, based on an overall evaluation, the optimal array solution for WVSF is suggested. Finally, an assessment for Norway identifies potential for large scale solar PV.

Chapter 7 summarises the conclusions drawn from the research.

Recommendations for further work are presented in Chapter 8. The need for quality control, the potential for a hybrid solution of solar PV with existing hydro in Norway and the opportunity for efficient system management by utilizing data analytics is outlined.

2 SOLAR PV SYSTEM

The general concept of a large scale grid connected solar PV system is explained in this chapter. Firstly, the essential system components and their function are described. Thereafter, common performance measurements for a solar farm are defined. Lastly, faults and failures are discussed and related to Australian industry experience. The theory presented is limited to considering what is relevant for the thesis objective.

2.1 System Components

A grid connected solar photovoltaic system consists of several components to properly convert, conduct, control and distribute the electricity generated, as further elaborated according to [17]. In addition to the solar modules, the Balance of System (BOS) comprises of other components necessary to achieve the desired functionality. These include mounting hardware, wiring, and inverters. Grid connected power stations also require transformers, a substation and a network connection to export the electricity generated. Furthermore, other elements such as a tracking system, weather station and monitoring are often included for larger solar PV farms. Additionally, storage solutions such as batteries may be included to stabilize the electricity grid and to increase the system's reliability. The structure of a grid connected PV system with its components is illustrated in Fig. 2.1

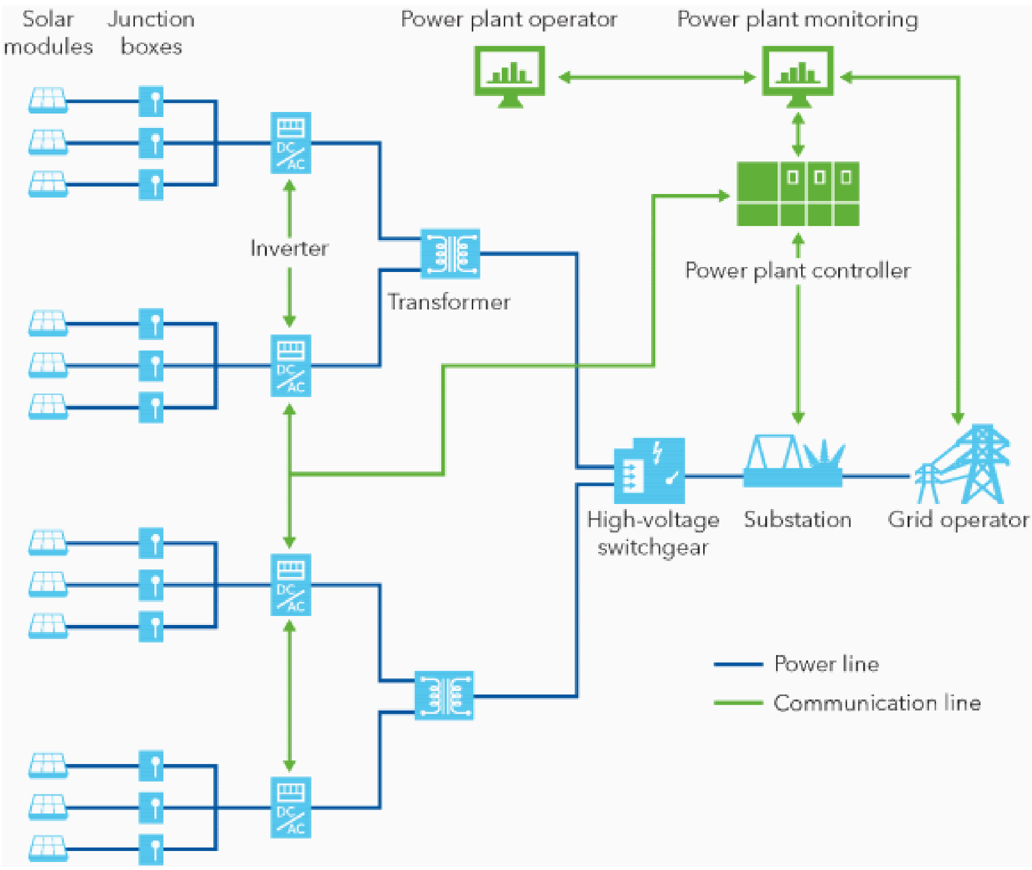


Fig. 2.1. Components of a grid connected PV system [18]

A PV array is a linked collection of solar modules, often referred to as panels, and its structure produces a specific amount of power, as further explained according to [19]. The primary element of the PV system is the solar cell. A PV module consists of multiple solar cells connected in series. While the cells carry the same current, the voltages of each cell in series are added. The number of solar cells determines the voltage from a PV module, and the current from the module depends on the size and efficiency of the solar cells. The desired voltage and power of the PV system is obtained by connecting PV modules in series, resulting in a PV string. The desired current of the PV system is achieved by connecting the strings in parallel. The output current is the sum of the currents from each individual string. The combination of PV modules connected in series and parallel gives a PV array. The structure of a PV array is illustrated in Fig. 2.2.

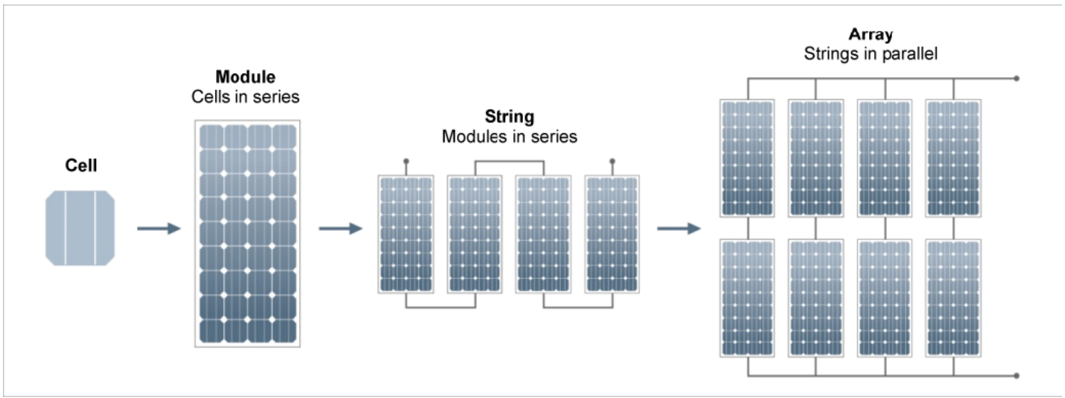


Fig. 2.2. Structure of a PV array [20]

A solar cell is an electronic device directly absorbing and converting sunlight into direct current (DC) electricity, as further explained in [21]. The light shining on the PV cell produces both a current and a voltage to generate electricity. The photovoltaic energy conversion is obtained by using a semiconducting material in the form of a p-n junction. Solar cell efficiency describes the performance of a solar cell and is defined as the fraction of incident power from the sun which is converted to electricity. The maximum theoretical efficiency in energy conversion in a single p-n junction solar cell in unconcentrated light is approximately 33.7%, known as the Shockley Queissar Efficiency Limit [22]. The University of New South Wales is in the forefront of achieving increased cell efficiencies [23].The solar cells are sealed in a laminate, protecting them from mechanical damage and preventing water or water vapour from corroding the electrical contacts. Further elaboration of the solar cells functionality can be found at [21].

As detailed by [24], the most common types of solar cells include those made of crystalline silicon and the ones utilizing thin film technology. Crystalline silicon cells are distinguished between mono- and polycrystalline cells, where the former offers the highest efficiency due to greater purity. By having an ordered crystal structure, monocrystalline exhibits a predictable and uniform behaviour, but is more expensive. Polycrystalline silicon, on the other hand, is cheaper due to simpler production techniques, but has a lower material quality due to the presence of grain boundaries. Thin film solar cells offer a greater advantage in hot climates as well as lower manufacturing and installation costs, but require a larger area. The suitability of the thin film versus monocrystalline solar cells to higher ambient temperatures becomes evident in the thesis.

The inverter is an essential device required to convert the direct current output from the solar panels to alternating current (AC) suitable for the grid connection [25]. In addition to securing that the power injected into the grid meets power quality requirements, the inverter should ensure power optimization. The importance of distinguishing between the installed array capacity (DC) and the inverter power rating (AC), referred to as the array-to-inverter ratio or DC/AC ratio, is discussed further in Section 2.3.

2.2 Performance Measurements

Common performance measurements of solar PV systems include peak power rating, specific yield or specific production, annual capacity factor and performance ratio. These indicate the amount of electricity a PV system can produce along with how well it performs. The following explanations are based on [16,26].

Power rating, [kWp]
The peak power, also referred to as the nameplate capacity, represents the size of the PV system. It is measured at Standard Testing Conditions (STC) which is an industry-wide standard indicating the performance of PV modules. The conditions specify a cell temperature of 25°C, an irradiance of 1000 W/m^2 with an air mass ratio equal to 1.5. As it is independent of location and panel orientation, it allows for a comparison of solar modules.

Specific yield, [kWh/kWp]
Specific yield, or specific production, refers to the amount of energy in kWh produced for every kWp of module capacity installed for a certain period of time. It is commonly used for comparing operating results from systems installed at different locations or with different designs and technologies. For evaluating the yield of tracking systems compared to a fixed tilt array, Equation (1) can be utilized [16].

$$Energy\ yield_{Tracking} = \frac{Production_{Tracking-} - Production_{FT}}{Production_{FT}} \quad (1)$$

Performance ratio
The performance ratio is typically used as a quality factor describing the relationship between the actual and theoretical energy outputs. It includes system losses, is independent of location and used for evaluating the long term performance of the PV system.

Capacity factor
The capacity factor represents the ratio of actual electricity produced over a given period of time to the maximum possible output over that period. Typically, it refers to the Annual Capacity Factor (ACF), and is given by Equation (2) [16]. Thus, the numerator represents the actual electricity generated, and the denominator is the system's nameplate capacity times the number of hours in a year.

$$\mathrm{ACF} = \frac{\text{Annual Production}}{8760 * \text{System Capacity}} \quad (2)$$

The importance of the system's DC/AC ratio should be emphasized. ACF is typically given using AC output. While costs are related to the installed DC capacity, revenue is determined by the AC output injected to the grid. By over dimensioning the panels, a higher ACF may be achieved, but at the expense of higher costs. Solar farms´ capacity commonly are dimensioned according to the grid connection AC limitations (e.g. GSRF), while a greater DC capacity is installed. With the low panel prices, it can be advantageous to oversize panel capacity over the inverter power rating.

2.3 Faults and Failures

Despite the fact that faults and failures experienced are typically not desired to be published, some issues occurring in Australia were revealed. Concerns over the dramatic cost reduction at the expense of module quality are present. As 78% of the global installed PV capacity has been in the field for less than five years, there is a lack of lifetime data [27].

According to private communications with Australian solar industry participants, certain faults and failures at solar PV farms have been experienced [8]. Problems related to the installation and alignment of the piles, electrical work and programming of inverters have occurred. Moreover, SAT systems have been exposed to many challenges, and issues are related to programming, failure of universal coupling joints and shading.

- Piles for the mounting system have been sinking resulting in panels falling off. This occurred as the piles were not driven or drilled in, but rather placed in an excavated hole and then backfilled.
- A farm suffered from many inverters being damaged. This was due to that the programming of the inverters not being done by qualified personnel.
- Questionable electrical work that did not meet installation codes.
- Programming issues with the tracking system have occurred, resulting in rows becoming stuck at a certain angle.
- Due to a misalignment of the piles and bearings, universal coupling joints have broken in the drive shaft. Seemingly, the bending of the bars as they go up the hill was visible.
- As the unevenness of a site was not taken into consideration, some modules were exposed to shading, as illustrated in Fig. 2.3. This issue could have been

avoided through several steps of the project development. Firstly, the unevenness of the ground could have been accounted for in the design phase by spacing the rows further apart. Secondly, the issue should have been detected and adjusted for during the construction phase. Thirdly, shading could have been avoided during the programming phase by limiting the range of tracking.

Fig. 2.3. Self shading of a SAT system [28]

A cooperation between Australian Renewable Energy Agency (ARENA) and the University of New South Wales, amongst others, initiated a project aiming to investigate PV system faults that have been experienced [29]. “Photovoltaic module and system fault analysis” presents issues reported in Australia. Despite the reported challenges seemingly mostly being from smaller PV installations, certain results are also relevant for larger scale installations. Specifically, issues related to module certification and failures of modules were reported. This is to be expected in a rapidly expanding market, with a strong focus on low capital expenditure and less experience in the long term effects of poor quality control.

DNV GL's 2017 PV Module Reliability Scorecard presents the most complete publicly available comparison of PV module reliability (at the time of writing this thesis) [27]. It addresses ageing mechanisms and failure modes by performing laboratory testing. Despite most PV projects requiring certification to ensure a minimum level of robustness and safety, it is evident that such standards are not sufficient to demonstrate PV module reliability and consistency. Quality control of all components and project phases is a critical activity for any installation and is the key to achieving high ACFs, good project economics and meeting investor expectations.

As emphasized and further detailed in [21], issues such as shading may have drastic effects as the output of a module is determined by the solar cell with the lowest output. Since the cells in a module are connected in series, the shading of a single cell can causes the current in the string of cells to reduce to the same level as what experienced by the shaded cell. Mismatch losses is a critical issue and is caused by the interconnection of solar cells or modules which are exposed to different conditions or do not have identical properties. Shading of one solar cell can cause the power being produced by the cells not being shaded to be dissipated by the lower performing cell rather than powering the load. This can cause highly localized power dissipation resulting in local heating, referred to as “hot spots”, which may cause irreversible damage. Additionally, the solar cells are sensitive to temperature and increasing temperature reduces the power output. Moreover, elevated temperatures can result in several failure modes and increase degradation rates.

3 FUNDAMENTALS OF SOLAR ENERGY

This chapter presents the fundamental theory related to solar radiation, the apparent motion of the sun and orientation of the PV panels. This is essential for the further evaluation of tilt angles and tracking systems along with the parameters affecting their performance. Potential energy harvested is determined by the solar intensity, the angle at which the incident sunlight strikes a PV module and the energy from the sun for a particular surface throughout a certain time period. First the properties of solar radiation are described along with the effects of the atmosphere and weather. Thereafter, the apparent motion of the sun is explained including daily and seasonal variations. Finally, the effect of the orientation of solar panels is discussed.

3.1 Solar Radiation

The solar radiation incident at the Earth's surface varies significantly due to atmospheric effects, latitude of the location, weather as well as the time of day and season of the year, as further elaborated below [21]. Solar radiation is commonly measured as irradiation or irradiance, referred to as energy and power (or intensity), respectively. However, the expressions are used interchangeably. Irradiation, indicates the amount of energy accumulated over a certain amount of time and is measured as kilowatt-hours per square meter (kWh/m^2). Irradiance relates to the rate of energy transfer and takes account of the sunlight at a given instance, measured as watt per square meter (W/m^2).

Atmospheric effects

The sunlight travelling through the atmosphere is exposed to absorption, reflection and scattering, see Fig. 3.1. What passes through the atmosphere without being affected, is referred to as the direct, or beam, radiation. Albedo radiation indicates the reflected sunlight. Scattering results in diffuse radiation, and is mainly determined by weather conditions. Absorption and scattering occurs due to air molecules and dust, and causes a power reduction dependent on the distance through the atmosphere. Air mass refers to the amount of atmosphere the sunlight needs to get through. A sun path with a lower sun angle will both have shorter days and the sunlight needs to travel through more atmosphere, resultantly becoming more scattered and diffuse.

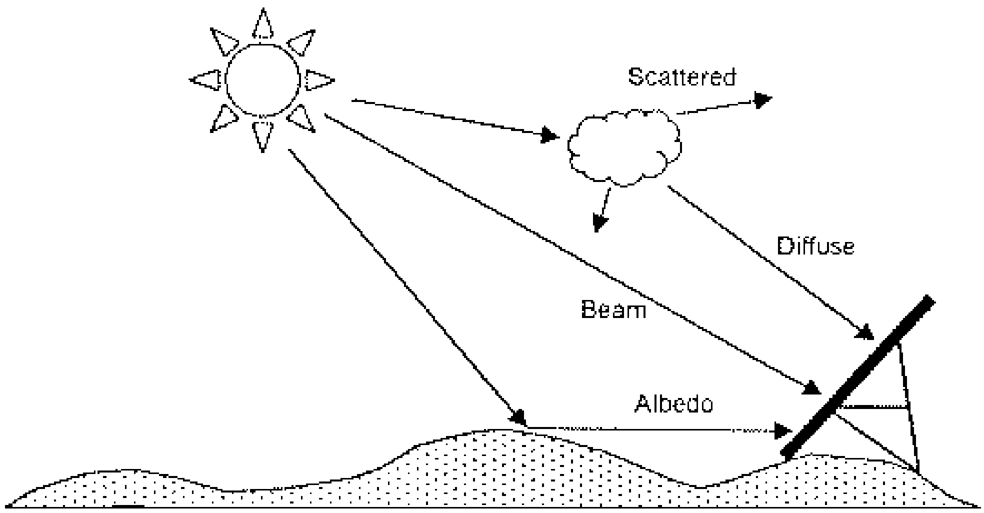


Fig. 3.1. Direct, diffuse and albedo irradiance [31]

Cloud coverage
Clouds can vary widely with location, throughout the day and seasons, and significantly influence the amount of direct and diffuse radiation reaching the Earth's surface, as further elaborated in [32]. Over 60% of the planet is covered by clouds, and clouds reflect 20-30% more sunlight. Clouds differ with latitude, and the tropics and the temperate zones are the cloudiest regions while the subtropics and polar regions experience 10-20% less clouds. However, high-latitude clouds are nearly twice as reflective as other clouds.

3.2 The Apparent Motion of the Sun

The position of the sun is determined by the location on the Earth, the season of the year and the time of the day. The rotation of the Earth causes the apparent movement of the sun, changing the angle of the direct radiation striking the Earth's surface. The presented theory is based on [21,33].

Seasonal variations in the sun's position are caused by the tilt of the Earth on its axis of rotation. This inclination is referred to as the declination angle, δ, and is currently 23.5°. The maximum angular distance between two such points is referred to as the angle between the summer and winter solstices.The equinox occurs between the solstices. As a result of the Earth orbiting the sun, the Northern/ Southern Hemisphere are oriented towards/ away from the sun during summer/winter.

When a part of the Earth is oriented towards the sun, it receives a more direct angle of sunlight and increased solar radiation. During summer the sun is higher in the sky and also for a greater time due to travelling a longer arc length, while the opposite is experienced during winter, as illustrated in Fig. 3.2. Further away from the equator this effect is accentuated, midnight sun being the extreme case. The increased seasonal impact on the sun's arc for higher latitudes is visualized in Fig. 3.3 .

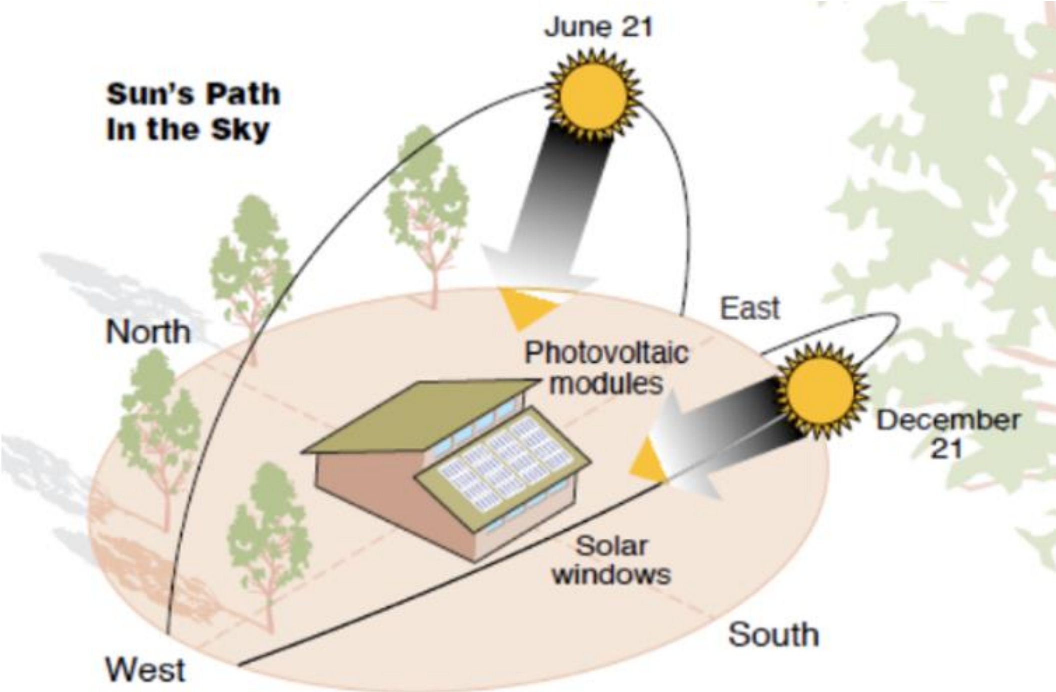


Fig. 3.2. The path of the sun during the summer and winter solstices [33]

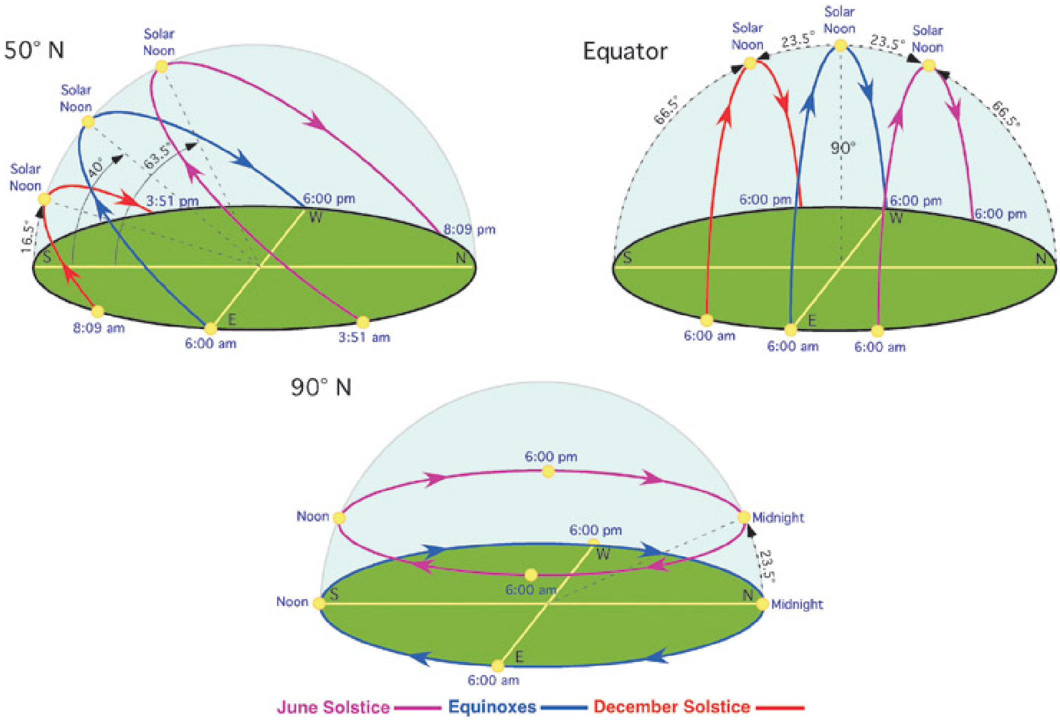


Fig. 3.3. The effect of latitude on seasonal variations [34]

The solar path for WVSF is shown in Fig. 3.4. This figures also illustrates the winter solstices and the sun's position at noon.

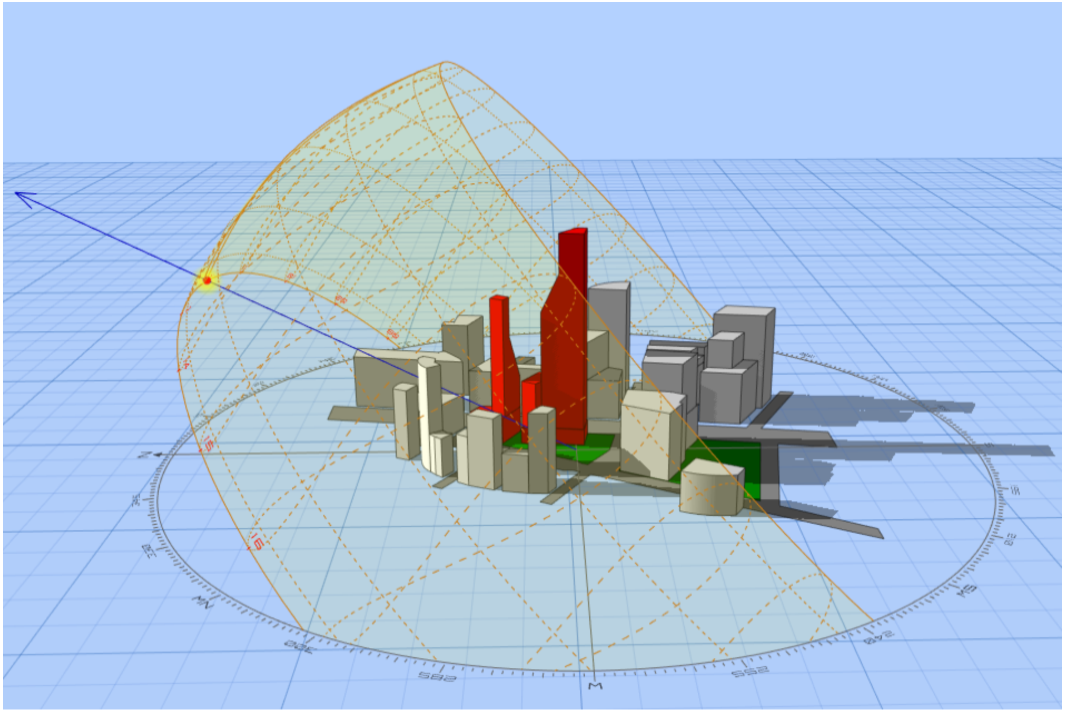


Fig. 3.4. The solar path at WVSF [35]

3.3 Orientation of the Incident Surface

The energy absorbed by a solar collector depends greatly on the angle between the sun rays and the incident surface. Generally, the optimal tilt angle of a solar panel under clear sky conditions is equal to the latitude of its location. However, depending on the ratio of direct and diffuse radiation as well as the intention of the energy harvesting, other tilt angles may be beneficial. The theory presented in this section is based on [16,21,36].

Solar angles

Fig. 3.5 relates solar angles to a PV panel. The declination angle, δ, is given as the angular position of the sun at solar noon with regards to the plane of the equator. The elevation angle (altitude angle) γ_s, is defined as the angular height of the sun measured from the horizon, while the zenith angle, θ, is defined as the angle between the sun and the vertical. This implies that the $\theta = 90° - \gamma_s$. The azimuth angle of the sun, α_s, indicates its relative direction along the horizon and varies from sunrise in the east to sunset in the west. The azimuth angle of the plane, α_p, indicates its deviation from true north/south, and the tilt angle of the panel is given by γ_p.

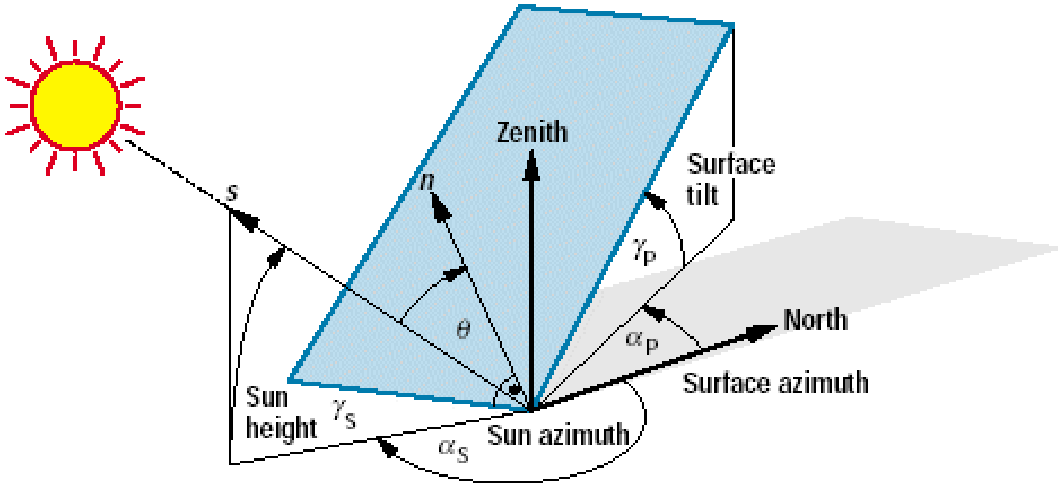


Fig. 3.5. Angles defining the position of the sun and the orientation of a tilted plane [37]

Solar intensity

When the sun is directly overhead in the sky the sun's rays are vertical and the Earth's surface will receive the maximum energy possible. However, if the sun is at an angle the sunlight is spread out over a larger horizontal surface with a lower concentration as indicated in Fig. 3.6. This effect increases the lower the sun is in the sky. The orientation of a surface is described by the zenith angle, and the solar intensity declines with increasing zenith angle. This implies that locations at lower latitudes achieves higher peak intensity. By tilting and tracking a solar panel, the effect of the the latitude with its associated zenith angle can be limited.

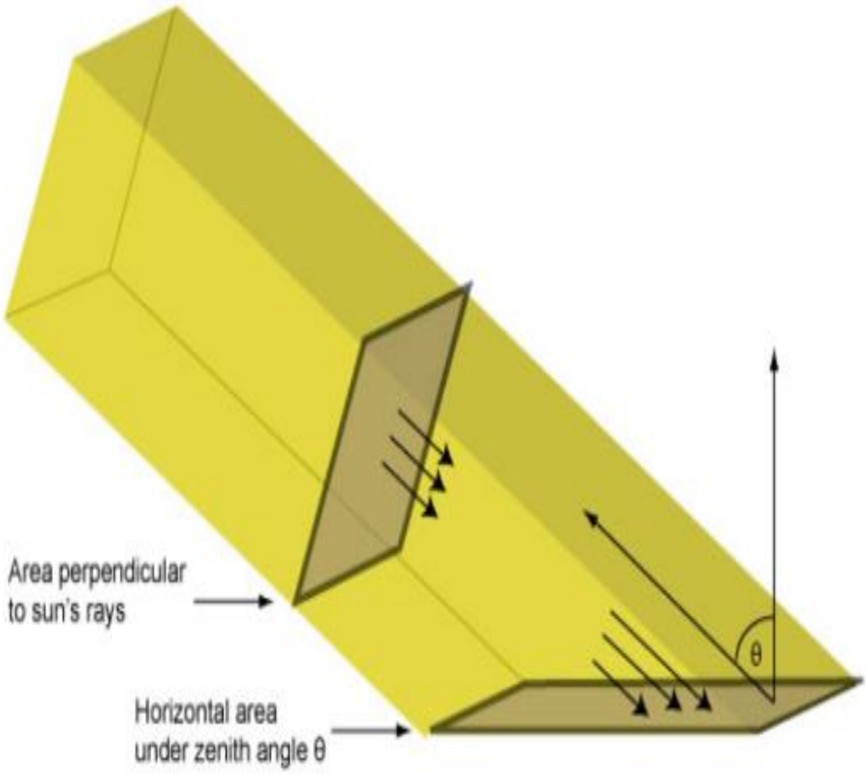


Fig. 3.6. Intensity increases with the elevation of the sun [38]

The Global Horizontal Irradiance (GHI) is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and the ground-reflected radiation. The latter is usually insignificant, and the total solar radiation is given by Equation (3) [36]. The ratio of direct radiation received on a tilted versus horizontal surface is a geometric parameter dependent on the latitude, horizontal tilt, surface azimuth and declination angle. The diffuse radiation received on a tilted surface, however, is solely determined by the diffuse radiation of the horizontal surface and the horizontal tilt angle. This assumes an isotropic distribution of the diffuse radiation over the hemisphere, and considers that the tilted surface only sees a section of the hemisphere. A tilted surface will in addition to the direct and diffuse radiation receive reflected radiation. It depends on the ground's ability to reflect, indicated by its albedo factor. The albedo factor varies from 0.1 for asphalt to 0.9 for snow.

$$GHI = DHI + DNI * \cos(\theta) \qquad (3)$$

Orientations for harvesting solar energy

By tilting a solar panel so it is perpendicular to the sun's rays, maximum intensity can be gained. For a PV panel installed with a fixed tilt, the maximum power gained over a year is generally achieved by having the tilt angle almost equal to the latitude of the location. Energy from the high winter sun and low winter sun is not collected as efficiently, however, the average yearly harvesting is maximized. The optimal tilt angle under clear sky conditions is linearly proportional with latitudes of 40°, before declining [16]. Solar panels should be facing due north in the Southern Hemisphere and due south in the Northern hemisphere.

Increasing tilt angle decreases the potential gain from diffuse radiation. Maximum diffuse radiation is gathered by laying the panels flat. Generally, for cloudier regions resulting in a larger ratio of diffuse radiation, optimal tilt angle is less than the latitude. Furthermore, if the panels are not facing due south/north, it is likely better to choose a lower tilt than the otherwise optimized tilt angle. This effect is seemingly of increased importance for higher latitudes.

Tilt angles are typically optimized for maximum annual energy production, however, the ultimate angle may vary according to seasons, weather conditions, energy demand and electricity prices. Lower tilt angles are used to gain a greater fraction of the radiation during summer (and diffuse irradiance collected), while steeper angles optimize winter generation (but reduces diffuse irradiance collected). It may be beneficial to choose a tilt angle favouring the sun's path during summer in regions where the majority of the irradiance occurs at that time.

4 TRACKING TECHNOLOGY

This chapter presents the mechanisms of the various array technologies and discusses factors influencing the suitability of their deployment. It is based on the theory previously described along with [7,39]. Moreover, observations made from solar farm visits and private communication with industry participants in Australia provide insight of issues which should be emphasized. FT, SAT and DAT are illustrated in Fig. 4.1, Fig. 4.2 and Fig. 4.3, respectively, and the parameters influencing array selection are summarized in Table 4.1.

Fig. 4.1. Fixed tilt array, Australia [28]

Fig. 4.2. Single axis tracking array, Australia [28]

Fig. 4.3. Dual axis tracking array [40]

In addition to the tracking systems' ability to increase the energy production for a given nameplate capacity, their production profile typically matches the demand load, increasing the stability of the grid as well as improving the grid utilization [8]. As SAT captures a significant amount of energy with a relatively cheap, robust and simple tracking mechanism, it is currently dominating the large scale PV market [41]. However, in Australia, the shift from FT to SAT being the preferred solution only occurred in the last two years [8]. In the U.S., the cumulative number of tracking system installations increased to 64% in 2016, while 80% of the farms developed the same year included tracking [5]. The trend is expected to continue to almost 90% of ground mounted solar to be SAT by 2021, at the expense of FT [41]. However, the ideal array solution is determined by the project environment and goals, influenced by latitude, solar irradiance, weather, site conditions as well as available area and grid capacity [41].

4.1 Array Technologies

Fixed tilt

Fixed mounted solar arrays are stationary systems installed with a tilt angle. They are typically configured in rows with the axis in east/west alignment, with the panels facing south or north, and with a tilt angle approximately equal to local latitude. This technology is commonly utilized for residential and commercial scale applications, as well as traditional larger scale farms. Typically, FT is advantageous in high latitude regions where tilting towards north or south is the most effective way of harvesting the solar energy.

Single axis tracking

SAT follows the sun throughout the day, tracking from east to west. This tracking mechanism rotates around one axis, offering one degree of freedom. Being structurally more rigid, faults and failures are less likely to occur than with a DAT. Variants of SAT include horizontal single axis tracking, tilted single axis tracking, vertical single axis tracking and polar single axis tracking. Horizontal axis tracking is dominating the large scale solar PV market and is considered further in this thesis. It is referred to as SAT. It should be noted that the tilted version may perform better at higher latitudes, however, due to limited real generation data and cost estimates, it is excluded from the analysis. SAT is especially suitable closer to the equator, where the seasonal variation of the sun's path has a lower impact upon direct irradiance as oppose to higher latitudes. One weakness of the SAT system is that it typically uses a long shaft to drive many panels at the same time. If the supports for the shaft come out of alignment then failure of the row can occur.

Dual axis tracking

By maintaining perfect perpendicular orientation of the solar panels to the sun throughout the day and year, dual axis tracking achieves maximum exposure of direct irradiance. Having two axes of orientation, it can adjust according to the seasonal variation of the sun's path. The additional complexity makes DAT more expensive and historically associated with more faults resulting in it being utilized less. As the DAT's are mounted with only one pole into the ground and have a stow level height of around 3-4 meters, the surrounding land is available for agriculture and animal farming with easy vegetation management, resulting in efficient land utilization [40]. DAT can become more advantageous in higher latitudes with greater seasonal variations, especially during summer [42].

4.2 Factors Influencing Array Type Selection

Factors determining the suitability of the array technologies are further evaluated below, independently from the influence of other parameters. Broadly, these can be structured into the following categories: location; weather; site conditions; investment strategy and market environment. If not specified otherwise, DAT is typically a more extreme case of SAT. Moreover, factors are generally evaluated based on maximising annual energy harvested, unless otherwise is indicated. Factors considered to be of most interest are summarized in Table 4.1.

Table 4.1. Factors influencing the suitability of the arrays

	FT	SAT	DAT
Irradiance	Diffuse	Direct	Direct
Latitude	Higher	Lower	Higher
Weather	Overcast	Sunny	Sunny as well as snowy environments
Site conditions	Capable of challenging geotechnical conditions and site topography	Requires more flat and even ground	Appropriate for combining with farming and agriculture as well as difficult terrain
Project size	Smaller as well as larger	Larger	Smaller as well as larger
Reliability	Most reliable	Some faults/failures	Most faults/failures
Capital exposure	Least	Middle	Highest
Objective	Maximise peak capacity per area	Favour higher energy yield and grid utilization rate	Maximize energy yield and grid utilization rate

4.2.1 Location

Solar irradiance

Global irradiance is the most important factor for determining potential energy yield [16]. It is split into direct and diffuse irradiance and understanding the contributions is of great importance. Typically, panels are installed to harvest energy from the direct irradiance and energy absorbed increases with the alignment of panels and the sun rays. Thus, energy harvested from direct irradiance increases with the complexity of the tracking system, favouring DAT. However, if the proportion of diffuse irradiance is significant, panels lying flat are advantageous, thereby favouring FT. As a result, the potential gain increases with tracking ability in sunny locations with direct irradiance, while overcast locations, with a larger ratio of diffuse irradiance, favour fixed, horizontal lying panels.

Latitude

The seasonal variation of the sun’s path and position is the same over the planet, but the effect of that variation is greater further away from the equator as irradiance is related to the cosine of the latitude. Closer to the equator, with minor seasonal variations, SAT is preferable, with its ability to track throughout the day. At higher latitudes the effect of seasonal variations is greater and DAT is more desirable.

4.2.2 Weather

Clouds

While a clear sky favours more advanced tracking solutions, horizontal FT panels are preferable during heavy overcast weather dominated by diffuse sunlight. In fact, tracking may be counterproductive on overcast days, even resulting in less electricity produced [44]. The ratio of diffuse irradiance increases with cloud coverage, favouring flat lying panels. For systems utilizing tracking based on sensors measuring sunlight, maximum energy would be harvested with a DAT system which adjusts to a horizontal position when clouds occur.

Wind

Wind has been one of the most frequent causes of damage to the solar arrays and calculating wind load is of great importance for both stationary and tracking arrays, as further discussed based on [43]. The wind load's effect on FT systems is mainly dependent on tilt angle and row spacing, while wind dynamic effects are of greater influence for tracking systems. Dampeners or a torsion limiters are necessary to prevent the wind from making the arrays oscillate and perhaps hit resonance. As the outer edges of a field are typically more intensely affected by the wind, outer rows are typically built stiffer and stronger.

Traditionally, sites exposed to greater wind loads have favoured stationary arrays, or SAT if tracking is desirable. However, suppliers of both SAT and DAT, have expressed their products´ competitive capabilities of handling wind loads. Apparently, wind loads are now less of a constraint as SAT suppliers have strengthened their tracking systems and offer a "cyclonic" version of their products [8] as well as the capability for fast stowing speeds to avoid micro bursts.

Although tracking systems may withstand higher wind speeds by adjusting to a (horizontal) stowing position, this can affect output as the modules would not be at the preferred angle. In areas often exposed to such wind loads, tracking solutions may be an excessive investment. Indeed, high wind speeds determined the decision for selecting FT for a farm in Queensland (Australia) which otherwise would have favoured SAT [8].

Snow

As further elaborated in [44 ,45], snow induces issues such as covered panels, snow build-up on the ground and load exposure, while surrounding snow covered area increases production due to the additional reflected irradiance. In snowy environments, the taller DAT system can be argued to be most appropriate as it facilitates for shedding of snow, and faster melting as well as gaining most of the reflected sunlight.

The amount of electricity a panel generates depends on the amount of light able to reach it. While a dusting of snow has less impact as light can forward scatter through a sparse coating, panels are prevented from producing electricity when heavy snow accumulates. Moreover, the weight of the snow may increase stresses on the system's support structure as well as the tracking system. On the other hand, as dirt particles on the modules bond with the snow, the panels will be cleaned when the sun melts the snow and ice. Furthermore, surrounding snow coverage can significantly increase electricity generation by increasing the reflected sunlight. Due to the snow's high albedo factor, the ratio of reflected irradiance may be of importance and should be considered. The gain achieved from reflected sunlight in snow covered surroundings is found to increase with the advancement of tracking technology [44].

Snow can be an issue for FT as it can build up and higher tilt angles are required to shed it. The snow should slide off at a 30° tilt angle [46] and in the areas where snow is likely to be an issue the angle should be at least this. More of an issue is if the snow has somewhere to fall off to or if it will just build up on the lower edge causing shading. Tracking systems orient the panels in the morning, encouraging snow to slide off. As DAT continuously orient the panels towards the sun, ice and snow melt faster. Additionally, DAT systems may be preferable as they are tall enough to avoid any impedance of the system's function, both with regards to its movement and snow build-up [47].

Soiling
According to [16], soiling decreases with the advancement of tracking, thereby favouring DAT. The possibility to be able to clean the panels, without damaging them, is an important design consideration.

4.2.3 Site conditions

With limited ideal sites available for solar farms, an increasing number of projects are being developed on more challenging terrain, where fixed arrays or hybrid solutions may be advantageous. Unfavourable geotechnical conditions, irregular boundaries or obstructions, rolling terrain and steep slopes are factors favouring fixed tilt. This section will further discuss such considerations, based on [39,41].

Site topography
FT mountings are better suited for adjusting to undulating terrain by offering improved terrain-following capabilities compared to SAT. While SAT typically requires a slope less than 10% in the north/south direction, FT can accommodate for more variation and handle up to 20% slopes in the east/west direction [7]. However, the tracker slope tolerance has improved throughout the last years [8]. Of the different types of SAT trackers on the market, the distributed solution offers the most flexibility and is preferable for such sites. While SAT typically requires an area suitable for a long span of panels, FT provides the option of shorter rows thereby achieving a smooth row transition despite an uneven site. DAT with its mounting structure can also be suitable for smaller arrays as well as larger sites and is ideal for difficult terrain [40] .

A sloping hill may be considered as an opportunity rather than a problem as it facilitates for "natural" tracking. As illustrated in Fig. 4.1, FT arrays were mounted on a north facing hill sloping in both east and west direction. As a result, this farm could achieve similar characteristics as a flat site installed with tracking.

Foundations
While SAT´s foundation design still has its limitations, FT simplifies installation even in unpredictable and unfavourable soil conditions. Along with the trend of larger projects developed on less ideal sites, the chance of dealing with complex geotechnical conditions greatly increases. Furthermore, as the supporting piles are exposed to additional loads with trackers, the piles need to be larger and installed deeper.

One avenue to explore further is the use of small pneumatic air hammer rigs that are typically used for water or energy wells [48]. These drill the steel pile into the ground and are less effected by loose soils and rocks. They are quick, cost effective and easy to move around. Furthermore, they require no site preparation and can drill at an angle. In cold climates, installing the foundation pile below frost is important otherwise they can gradually move upwards, ultimately becoming unstable and definitely causing alignment problems with SAT.

Area
Generally, tracking systems require a larger area to avoid shading for a certain installed capacity. The area required increases with higher latitudes due to the lower winter sun angles. The Ground Covering Ratio (GCR) implies the ratio of PV module surface over the installation surface [6]. To harvest the full benefit of trackers, lower GCR and a larger area is necessary. Fig. 1.3 provides an indication of the additional required area for the tracking technologies. For this site, the area required drastically increased along with the complexity of tracking system.

Shading
Avoiding shading is of great importance and should be carefully assessed, especially for tracking systems [26]. Considerations regarding shading are simpler for a FT system. The area required for ensuring that shading will not occur increases with the advancement of tracking. It should be emphasized how an uneven site needs to account for the slope in the design phase. In addition to self-shading due to neighbouring rows, shading from surrounding obstacles like trees and mountains must also be considered. Backtracking can be employed to minimize self-shading and remove electrical shading losses due to mismatch by ensuring a uniform irradiance on the PV modules (further described in [26]).

4.2.4 Investment strategy

Objective
The optimal array solution and tilt angle is determined by the objective of the PV system. The PV installation may be designed with the intention of fulfilling one or more of the following:

- Match power demand
- Generate during peak electricity prices
- Favour generation during certain seasons or time of the day
- Complement other energy sources
- Facilitate for harvesting the direct, diffuse or albedo irradiance

.

Depending on the electricity demand, the optimal array solution may differ from what would maximize annual production and rather accommodate for production during certain times of the day or year. If it is desirable to supply the morning and afternoon demand, SAT or DAT is advantageous. Higher latitudes where FT is installed may rather tilt the panels closer to the summer equinox as the sun is around for considerably more hours than during winter. On the other hand, there may be greater demand and higher prices during winter due to heating requirements, thus favouring an alternative tilt angle suited for the winter.

Project size
As EPC contractors tend to favour simpler construction options for smaller projects, FT may be preferable for such farms [8].

Costs
Total costs include costs related to equipment, installation, land and operating and maintenance (O&M), all increasing with advancement in tracking systems due to their complexity and dynamics. The investment decision depends on its objective; maximising the projects peak capacity or its yield, i.e. installing a larger quantity of PV panels or including tracking. Both land area required and energy yield increases with the advancement of tracking technology. For a given area, a larger peak capacity is achieved with FT. However, for a certain number of panels, i.e. same peak capacity, more MW hours can be generated with tracking. As a result, the desirable array solution depends on the investment objective. Importantly, prices of SAT are also dropping significantly [39], and it can be expected that DAT will follow this trend.

Reliability
Despite the advancements in technology of the mechanics and electronics, fixed arrays are still considered as more reliable. New markets are more likely to begin with FT before maturing enough to employ tracker systems [8]. Being a dynamic mechanical system, tracking includes components prone to wear and fatigue. Good designs are needed for ease of maintenance and replacement of parts. FT arrays eliminate such issues and should be used if the priority is zero maintenance. Minimizing the need for human interference and associated labour costs are often prioritized [8]. Especially in remote locations, avoiding faults and failures can become of great importance.

Distance from load demand and infrastructure
Selecting a site in close proximity to the electricity grid, with strong transmission infrastructure and transport links is desirable [8]. As losses associated with distribution and transmission are significant, it is also preferable to be located closer to the electricity demand. Choosing a site closer to existing infrastructure can reduce costs considerably. For instance, this was likely a determining factor for a farm in Australia which was built in conjunction with an existing wind farm, exploiting its substation. The site next to the substation was likely chosen despite not being flat, because the advantages of the close proximity outweighed the disadvantages of not having tracking.

Bankability
From a financier's viewpoint, projects installing FT arrays are regarded as more reliable and therefore easier to get financed. In risk-averse markets where low costs and reliability are prioritized, FT may be preferable.

4.2.5 Market environment

Grid constraints
As project size often is limited by available grid connection capacity, trackers allow for increased production without exceeding the grid constraints [42]. Approval for connecting to the grid is an increasingly challenging issue for the implementation of solar projects in Australia [8]. Generally, electrical grid stability improves with more regular power supply, thus the trackers ability to match the grid energy load profile by also feeding the grid during morning and evening is beneficial. Furthermore, in addition to increasing the stability of the grid, tracking achieves a higher grid utilization rate.

Electricity spot prices
Depending on the market environment, electricity prices can vary significantly, creating incentives for selling electricity during peak demand periods. Tracking, with its ability to produce during morning and evening, may add value if electricity prices are higher at these times. General demand and price variations are predictable on a daily basis but It should be noted how the market can be unpredictable and even have a negative price making it favourable for generators to shut off their supply at that time [8]. Furthermore, the spot market is heavily influenced by network failures and outages which occur with no warning [8].

Storage and microgrid solutions
Tilt angles and tracking solutions may be optimized in accordance to an integrated microgrid solution. As solar PV farms are increasingly being built in conjunction with wind farms, adjusting the energy generated from solar PV to complement the wind's intermittent results in increased regularity. Alternatively, the solar farm can be installed to be aligned with a (pumped) hydro power station's generation pattern.

The optimal size and ratio, as well as when to supply the grid versus charge an integrated battery, is a highly discussed topic [8]. Simplified, tracking solutions would generate electricity for a larger portion of the day and reduce the battery capacity required as compared to the same capacity installed with FT. Furthermore the number of battery cycles for a given load is reduced [42].

5 METHODOLOGY

This chapter details the approach used for evaluating the performance of the three array technologies. The analysis was performed for the Wesley Vale Solar Farm (WVSF) in Tasmania, but the method used is described on a general basis and is applicable, for example, for Norway. The thesis relies on experience from the Australian solar PV market and private communication with industry participants. The Gatton Solar Research Facility (GSRF) in Queensland which has installed FT, SAT and DAT provided real data. It has been utilized for reference and guidance by evaluating its results in parallel with the assessment of WVSF. Furthermore, its comparison with WVSF highlights the properties of higher and lower latitude locations as well as simulated versus real data. The simulation software PVsyst was employed for estimating electricity generation and analysing the arrays' technical performance for WVSF. Thereafter, an economic analysis including Levelized Cost of Electricity was performed for the project. The suitability of the various array technologies was evaluated by including revenue streams from electricity sold at the spot market for both GSRF and WVSF. Electricity data including recommended retail price and demand was provided by the National Electricity Market. By detecting trends in electricity demand for the states in question, income potential for the different array solutions were evaluated. These trends were collated with weather from the Australian Government Bureau of Meteorology. Finally, the key cost drivers were identified by performing an uncertainty analysis using @RISK. The results were used to propose an optimal array solution for WVSF. Additionally, the results for WVSF were extrapolated to provide comparisons for Norway.

5.1 Australian Industry Experience

An understanding of the Australian solar PV market was achieved by:

- Establishing a comprehensive network throughout the whole value chain including investment, EPC (Engineering, Procurement and Construction) contracting, certification, manufacturing, operating, retailing, as well as governmental, consultancy and academia. Industry participants include PwC, Rystad Energy, DNV GL, Epuron, First Solar, Jinko Solar, NEXTracker, ArrayTechnologies, Signal Energy, AGL, Impact Investment Group, DIF, University of New South Wales and Australia Energy Market Operator (AEMO).
- Continuous dialogue and cross checking of facts and statements.
- Visiting operating large scale solar farms with fixed tilt arrays and single axis tracking.
- Attending commercial conferences and events.

The data collection phase was performed in Australia, at the DNV GL office in Sydney with support from their energy department in Melbourne.

5.2 Data Sources and Data Processing

Electricity data

The Australian National Energy Market (NEM) is a wholesale electricity market where generators sell electricity and retailers buy to resell to consumers, as further described in accordance with [49]. Generators offer to supply electricity at particular volumes and prices at set times. Due to the numerous generators and retailers participating, it is a highly competitive market. The NEM operates one of the longest interconnected power systems in the world, spanning from Australia's eastern coast to the south-eastern coast. The interconnected states consist of five price regions, namely Queensland, New South Wales and Australian Capital Territory, South Australia, Victoria and Tasmania. The electricity market works as a spot market determined by power supply and demand. The electricity production and consumption are matched instantaneously in real time. Based on the demand for electricity and supply from generators and their bid price, a dispatch price is determined every five minutes. Six dispatched prices are averaged every half hour to give the associated spot price. Thereafter, the spot price for each NEM region is determined every half hour, and this price is used for settling the financial transactions for all electricity traded in the NEM. As the wholesale market operates around the spot market, the spot price is an important indicator for investors.

NEM provides electricity data, including recommended retail price (RRP) and demand for each State on a half hourly basis. Data sets were downloaded for each month by State for 2015-2017 and then combined for each year to get an overall impression of Australia's electricity trends. Data sets for 2016 and 2017 for Tasmania and Queensland were utilized for further assessment. It should be noted how the electricity prices appear to be higher for 2017 than 2016. Apparently, this was a result of closure of coal fired power stations and infrastructure challenges [50].

Weather data

Maximum daily temperature and daily solar irradiance data were provided by the Australian Government run Bureau of Meteorology (BOM). For simulations of WVSF with PVsyst, the software used its internal links to a commercial data base, however, results were spot checked against historical data from BOM. GSRF was evaluated in accordance to weather for 2016 and 2017 from BOM. To ensure that the two years being studied (2016/7) were representative, weather trends from 1997-2017 were analysed (Appendix C).

Data processing

Electricity and weather data was available for download at the homepage of NEM and BOM, [51] and [52] respectively. Values from NEM are provided on a half hourly basis while BOM are on an daily basis. The data from NEM was processed in Microsoft Excel to be compatible with the generation values for WVSF and GSRF. As these sources had a different time base than GSRF (per minute) and PVsyst (per hour), the VLOOKUP function in Microsoft Excel permitted the data to be combined for detailed analysis and comparison. Furthermore, by performing a running average of the half-hourly spot prices, revenue was calculated.

Appendix D illustrates the format of the data collected for this study from the three sources (NEM, BOM and GSRF).

5.3 Gatton Solar Research Facility

Real data and cost estimates from GSRF for the three array technologies were used for guidance, reference and comparison throughout the report. The GSRF website permits download of power output and cumulative energy per minute on an annual basis for each array system [53]. Data for 2016 and 2017 was utilized as these were complete annual files with data reported from 05-19 hrs each day. The generation output from the real data was compared by making spot checks throughout a year against estimations from PVsyst. Weather data for the site was provided by BOM and used to identify the correlation between PV module efficiency, irradiance and temperature.

The full-scale testing facility comprises of the three types of array, each with identical type and number of panels and inverter. Thin film PV modules are used along with central inverters. Each array has a total DC power rating of 684 kWp. The inverters here have been specified to 630 kWac due limitations with access to the grid. The FT is installed with a 20° tilt angle. The SAT tracks from +/- 45° and being of the horizontal type, has zero tilt. The DAT has a slewing motion of 340° and +/- 90° tilt. Technical specifications and site data can be found in Appendix B.

5.4 Performance Analysis by Simulation in PVsyst

PVsyst is a commercial software for the design, simulation and data analysis of PV systems. It is a commonly used design and simulation tool used in the industry, offering a complete assessment of a PV system using hourly simulations. The input features utilized for this research included the selection of meteorological data, array technology, system design and the determination of losses. The results from each simulation are presented in a report. Additionally, comprehensive data analysis for a broad range of parameters can be performed. Further information about PVsyst and its features is available on their web page [26]. Version 6.7.2 of PVsyst was used for this thesis. The technical specifications for Wesley Vale Solar Farm can be found in Appendix B.

The primary purpose of the study was to compare the three array technologies and hence the assessment was limited to features considered to be relevant. The program component *Project Design* offers PV systems for grid connected systems and this was used for WVSF. Mandatory input parameters included meteorological data for the site, *Orientation, System* and *Detailed Losses*. Weather data for Wesley Vale was imported from Meteonorm 7.1, provided through *Meteo Database*. An albedo value of 0.2 was set together with an assumed annual soiling loss factor of 1.8%. WVSF was not expected to be affected by shading from surrounding obstacles [15]. Further design parameters were set to default values.

The *Orientation* module enables specifications for the various array technologies to be defined. The relevant parameters for WVSF are contained in Table 5.1. An optimal tilt angle of 35° was concluded upon for the FT array. This was determined by using the feature *Advanced Simulation* which offers an optimization tool (it was set to maximise annual production). The SAT array was defined to have a tracker rotation range from -60° to + 60° as specified in WVSF's Development Application [15]. Being a horizontal array, its tilt angle is 0°. For the design of the DAT array, the same technical aspects were used as for GSRF. A 340° slewing motions facilitates for tracking throughout the day, while a 180° range for the tilt angle allows for seasonal adjustments. Despite the site facing 11° east of true north, an azimuth angle of 0° was used, i.e. the panels are aligned with true north. The reduction in annual production resulting from this azimuth angle proved to be minimal (<0.25%).

Table 5.1. Technical specifications WVSF

Mean Values	Capex MA$	Opex MA$ p.a.	LCOE A$/kWh	Payback years	NPV MA$	IIR %	RRP A$/MWh
No Subsidies							
FT	21.8	0.249	0.083	12.5	1.55	0.057	87.73
SAT	24.9	0.323	0.083	12.5	1.76	0.057	86.98
DAT	40.8	0.41	0.118	21.6	-11.9	0.017	87.37
80 A$/MWh subsidy							
FT	21.8	0.249	0.083	5.6	26	0.158	167.73
SAT	24.9	0.323	0.083	5.5	30.4	0.161	166.98
DAT	40.8	0.410	0.118	8.6	19.7	0.097	167.37

The *System* configuration includes sizing of the project, the selection of components and design of the array. The size of the project can be entered as planned power output or available area. The former was used for this study, designing for a system with 15.6 MWdc capacity of the panels and a 12.5 MWac capacity of the inverters. Such under sizing of the inverter power is common (e.g. GSRF) due to the limited access to grid capacity along with that losses and non-optimal weather reduces the actual output from the panels. The idea is that it is accepted that on some days the output will be capped, but that the inverter quota will be filled as much as possible. System components were imported from the *Components Database* and all three arrays employed the same products; Jinko Solar's monocrystalline modules (JKM 360M-72-V (360W) modules) and five SMA Sunny Central 2500-EV inverters. It should be noted that the limit overload loss for design had to be increased from 3% to 3.2% for using the same design parameters for DAT as the other arrays.

In addition to the results provided in *Report*, data analysis was performed using *Detailed Results*. This permitted performance evaluation of the array technologies along with an assessment of the effects of temperature and the ratio of diffuse irradiation at the site. Hourly production data were generated by using *Advanced Simulation*. Values were exported from PVsyst to Microsoft Excel for further data processing and manipulation. The relative increase in annual production for the tracking systems compared to the FT was calculated by Equation (1).

5.5 Economic Analysis by Levelized Cost of Electricity

The levelized cost of energy, or electricity, (LCOE) is an economic measure allowing for the comparison of different energy generating technologies on a consistent basis [54, 55]. It is used as a common measure for evaluating PV systems and accounts for the cost throughout its lifetime, including the installation process, operational stability as well as generation efficiency. By performing a net present value (NPV) calculation, the price that the energy must be sold for to make the project break even, is determined. Both the costs throughout the lifespan and energy generated, regarded as revenue streams, are brought back to the present value. Due to its standardized nature, LCOE has limitations such as the effect of market factors. The LCOE for solar PV is expressed as the total lifetime cost divided by the total lifetime output, given by Equation (4).

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}} \qquad (4)$$

- I_t : Investment expenditures in the year t
- M_t : Operations and maintenance expenditures in the year t
- E_t : Energy generated in the year t
- d: Discount rate
- n: Expected lifetime of power system

It should be noted that the NPV method penalizes projects with high initial capex and also projects where the total income is spread over decades, i.e. it is a bit short sighted. Once the investment has been made, the focus switches to cash flow, loan repayment and opex reduction (the sun is free as compared to fossil fuels). So low capex, higher opex solutions, favoured by NPV analysis can be less interesting with a project life of several decades. Moreover, the opportunity cost, social economic benefits and the potential for increasing project value by selling electricity at the spot market are not considered. This becomes evident throughout the analysis.

5.5.1 Model assumptions and estimates for WVSF

A simplified LCOE was calculated with the purpose of quantifying the difference in economic viability of the three array technologies for WVSF. It relied heavily on assumptions of costs, distinguished between capital and operational expenditures (capex and opex), and annual capacity factor. Due to limitations in available cost data, especially for DAT systems, values employed were based upon the sources considered to be the most reliable and relevant, namely the National Renewable Energy Laboratory (NREL) [5] Rystad Energy [56,57] and GSRF [16,58]. SERA, a Rystad Energy company delivering high quality data analysis of the Australian renewable sector, possess the latest information on the country's market trends. NRLE recently published "U.S. Solar Photovoltaic System Cost Benchmark: Q12017". Despite the report being based on U.S.

conditions, similar price trends are considered to be applicable for this research. As GSRF is the only source found to contain cost estimates for all three arrays under identical circumstances, it is further utilized. Thus, assessments for WVSF were based upon capex and opex costs from [56,58] adjusted for price trends given by [5,57]. The uncertainty related to the model should be emphasized.

As further elaborated in Appendix E, the rapidly decreasing costs along with economies of scale are important to emphasize. Fig. 5.1 illustrates the decline in benchmarked expenditures for utility scale PV, from 2010 to 2017 reported by NREL. This includes price of modules, inverters, hardware BOS and soft costs. A constant decline of 22% per year was assumed over the period further assessed (2016-2018). Moreover, [57] reveals a drop from last year's EPC prices of over 30.3%. A similar reduction for NSW is somewhat lower, being estimated at 18.8%. For Tasmania, currently being a less competitive market, a lower reduction in capex was assumed to have occurred and is set to 15% per year. Fig. 5.2 indicates that the opex has been consistent from 2015 to 2017 and is assumed to be so for 2018 also [5]. Furthermore, an increase in project size from 10 MW to 100 MW, reduces capex with 19% [5].

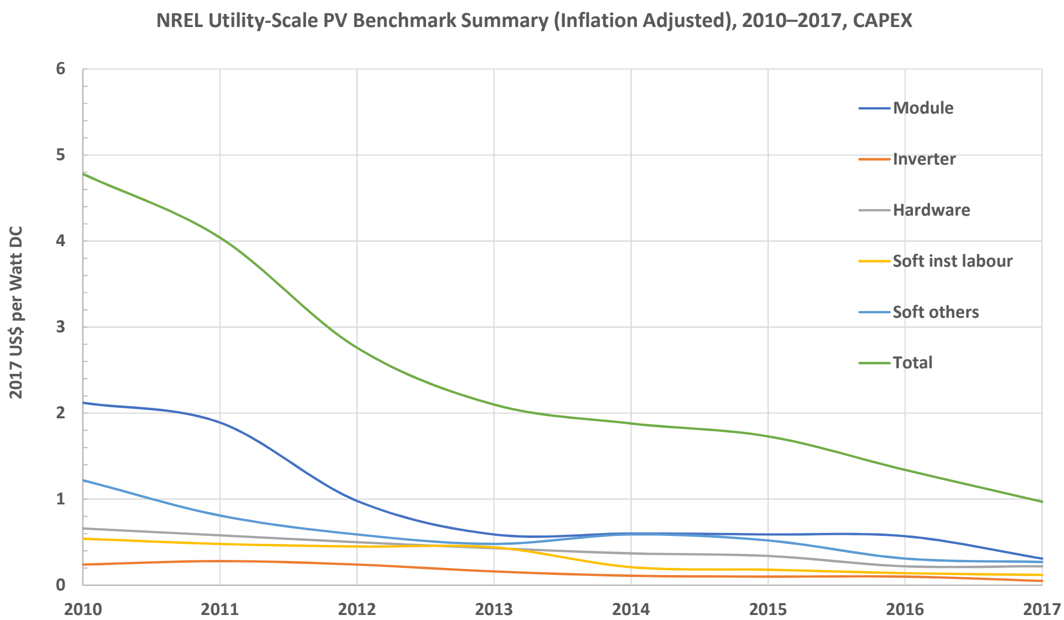


Fig. 5.1. Decline in capital expenditures, 2010-2017 [5]

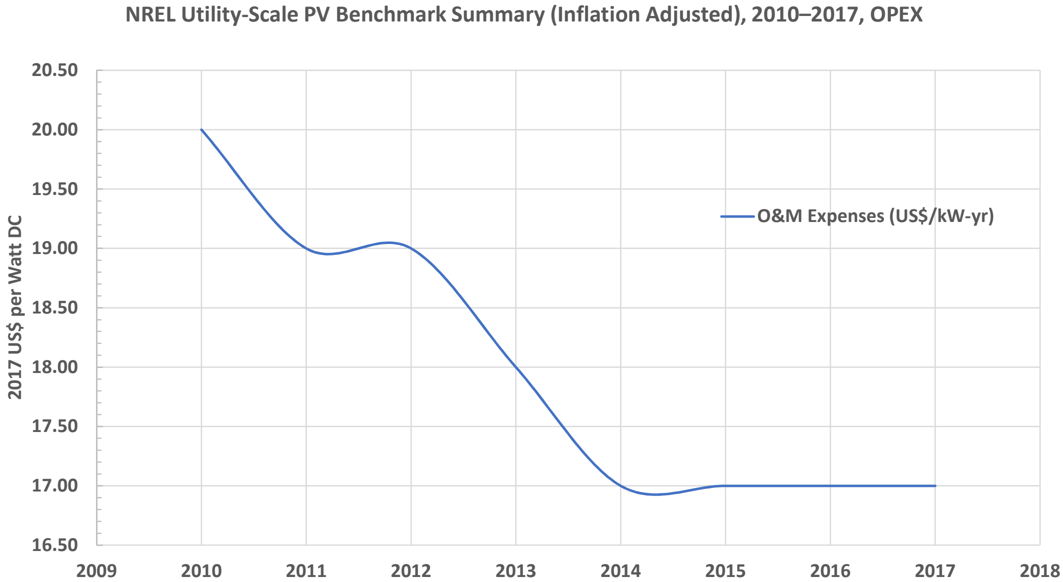


Fig. 5.2. Decline followed by a stabilization in operational expenditures, 2010-2017 [5]

Capex and opex estimates are based on [56,57,58]. Values found in [58] expressed as overnight cost of capital have been interpreted as capex (i.e. lumped to year 0). [56] however, refers to EPC costs and these are likely to exclude expenses occurring before installation (early development, approval process, tendering, land acquisition and insurance). By adding 10% to these values, they were used for estimations of capex. [56] provided estimates for the EPC prices for both FT and SAT in 2017. More specifically, a FT project seemingly had an EPC value of A$ 1.57/W, whilst a SAT project had A$ 1.80/W. The projects were similar in size, 100 MW, and located in QLD. It should be noted how other factors may have affected the prices, such as the possibility to connect to an existing substation. This was the case for the FT project, but not the SAT project.

Due to the stability in opex, values from [58] are used, adjusted only for economies of scale. O&M values from [58] are seemingly from 2015 and include several cost scenarios, however, average price estimates were adopted. Inflation is considered to have been negligible.

Assumptions:

- The effect of economies of scale is assumed to be consistent for all three array technologies.
- The effect of economies of scale is assumed to be linearly proportional to system size for farms in the range from 10 MW to 100 MW.
- Projects smaller than 10 MW are assumed to not be influenced by economies of scale.
- The recent decrease in costs found are assumed to be consistent for all three array technologies.
- Despite Queensland having a higher annual capacity factor than Tasmania, the associated costs are considered to provide valid estimates for WVSF.
- The capital costs for FT and SAT to be used in Tasmania are based on the 2017

rated values A$ 1.57/W and A$ 1.80/W respectively.

- DAT prices are based on [58].
- Opex expenses are based on [58].
- An annual reduction in capex of 15% is assumed during the period of interest (2015-2018).
- Annual inflation: r=0%
- Discount factor: d=5%
- Lifetime: n=25 years
- Annual degradation rate: β=0.89%
- Downtime: FT=1%, SAT=3%, DAT=5%

Assumptions and obtained price estimates were validated by comparing with real values for capital costs from 2016 given in [58]. Capex estimates are given by Equation (5) and Equation (6). First 10% of the quoted EPC prices for FT and SAT from 2017 were added to create capex estimates. Thereafter, the estimates were adjusted from their initial values to remove the effect of economies of scale. This was accounted for by multiplying with an additional 19%. Thereafter, the decrease of 22% in capital cost from 2016 to 2017 was account for.

$$\mathrm{CAPEX}_{\mathrm{GSRF,FT,2016}} = \frac{\$1.73}{\mathrm{watt}} * (1 + 19\%) * \frac{1}{(1-22\%)^1} \tag{5}$$

$$\mathrm{CAPEX}_{\mathrm{GSRF,SAT,2016}} = \frac{\$1.98}{\mathrm{watt}} * (1 + 19\%) * \frac{1}{(1-22\%)^1} \tag{6}$$

The differences from the initial GSRF values were considered to be minimal. The assumptions made are regarded as appropriate for the purpose of the study and further analysis. Note, calculated estimates for FT and SAT are 6.9% lower and 3.1% higher respectively than the initial values given for GSRF, i.e. well within the accuracy of the data available and aligned with Appendix E.

Capital expenditures

The estimates for capex of FT and SAT are based on [56] adjusted for economies of scale and the assumed decline in costs for Tasmania. Having a capacity of 12.5 MWac, WVSF will benefit slightly from economies of scale. Capex for FT and SAT is given by Equation (7) and Equation (8), respectively.

$$\mathrm{CAPEX}_{\mathrm{WVSF,FT}} = \frac{\$1.73}{\mathrm{watt}} * \left[1 + \left(19\% * \frac{12.5-10}{90}\right)\right] * (1 - 15\%) \tag{7}$$

$$\mathrm{CAPEX}_{\mathrm{WVSF,SAT}} = \frac{\$1.98}{\mathrm{watt}} * \left[1 + \left(19\% * \frac{12.5-10}{90}\right)\right] * (1 - 15\%) \tag{8}$$

The estimate for DAT is based on values from [58] adjusted for economies of scale and the assumed decline in costs for Tasmania. Capex for DAT is given by Equation (9).

$$\mathrm{CAPEX}_{\mathrm{WVSF,DAT}} = \frac{\$4.53}{\mathrm{watt}} * \frac{1}{\left[1+\left(19\% * \frac{12.5-10}{90}\right)\right]} * (1-15\%)^2 \qquad (9)$$

Operational expenditures

Estimations for opex are based on [58] and adjusted only for economies of scale. Opex rates are given in A$/kW/Year and A$M/Year.

Annual Capacity Factor

The electricity produced is given by Equation (10), where US represents the unit size, ACF is the Annual Capacity Factor, L is the degradation loss and 8760 is the number of hours in a year of 365 days.

$$\mathrm{E(t) = US * ACF * L(t) * 8760} \qquad (10)$$

As solar systems degrade over time, the loss factor accounts for a reduction in electricity produced over time. More specifically, it will be reduced over its life time of n years based on a degradation rate, β. As given in Equation (11), L(t) denotes the associated loss in year t [26].

$$\mathrm{L(t)} = (1-\delta)^{\mathrm{t}} \qquad (11)$$

If the system is designed with an overcapacity (DC versus AC output) then the effects of panel degradation are limited to early morning and late evening. After a number of years, the designed overcapacity will be consumed by degradation and the equation above will be fully correct.

The Annual Capacity Factor is thus the ratio of the actual annual electricity produced divided by the theoretical annual maximum assuming it operates at its peak (AC) rated capacity every hour of the year. The numerator thus represents the actual electricity produced and delivered annually to the grid. In this analysis, these values were adopted from the simulations performed in PVsyst. The denominator represents the system's nameplate capacity of 12.5 MWac times the number of hours in a year. ACF is given by Equation (2).

Calculation of LCOE for WVSF

The LCOE was determined by calculating the discounted value of the annual plant costs (capex and opex) divided by the discounted volume of electricity produced, over the plants' lifetime. As a solar farm can be argued to be exposed to relatively low technical risk and it is a utility supplying a Government controlled market, a discount rate of 5% has been used, together with zero inflation on costs and electricity prices. This simplification was justified by:

- Large number of assumptions made in the cost estimates for capex and opex.
- Desire to remove future speculation regarding electricity prices.
- Importance of focusing on the differences between FT, SAT and DAT and not be distracted by a need to reach an economic hurdle.
- The difference between 5% and the bank lending rates (ca. 2%) is sufficient to account for electricity price risk.

A simple pre-tax cash flow model was built in Microsoft Excel to model the three different types of arrays at WVSF. All of the capex was assumed to occur in year 0 (so called "over- night cost"), with income and operating costs starting in year 1. The project life was set to 25 years and the Panel Degradation Factor β=0.89% equated to a reduction of output to 80% after 25 years (typical factory warranty). As ACFs from PVsyst simulations were found to be a little high as compared with those achieved by GSRF, an Annual Downtime factor was introduced. It must be emphasized that tax, depreciation and financial costs were excluded from this model. The cash flow model then calculated NPV, IRR, LCOE, time to payback and maximum capital exposure.

5.6 Spot Price Electricity Market

The economic viability of the different array technologies was further evaluated by considering real variations in the spot price electricity market for both WVSF and GSRF. As opposed to using a flat price such as done in previous publications of GSRF, actual electricity demand and price data were employed to give the analysis a measure of reality. The objective was to capture the characteristics of the three systems and their relative performance, during the day and year. For WVSF, generation output for a simulated average year from PVsyst was used, while real data was utilized for GSRF. The electricity produced was evaluated in accordance with actual spot prices for Tasmania and Queensland.

Firstly, revenue from electricity sales were calculated by matching the electricity generated by the associated spot price. An average effective annual sales price was calculated for each array type. Thereafter, the income at this average price was compared with what could have been achieved at various percentiles of the actual daily spot market (from P05 to P95 in steps of 5%). The purpose of this exercise was to identify the potential benefits of electricity storage for maximising sales income.

As the wholesale market operates on half-hourly spot prices based on power supply and demand, selling electricity at certain times may be more profitable than others. By analysing data of electricity supply and demand from NEM, it was attempted to identify patterns in power consumptions. Yearly, monthly and daily graphs were analysed for both WVSF and GSRF and findings with their potential are discussed.

5.7 Uncertainty Analysis for WVSF

Identification of the key cost drivers was achieved by utilizing the Microsoft Excel based risk analysis software, @RISK [61]. The economic model previously described was utilized. Functions were added whereby each variable was assigned a triangular distribution where the variable could range from -20% to +20% of its assigned mid value. It would be natural to have more complex distributions than triangular, but there was insufficient time and data to support their use. Output cells were assigned for NPV, IRR, LCOE, time to payback and maximum capital exposure.

The model was then run in Monte Carlo mode for two cases; firstly, base electricity prices as described above (+/-20%) and secondly with the additional (fixed) Government subsidy of 80 A$/MWh for the project life. The main objective of the simulations was to demonstrate:

- How the economics vary for the three different types of array.
- What the key variables were with the greatest and least impact on NPV.
- What impact the inclusion of the subsidies had on the conclusions.

The results are summarised in two types of plots. The first, a traditional Tornado plot, the second, a plot of NPV versus cumulative probability and the slope (derivative) of the NPV versus cumulative probability. The same process can be used for a full analysis of the project, breaking down capex and opex into their individual components, if the data is available.

6 RESULTS AND DISCUSSION

This chapter presents and discusses the results obtained in connection with the thesis activities. Technical and economic aspects were assessed separately before an overall evaluation was conducted for the different arrays at Wesley Vale Solar Farm, in accordance with the experience gained from Gatton Solar Research Facility. First, the results of the arrays' technical performance are evaluated along with the effect of temperature and ratio of diffuse irradiance. Thereafter, results from the LCOE calculations for WVSF are presented and the economic viability evaluated by including income from selling the electricity at the spot market. Moreover, commercial differences and potential for both WVSF and GSRF were identified by analysing market trends on a state basis as there were clear differences in life style and energy needs. Then, results from the risk assessment identified the major cost drivers for each array technology at WVSF. Finally, an overall evaluation including opportunities for increasing project value were discussed before the final optimal array solution for WVSF was proposed. Additionally, the potential for solar PV in Norway along with suitability of the array technology was investigated.

6.1 Technical Performance by Simulation in PVsyst

The following section presents the results for WVSF obtained from simulations in PVsyst and discusses the various arrays' technical performance. The suitability of the different array technology throughout the day and year is presented. Comparison of the simulated data for WVSF with real data from GSRF reveals the arrays' actual output experienced as well as demonstrating the influence of latitude. More specifically, the effect of the type of irradiance and ambient temperature on the systems´ performance was identified. As a result, the importance of consideration of the location upon output was determined. The main findings for the arrays' generalized competitive advantages include:

- FT with a smaller tilt angle is ideal when exposed to a higher ratio of diffuse irradiance (overcast weather, higher latitude locations and during winter) and at midday.
- SAT is superior closer to equator. When sunny, it is ideal during the morning and evening, however, if it is overcast weather it is better during midday.
- For clear sky conditions, DAT always performs best, and its advantage increases with latitude.
- In addition to increasing energy yield, tracking solutions exploit the PV cells higher efficiency during the morning and evening with the associated lower temperature.

Detailed summary sheets (simulation parameters, main results and loss diagram) are included for WVSF (FT, SAT and DAT) and for GSRF (FT) in Appendix F.

6.1.1 Electricity generated

Annual results

At the location of WVSF, SAT and DAT resulted in 18.5% and 32.2% higher efficiency than FT, respectively. The values are well aligned with industry experience and as expected, SAT and DAT outperform FT on an annual basis. Fig. 6.1 illustrates the seasonal variation and the arrays´ ability to adjust thereafter. While DAT constantly moves to face the sun and achieves maximum electricity generation, the relative performance of FT and SAT varies. As the horizontal SAT has zero tilt angle, it is installed to favour the summer solstices as proven by a high efficiency during the summer months. During winter, when the sun is lower in the sky, it receives less direct sunlight and its production is reduced. FT, on the other hand, with its tilt angle of 35°, is more suitable for the lower sun during winter and thus outperforms SAT at that time. The increase in energy yield experienced for the tracking systems compared to FT for both WVSF and GSRF are presented in Table 6.1. The results indicate a relative greater increase in efficiency experienced for SAT at GSRF and DAT at WVSF. This is expected, as SAT has a competitive advantage closer to equator and DAT at higher latitudes.

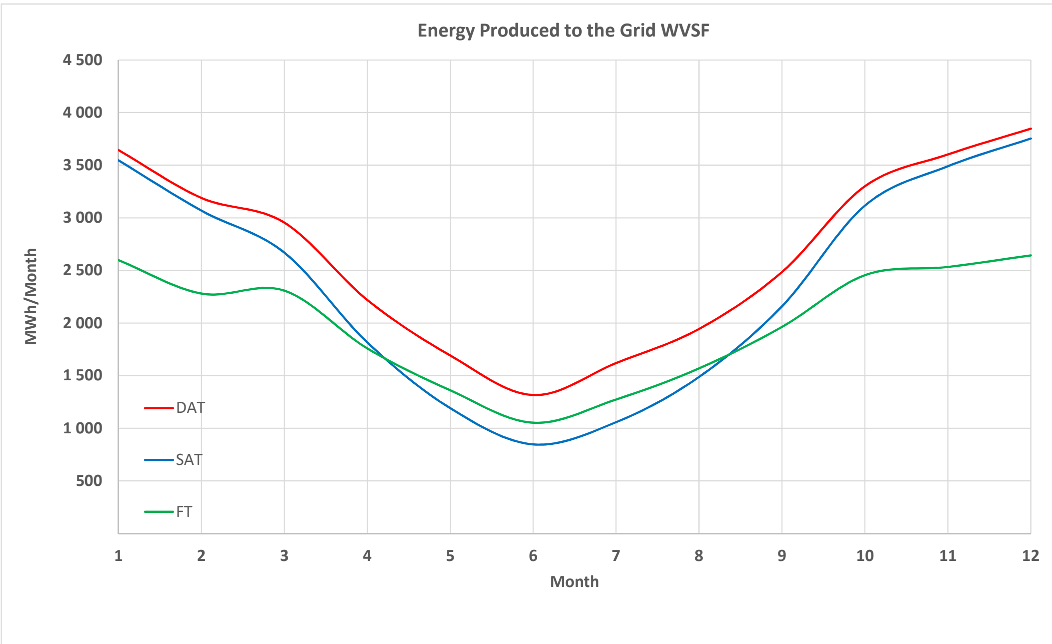


Fig. 6.1. WVSF energy produced to the grid

Table 6.1. Increase in production with tracking arrays

	Production SAT	Production DAT
WVSF	19%	32%
GSRF	20%	25%

Despite experiencing the same array characteristics (on an annual and daily basis), data from GSRF reveals the fluctuations actually experienced. This is visualised in Fig. 6.2 where the annual output for the arrays are plotted along with the irradiance. As expected, generation output is determined by irradiance. As the data for GSRF was provided in time steps of 1 minute, fluctuations in production, likely due to clouds passing, causes an uneven graph. Such issues were not detectable for WVSF as only hourly synthetic data was available, and this is likely to be the main cause for distortion in the graphs for GSRF.

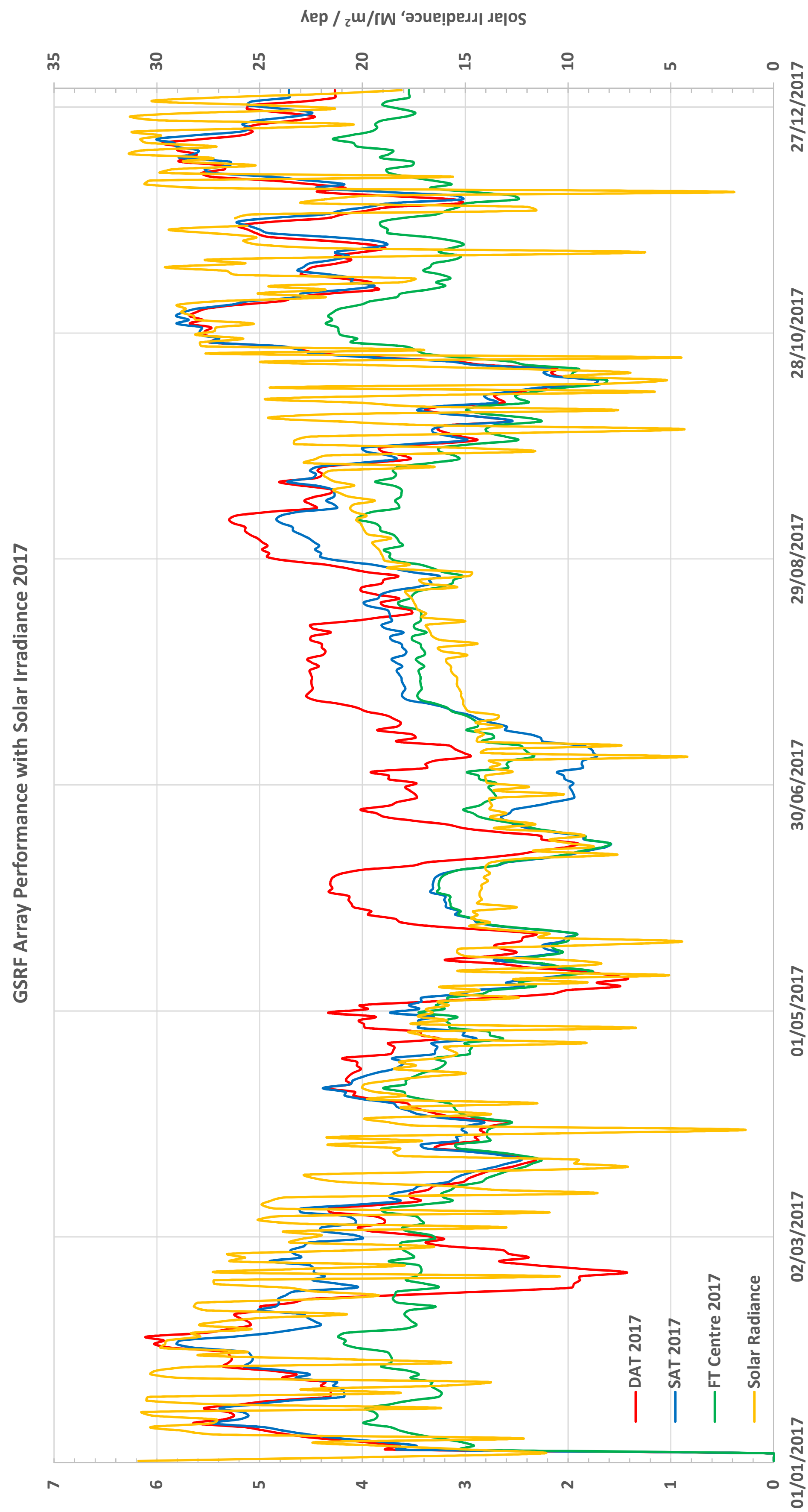


Fig. 6.2. GSRF array performance with solar irradiance 2017

Faults and failures have typically been associated with tracking systems, and Fig. 6.3 illustrates non-productive time experienced for the DAT array (flat period in the graph at the end of the year). As such issues are not included in the simulations for WVSF, assumed downtimes were used for the economic assessment.

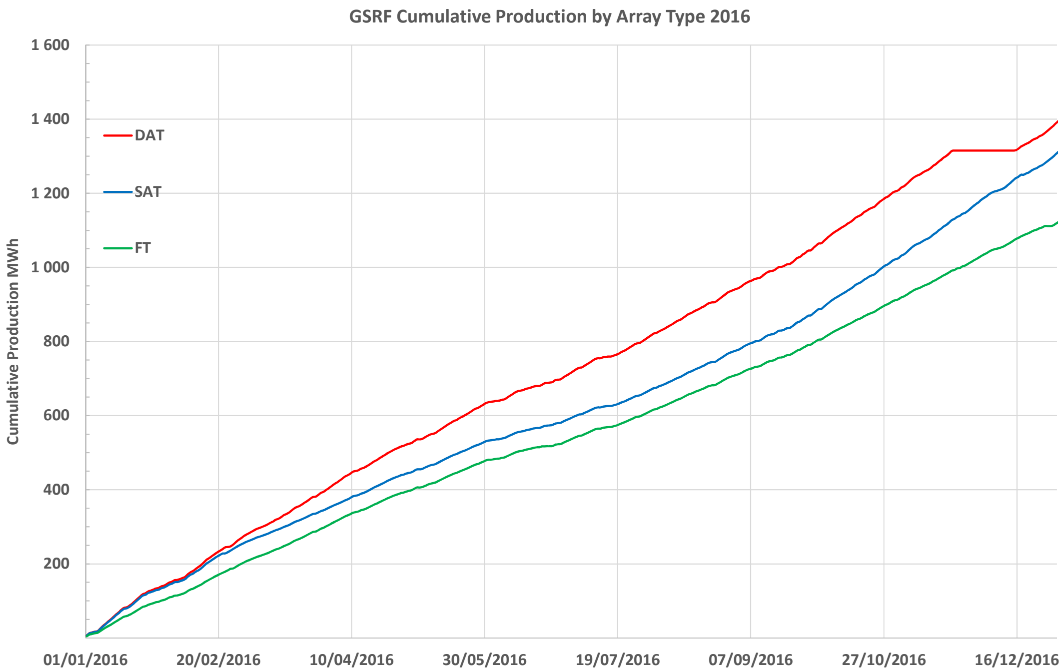


Fig. 6.3. GSRF cumulative production by array type 2016

Effect of tilt angle

A comparison of a FT system for WVSF with a tilt angle equal to its latitude (41°) and the adapted tilt angle optimal for maximal annual production (35°) shows the different angles' suitability throughout the year for capturing direct and diffuse irradiance. A tilt angle equal to 35° resulted in higher electricity generation during summer and lower during winter as compared to one with 41° This was expected as tilt angles of 35°/ 41° are better aligned during the summer/ winter solstices respectively. The difference in electricity generated is marginal, but important if the system is to be designed for optimizing seasonal production. Fig. 6.4 provides an illustration of the effect of tilt angle for a fixed system.

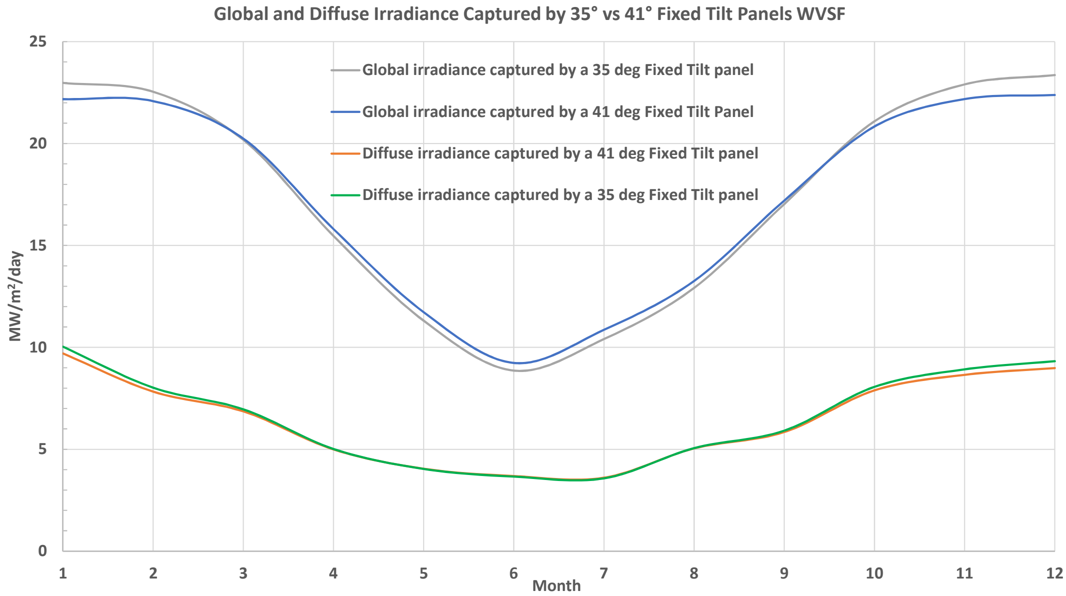


Fig. 6.4. WVSF global and diffuse irradiance captured by FT with a tilt angel of 35° and 41°

Results for sunny days

Analysis of the daily output throughout the year highlights the differences in each arrays' performance characteristics. Production graphs for a summer, spring/ fall and winter day are presented for both WVSF and GSRF, with simulated and real data respectively. The selected days (Fig. 6.5, Fig. 6.6 and Fig. 6.7) represent an ideal sunny day with maximum potential for harvesting energy from direct irradiance. More specifically, days close to the solstices and the equinox were chosen.

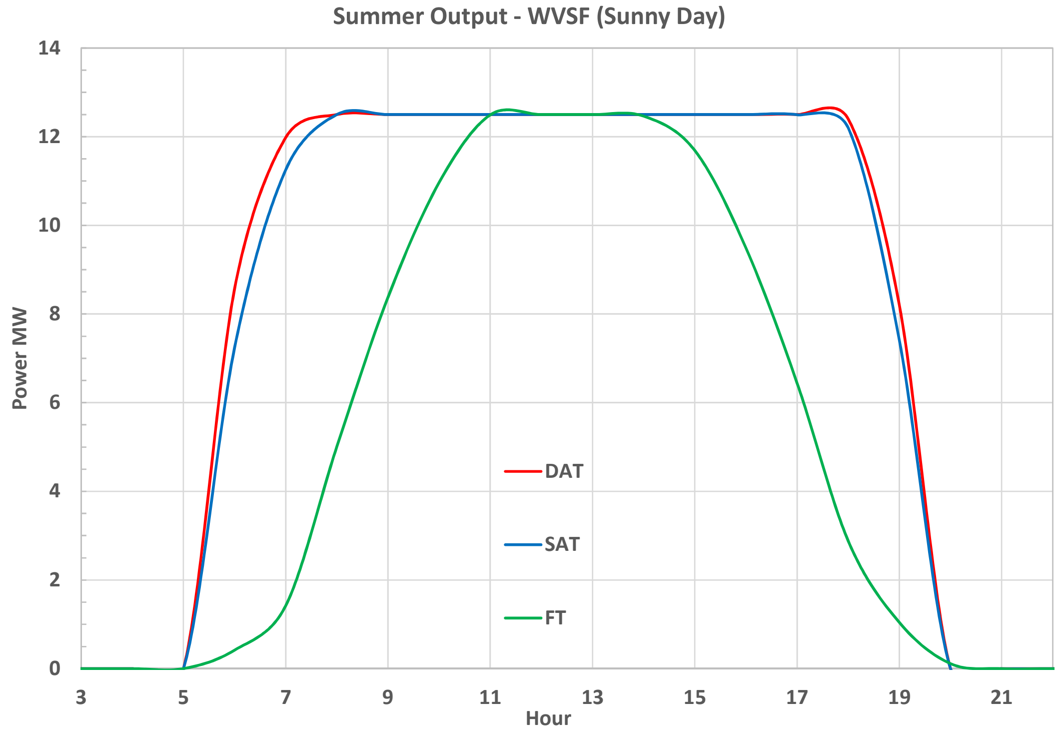


Fig. 6.5. WVSF performance during a sunny summers day

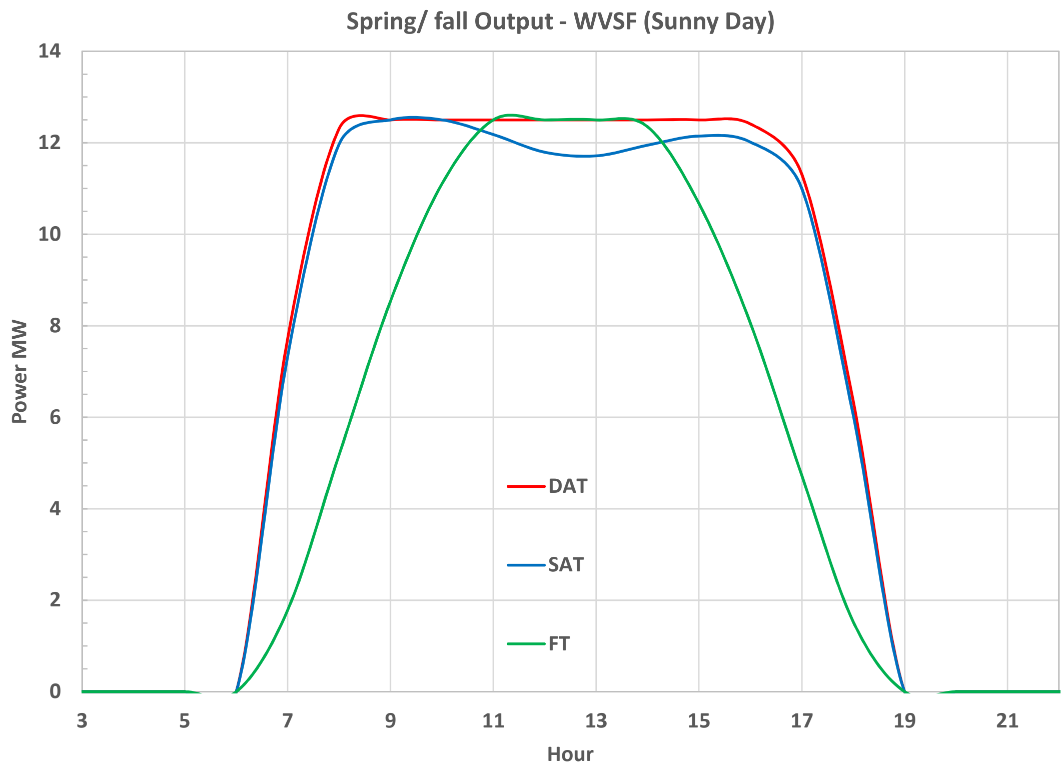


Fig. 6.6. WVSF performance during a sunny spring/fall day

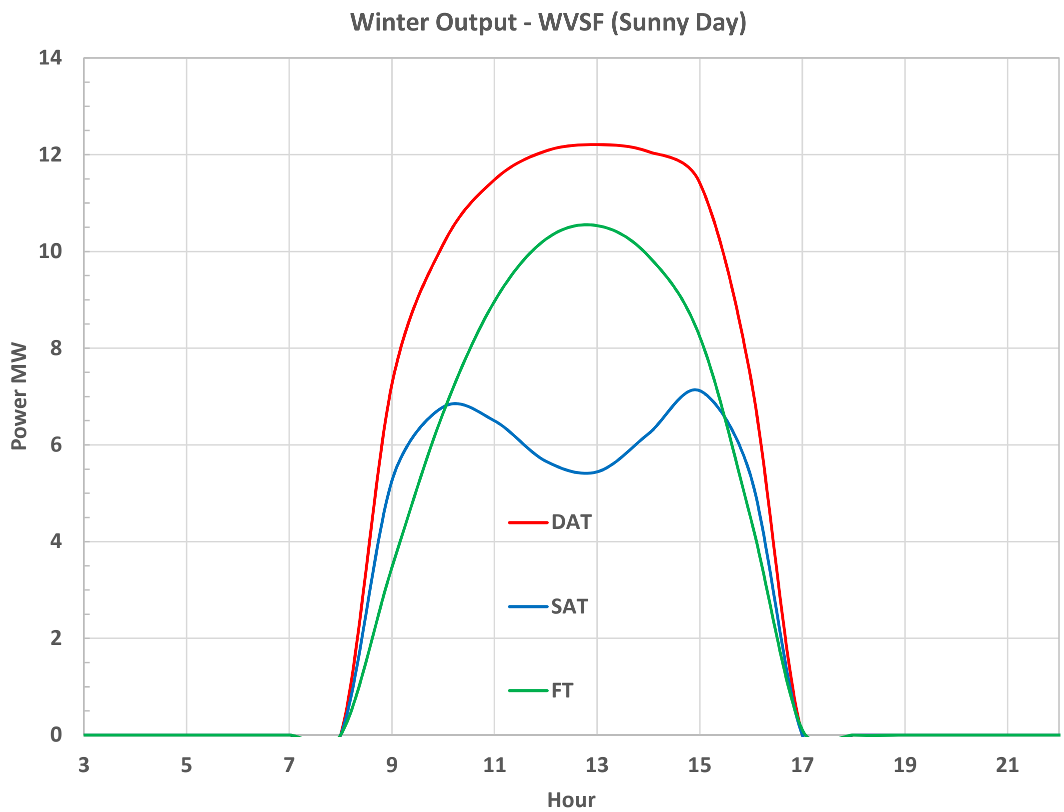


Fig. 6.7. WVSF performance during a sunny winters day

Results for WVSF indicate that on a daily basis, DAT outperforms the other arrays. However, it becomes evident that SAT is just about as productive as DAT during the summer. Throughout the spring and fall it can be seen that FT becomes more efficient relative to the other arrays during midday whilst SAT begins to suffer from being horizontal and its lack of tilt angle at this time. Not to be ignored, SAT and DAT still produce significantly greater amounts of electricity during the shoulder hours of the day (05-08 and 16-19 hrs). During winter, the most apparent drawback of SAT occurs with its low output during midday, indicating the advantage of having a tilt angle.

Similar general performance characteristics as previously discussed are applicable for GSRF on a daily basis. Interestingly, and somewhat surprisingly, the SAT seemingly still suffers from its lack of tilt angle during midday in the winter season. This suggests that a SAT system installed at a relatively low latitude (27°) can still be expected to under perform during this period of time and year. Moreover, as the following figures (Fig. 6.8, Fig. 6.9 and Fig. 6.10) indicate, Queensland is also exposed to seasonal variations.

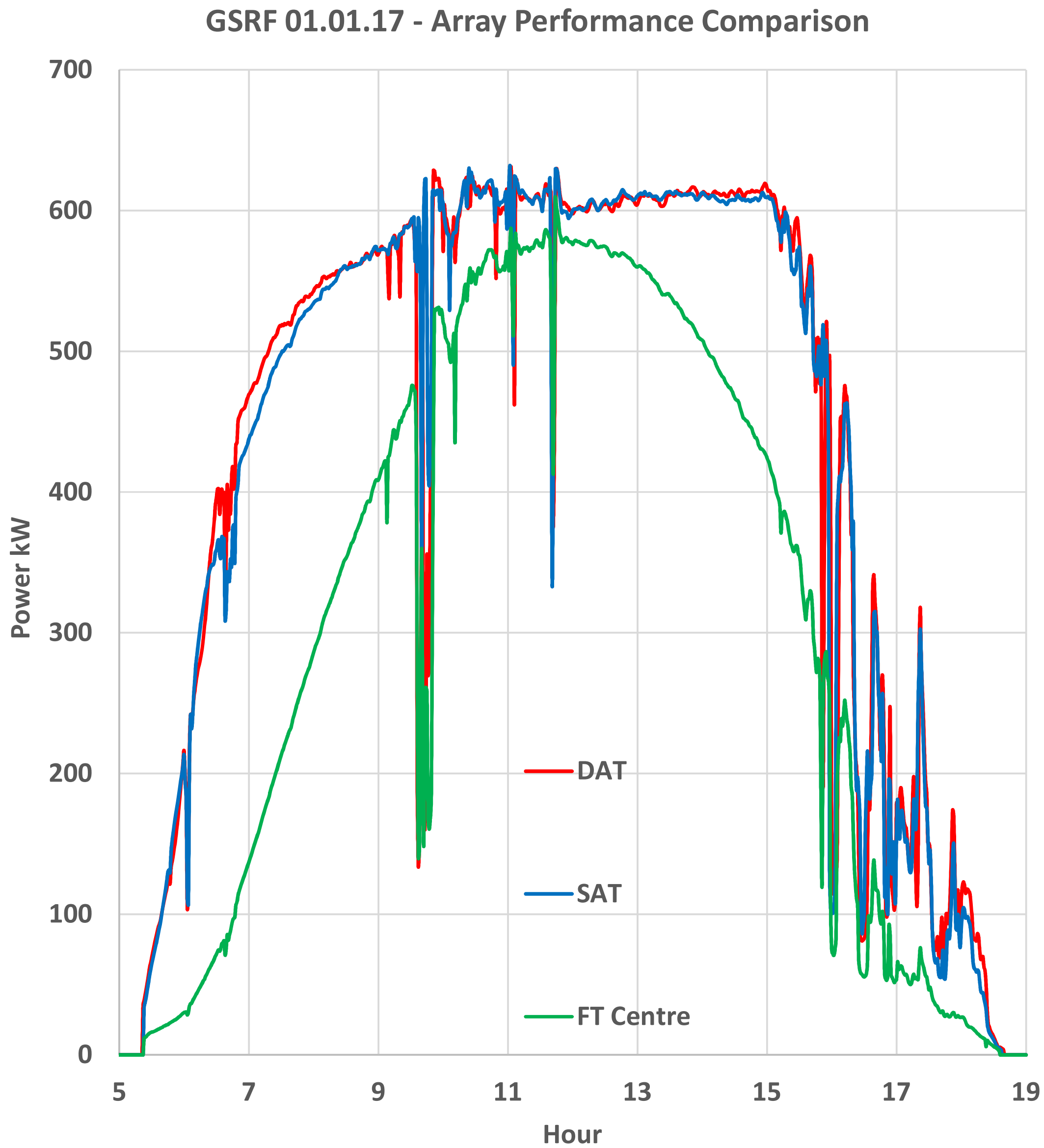


Fig. 6.8. GSRF performance during a sunny summers day

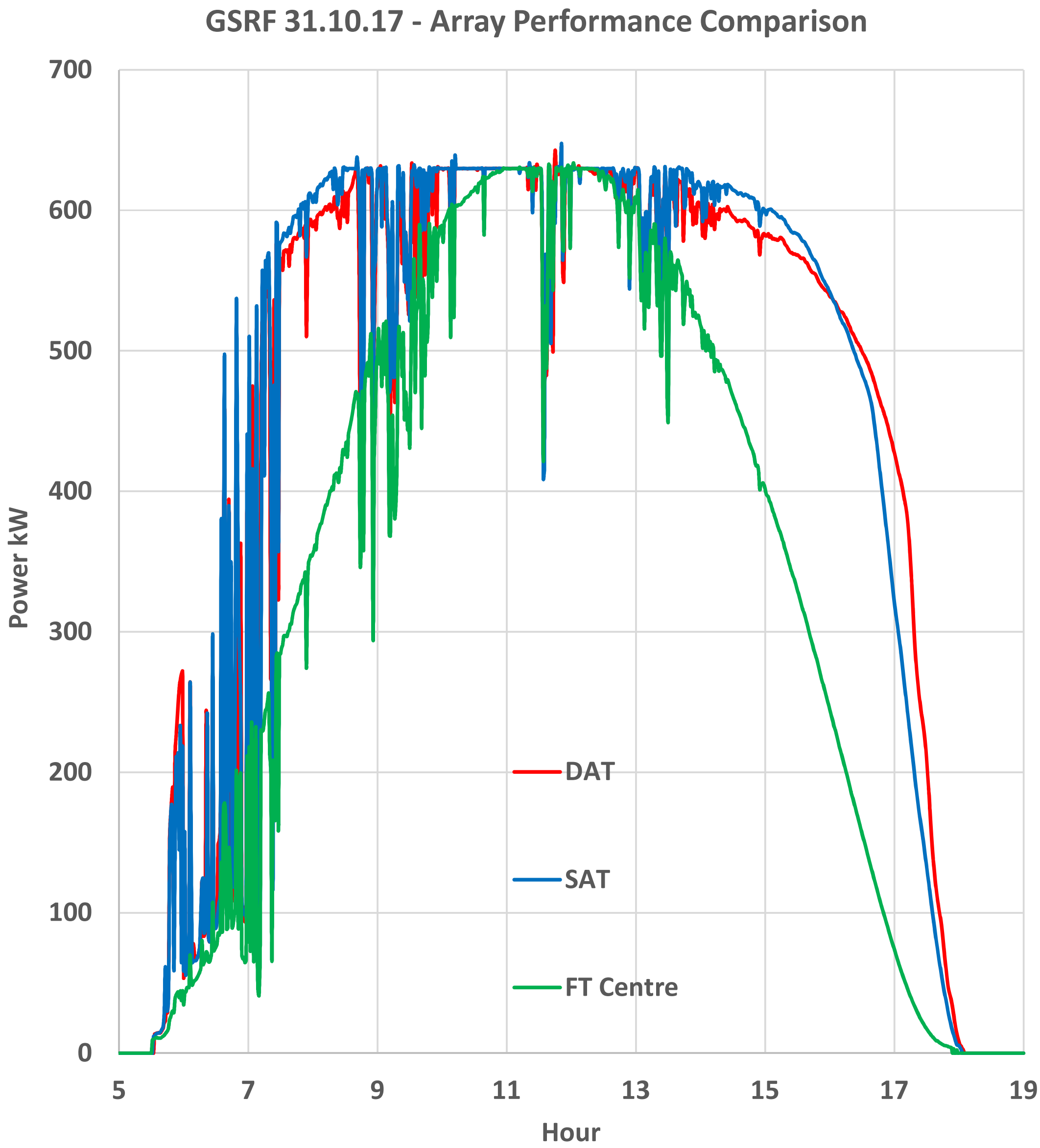


Fig. 6.9. GSRF performance during a sunny spring/fall day

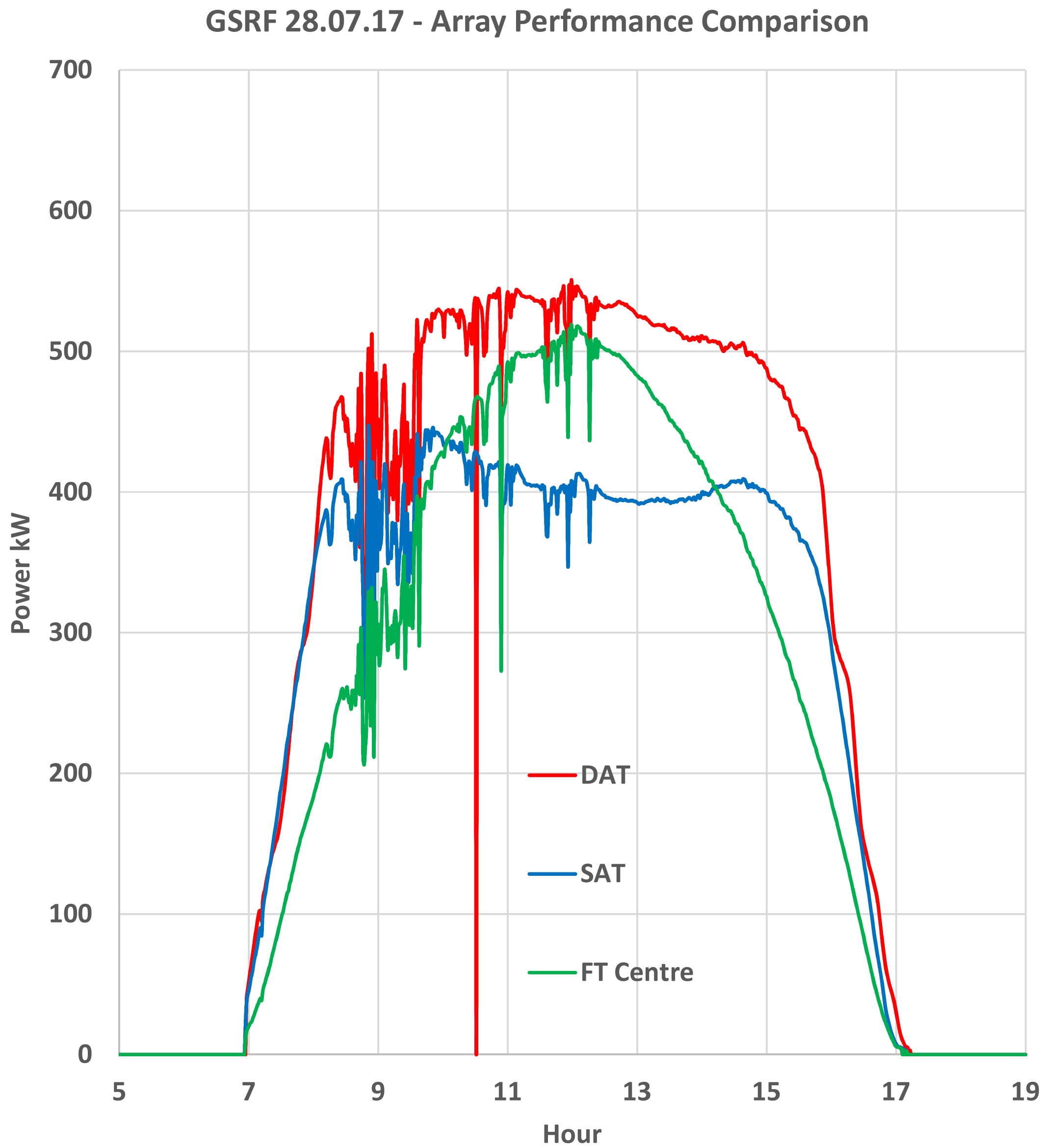


Fig. 6.10. GSRF performance during a sunny winters day

Results for overcast days

The arrays' performance during overcast days throughout the seasons was investigated for WVSF. Although Wesley Vale is described as a sunny place, it is important to acknowledge the less ideal circumstances the farm may be exposed to. Moreover, such conditions may be representative in other cloudier regions, such as places in Norway. Clouds result in a larger ratio of diffuse irradiance at the expense of direct irradiance. Results from an overcast day from summer, spring/ fall and winter are plotted below. Importantly, the production characteristics differed from sunny days, and the relative performance of FT was superior for all seasons.

The tracking systems ability to produce during the shoulder periods becomes absent and FT actually performs better during these hours. However, during midday in the summer season, SAT has the greatest output due to being horizontal and optimally angled for absorbing diffuse irradiance. During winter, FT outperforms the tracking systems throughout the whole day, and SAT is the least productive system. Only marginal differences are detectable during spring/ fall (see Fig. 6.11, Fig. 6.12 and Fig. 6.13).

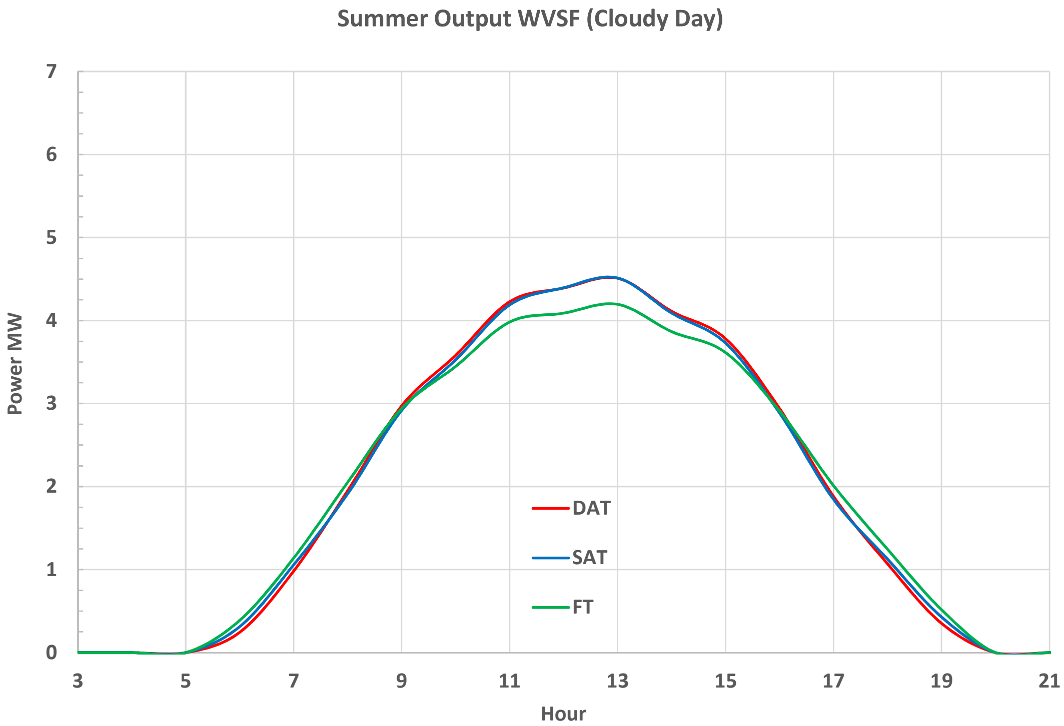


Fig. 6.11. WVSF performance during a cloudy summers day

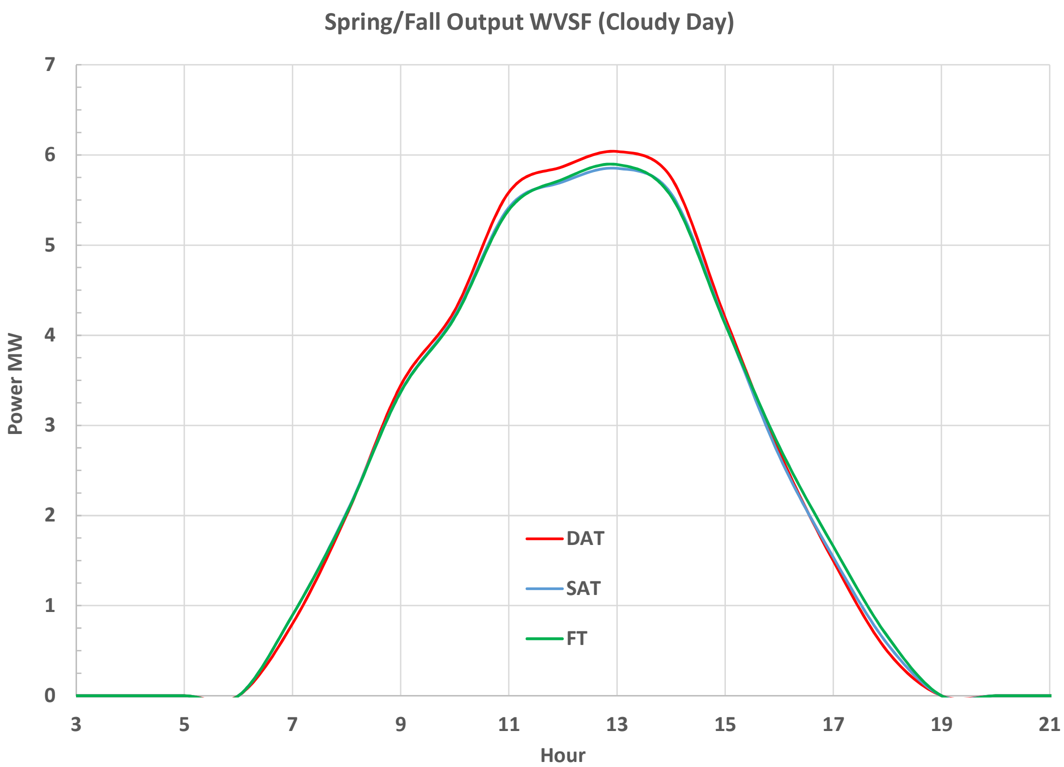


Fig. 6.12. WVSF performance during a cloudy spring/fall day

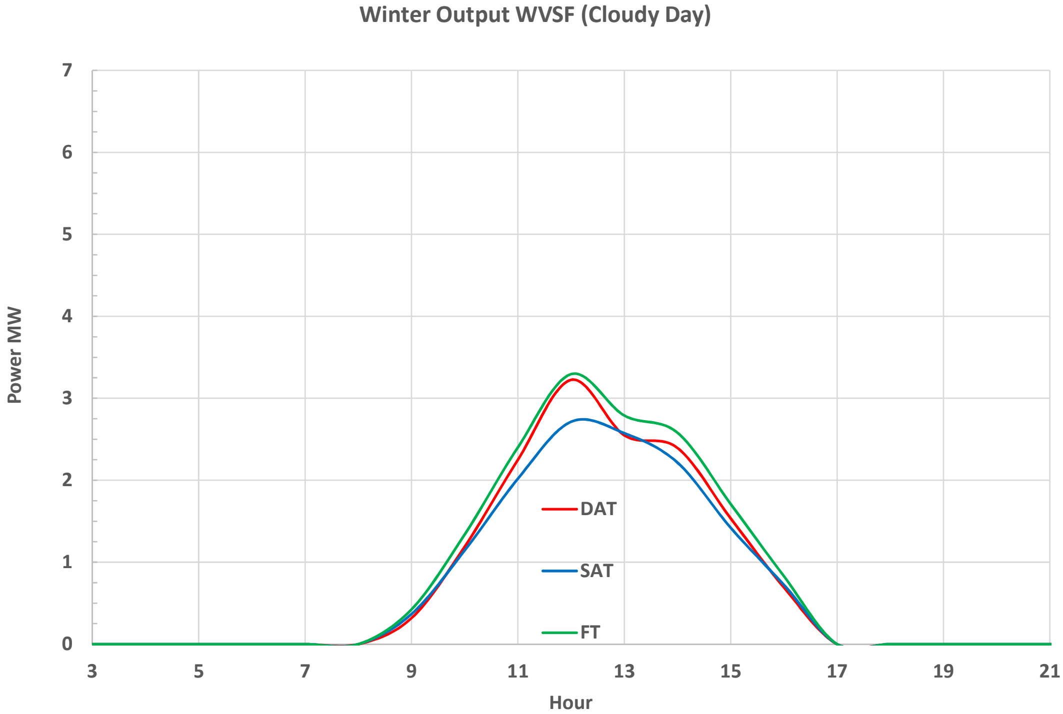


Fig. 6.13. WVSF performance during a cloudy winters day

6.1.2 The effect of diffuse irradiance

As higher latitude locations typically contain a greater ratio of diffuse irradiance, the impact was evaluated further. By comparing the horizontal global irradiation and horizontal diffuse irradiation in Tasmania and Queensland, two theories are proved. Firstly, greater latitude locations generally receive less solar intensity than regions closer to the equator. Secondly, a greater ratio of diffuse radiation is experienced at higher latitude locations. This can be observed in Fig. 6.14.

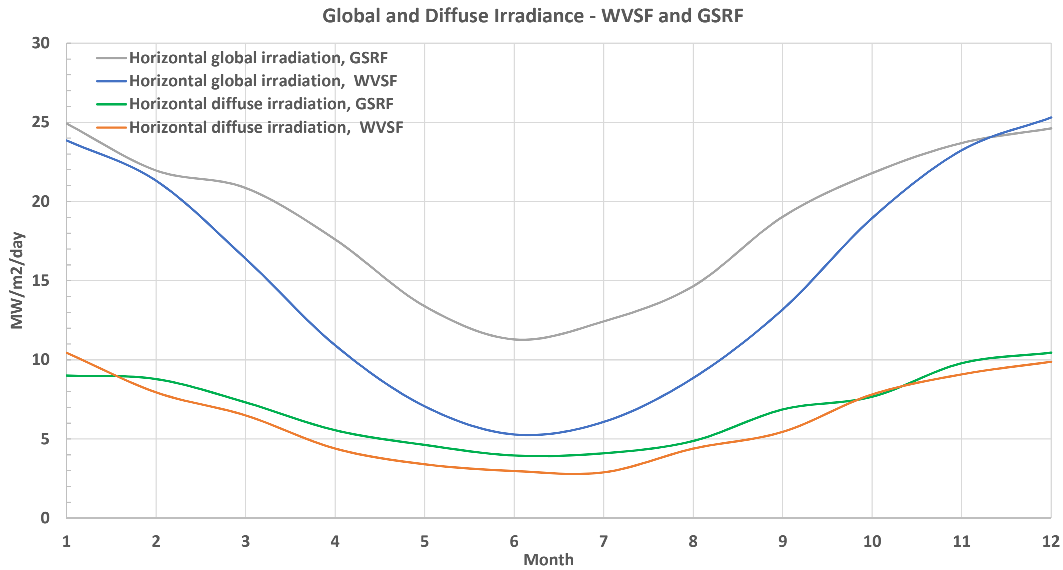


Fig. 6.14. WVSF and GSRF global and diffuse irradiance

The amount of diffuse irradiance at WVSF varies throughout the year as indicated in Fig. 6.15. Generally, the diffuse irradiance reaching WVSF is around 40% of the global irradiance, however, it surpasses the direct irradiance during winter. The direct irradiance still dominates the incident irradiance reaching the PV modules. This is expected as these arrays are designed to optimize the collection of direct irradiance. The same trends for the different array technologies hold for their uptake of direct irradiance as illustrated in Fig. 6.16; DAT collects most direct irradiance, followed by SAT during summer but FT during the winter.

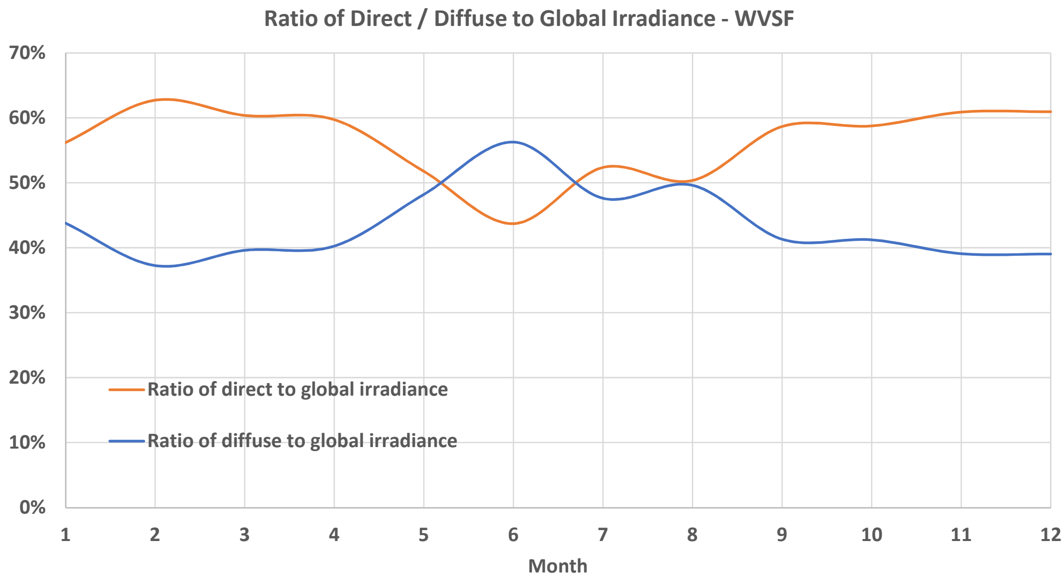


Fig. 6.15. WVSF ratio of direct and diffuse to global irradiance

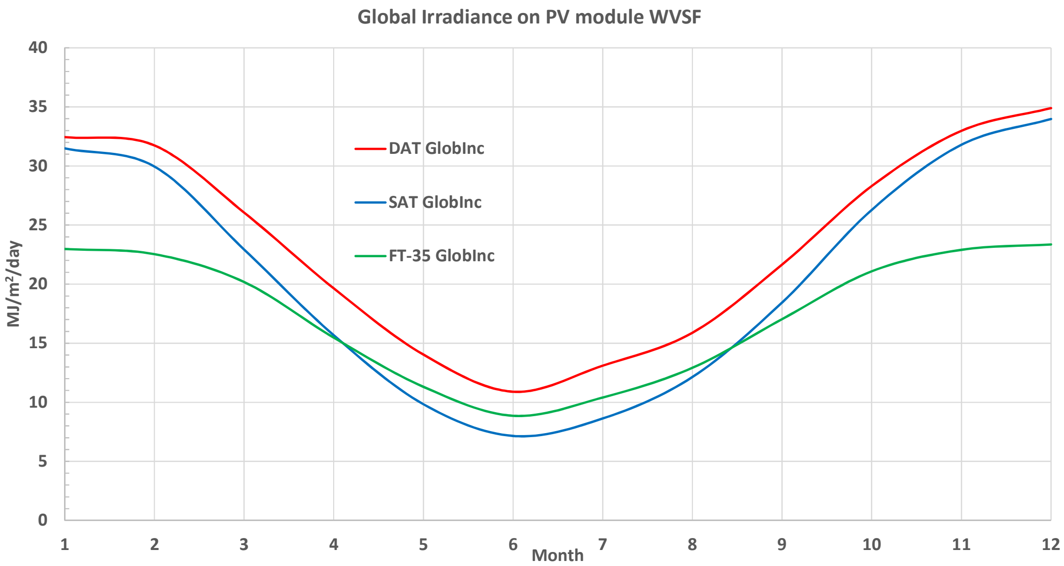


Fig. 6.16. WVSF global irradiance on PV module

The arrays´ ability to absorb the different types of irradiance is indicated in Fig. 6.17 , showing their relative uptake of diffuse irradiance. DAT, which continuously tracks the sun, has the lowest relative collection of diffuse irradiance. Again, FT and SAT vary according to season. While SAT's absorbed irradiance during summer is dominated by direct radiation, a greater ratio of diffuse radiation is collected during winter when it is less ideally angled for the direct radiation. The opposite is experienced for FT.

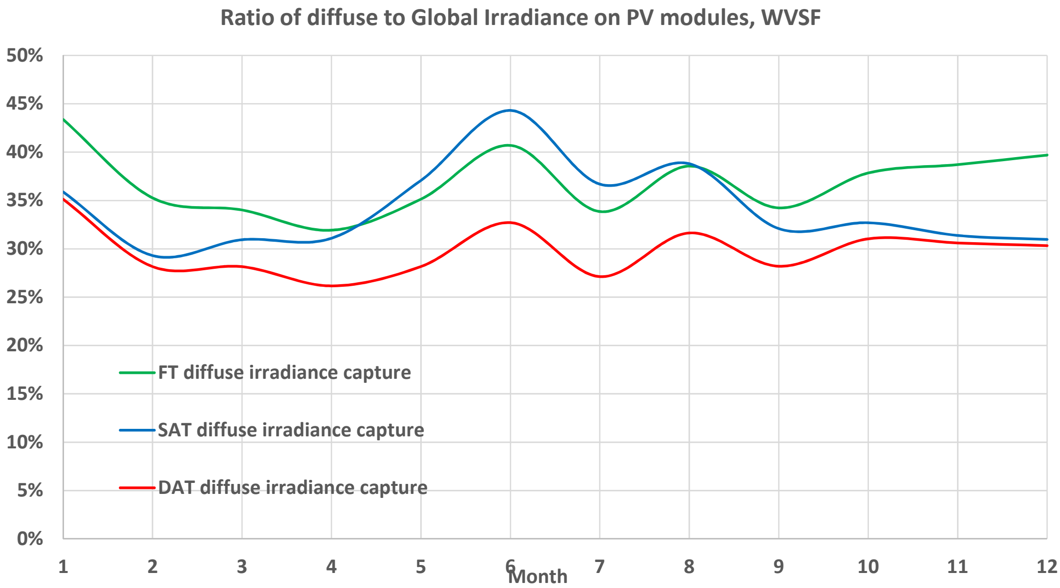


Fig. 6.17. WVSF ratio of diffuse to global irradiance on PV module

6.1.3 The effect of temperature

As solar irradiance increases, so does the maximum daily temperature (Fig. C.1) and this in turn reduces the efficiency of the panels . More solar irradiance increases the output but the efficiency of the PV cells falls off at higher temperatures. Locating panels in a cold environment thus helps to compensate for the potentially lower solar irradiance. The relationship between ambient temperature and module performance is shown in Fig. 6.18 using data for GSRF. The effect of temperature on efficiency of a panel can is illustrated by taking the ratio of the energy produced divided by the solar irradiance. In Fig. 6.19 for DAT at GSRF, efficiency points have been collected into 5°C temperature "buckets" and then statistical values have been selected to represent efficiency at that temperature interval ($P_{90}/P_{50}/P_{10}$). The relationship is less clear below 20°C but above there is a clear downward trend in performance. An interesting point to note is that all three systems will have had a greater efficiency during the cooler mornings and evenings when the cells are operating at their highest efficiency. The lower temperatures then favour the SAT and DAT systems because they are tracking to optimise power output also during the shoulder period of the day, i.e. they have a double advantage over FT at these times.

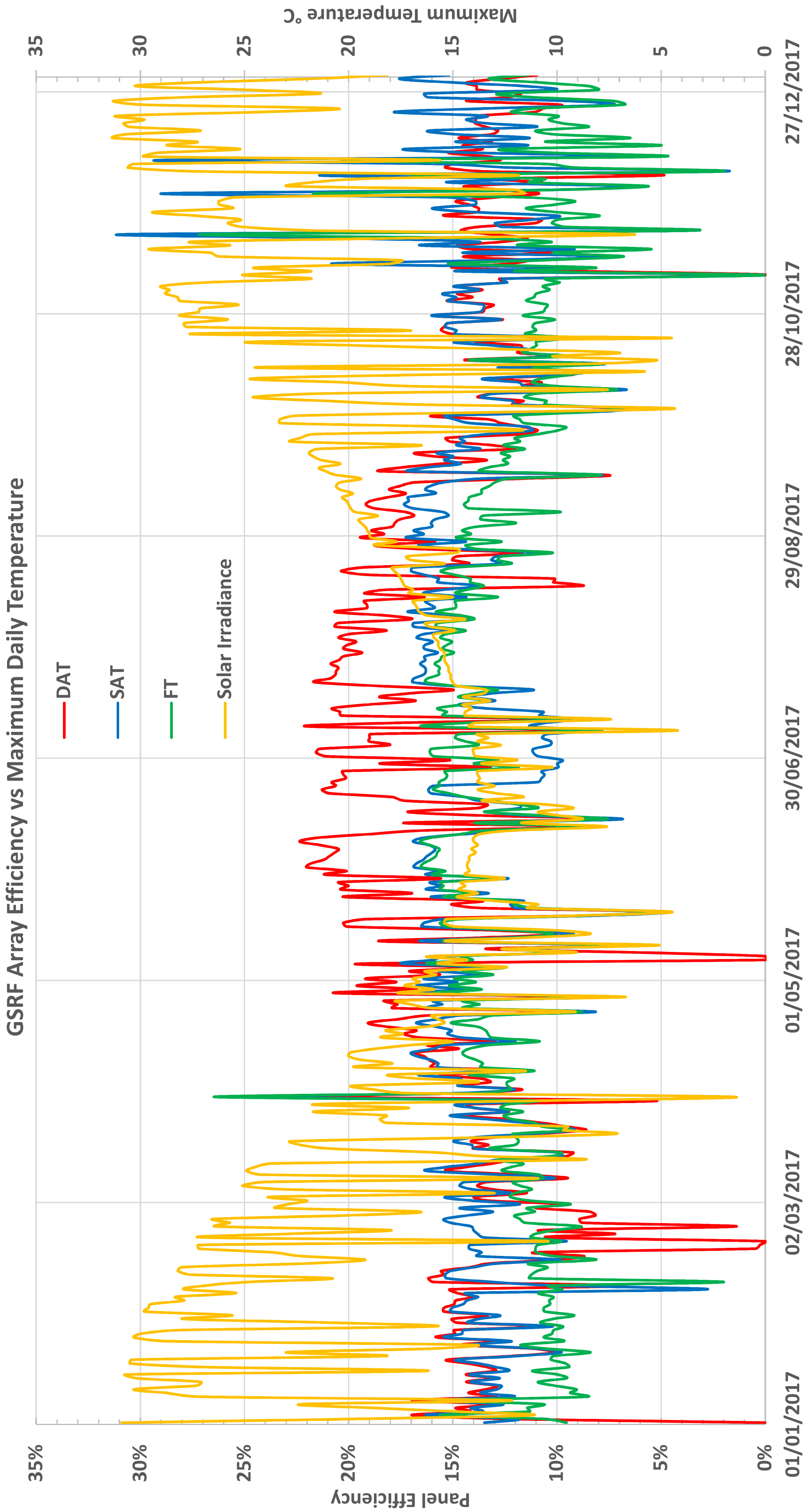


Fig. 6.18. GSRF array efficiency vs maximum daily temperature

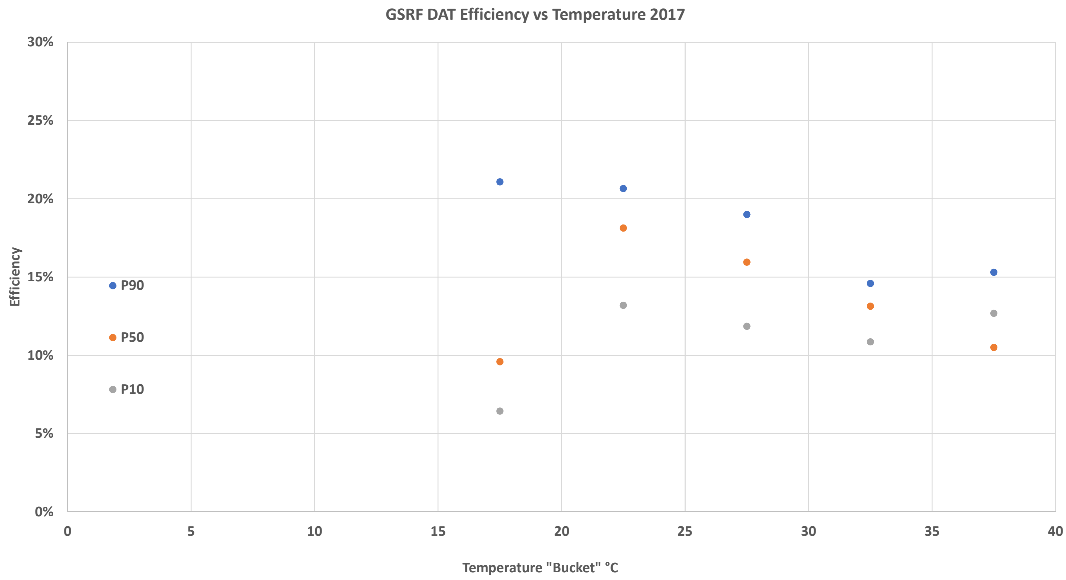


Fig. 6.19. GSRF efficiency of DAT vs maximum daily temperature

As certain modules are more suitable for higher temperature regions, these may be used to reduce the associated loss. GSRF employs such PV modules, more specifically First Solar´s thin-film modules. Fig. 6.20 illustrates the energy loss with temperature as a result of higher temperatures at various points throughout a year for GSRF and WVSF with two types of panel (monocrystalline modules and thin film). Note how the thin film panels excelled in the low latitude warm environment of GSRF, whilst the monocrystalline modules were more suited for the cooler Tasmanian conditions, and in addition, they have a higher overall efficiency thereby requiring less area (WVSF is space constrained).

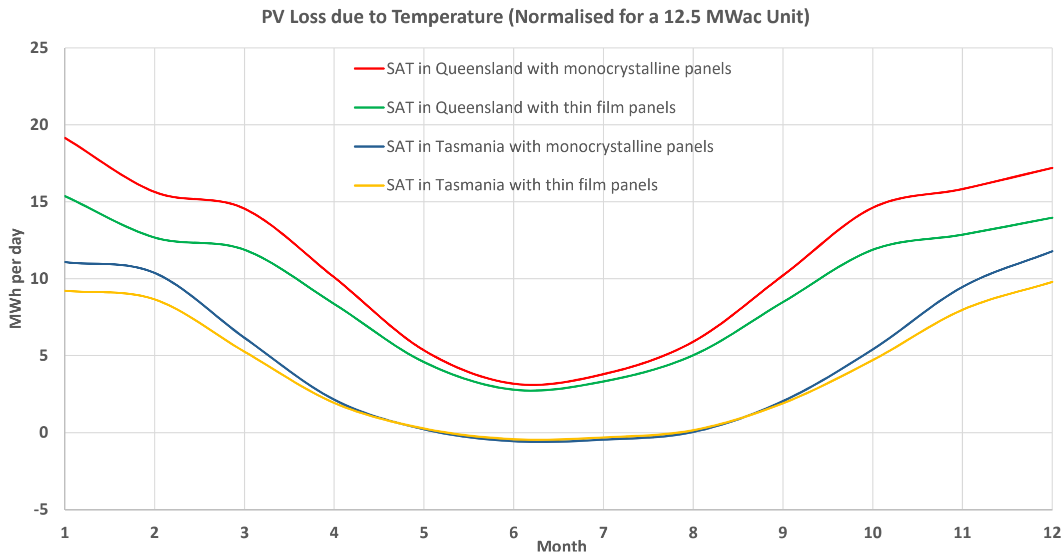


Fig. 6.20. PV loss due to temperature (normaliized for a 12.5 MWac unit)

6.2 Economic Viability

The levelized cost of electricity and the expected income from selling the electricity at the spot market is further discussed. Previous work has focused on the ability of tracking to out perform fixed systems based upon productivity (ACF) [58]. However, this thesis takes the analysis further and has examined how the income stream has varied between the systems by accounting for the fluctuating electricity prices at the spot market. Price is a function of demand and can vary during the year, week day and with temperature. In the same way, the various systems perform differently during the day and year. By using real prices, the actual advantages of tracking could be quantified in financial terms. Estimates for WVSF are provided for both with and without the subsidy of A$80/MWh. The results are summarized in Table 6.2 and include capital and operational expenditure, levelized cost of electricity, payback time, net present value (NPV), internal rate of return (IRR) and recommended retail price (RRP).

Table 6.2. Key performance indicators

Mean Values	**Capex**	**Opex**	**LCOE**	**Payback**	**NPV**	**IIR**	**RRP**
	MA$	**MA$ p.a.**	**A$/kWh**	**years**	**MA$**	**%**	**A$/MWh**
No Subsidies							
FT	21.8	0.249	0.083	12.5	1.55	5.7%	87.73
SAT	24.9	0.323	0.083	12.5	1.76	5.7%	86.98
DAT	40.8	0.41	0.118	21.6	-11.9	1.7%	87.37
80 A$/MWh subsidy							
FT	21.8	0.249	0.083	5.6	26	15.8%	167.73
SAT	24.9	0.323	0.083	5.5	30.4	16.1%	166.98
DAT	40.8	0.410	0.118	8.6	19.7	9.7%	167.37

6.2.1 Levelized cost of electricity

Results of the levelized cost of electricity for WVSF are presented in Table 6.2 for each tracking solution. Associated capital and operational expenditures are included. As expected, both capex and opex increase with the advancement of tracking. However, the greater production output of SAT compensates for its higher associated costs and achieves the same LCOE as FT. Despite its superior electricity generation, DAT has the highest and least favourable LCOE. More specifically, the LCOE obtained were A$0.083/kWh for FT and SAT and A$0.118/kWh for DAT. While FT and SAT have the same and lowest LCOE, SAT is expected to have a greater generation output and thereby be more economical than FT.

6.2.2 Income from the electricity sold at the spot market

In a novel approach, this thesis evaluates the income gained from selling the electricity to the spot marked when accounting for the associated fluctuating prices. In contrast to publications of GSRF where a fixed electricity price is assumed, this study is able to discover the actual benefits of including tracking by utilizing real, half hourly spot prices. The additional increase in income for the tracking systems are presented in Table 6.3 along with the their increase in energy yield. The volatility of the electricity prices is illustrated in Fig. 6.21, where a spike in demand resulted in drastically higher prices.

Table 6.3. Increase in income for the tracking arrays

	Production SAT	Production DAT	Income SAT	Income DAT
WVSF	19%	32%	16%	31%
GSRF	20%	25%	36%	40%

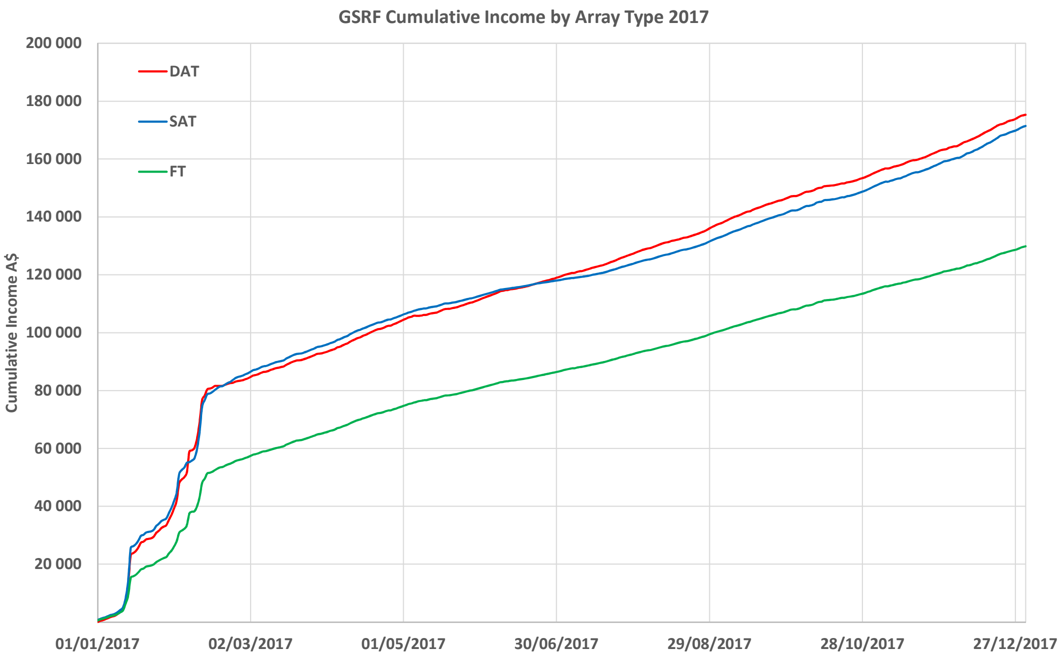


Fig. 6.21. GSRF cumulative income by array type

Comparison of the increase in efficiency and income for WVSF and GSRF reveals the arrays' ability to generated electricity to higher spot prices. For WVSF it can be seen that the increase in income is lower than the associated increase in production, especially for SAT. More specifically, the increase in production is 19% and 32% for SAT and DAT, respectively, while the increase in income is only 16% and 31%. This implies that the comparative advantage for the tracking systems is rather low, and the electricity prices in Tasmania are likely rather stable. At noon, FT performed relatively well, while SAT under performs. GSRF, however, greatly benefits by employing tracking solutions. The additional 20% increase in production by SAT results in a increase in income of 36% compared to FT. For DAT, the increase in production of 25% gives a 40% gain in income. Clearly, the tracking solutions' production profile at GSRF matches the electricity demand significantly better than at WVSF.

Spot sale versus storage potential

An analysis was also performed whereby the income at the weight averaged price achieved was compared with what could have been earned if the electricity was stored and sold at higher rates during the day. The results are shown graphically in Fig. 6.22 and Fig. 6.23 for WVSF (simulated) and GSRF respectively. The array systems at WVSF would have been selling at around 65 percentile of daily electricity prices, which is rather low. A marginally higher price was achieved for FT. Comparably, SAT and DAT at GSRF achieved 80 percentile of daily prices, and FT was selling at closer to the 75 percentile.

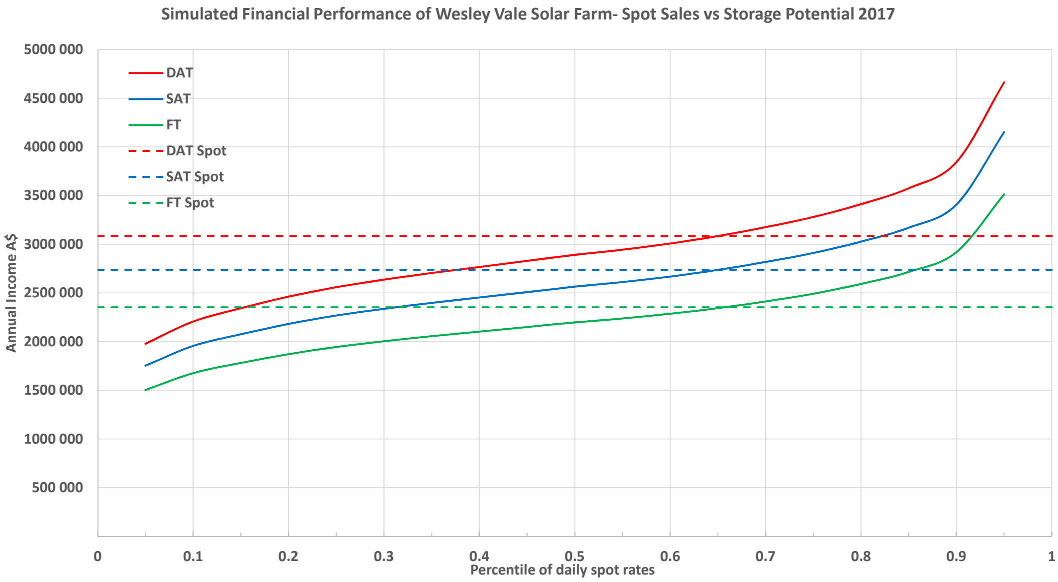


Fig. 6.22. Simulated financial performance of WVSF - spot sales vs storage potential 2017

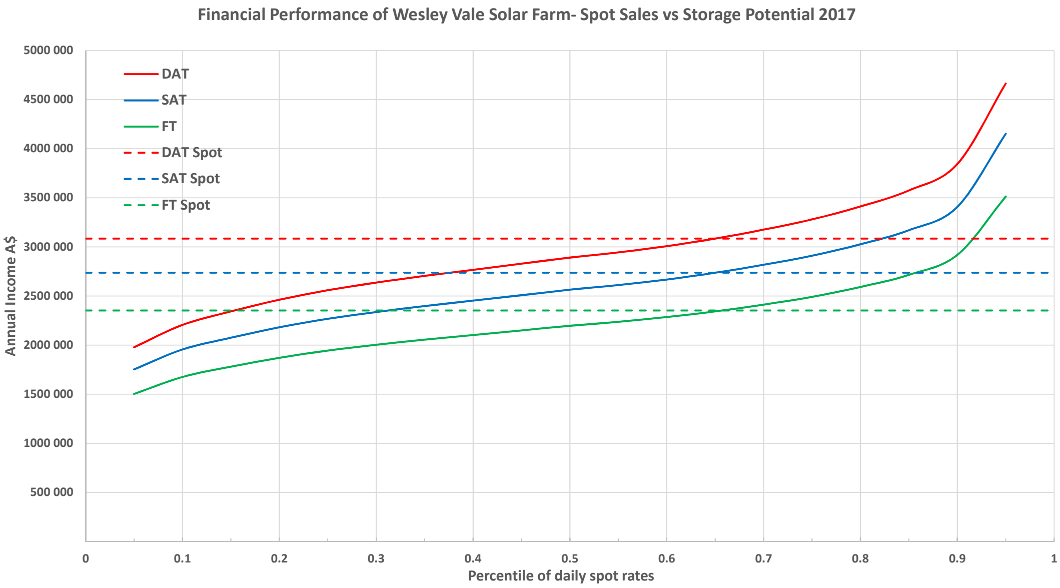


Fig. 6.23. Financial performance of GSRF - spot sales vs storage potential 2017

There is clearly potential to store the energy in a battery and mostly sell at peak demand/prices, however this is an opportunity open to any producer with storage, so a perceived advantage can soon vanish. In a project analysis this should be regarded as an eventual upside rather than the basis for an investment decision. There is a greater advantage for WVSF and the FT array at GSRF to exploit this opportunity as the tracking systems at GSRF are already selling at higher daily prices.

6.3 Trends in Electricity Demand and Prices

The difference in average spot price achieved for the two solar farms creates incentives for investigating trends in electricity demand and prices. By analysing historical data for electricity demand and prices for 2016 and 2017 in Tasmania and Queensland, patterns were identified. While no clear trend was detectable for Tasmania, both daily, weekly, annual and temperature dependent trends were discovered for Queensland.

Tasmania
No clear electricity price trends were detected in Tasmania, except for the fact that prices generally were slightly higher during midday. At WVSF, FT achieved (by simulation) the highest average annual price as it is producing most of its electricity during midday to a higher price. SAT, however, with its simulated lower generation during midday, sells to the lowest average annual price. Volumes of energy sold to the grid were higher for DAT and SAT than FT.

Queensland
The higher price achieved per MWh sold to the spot market for GSRF can be interpreted as that the PV system's output matches the demand profile in Queensland. Fig. 6.24 indicates that demand increase with temperature, likely due to air condition usage. This in turn pushes up the RRP (recommended retail price). In extreme cases where the market appears to be unable to deliver, spot RRPs exceed A$500/MWh. However, there is no simple correlation (temperature / demand / price), just an overall trend with temperature. Rather the large changes in price appear to be driven by consumer behaviour and infrastructure limitations. The advantage with tracking is in its ability to generate throughout the whole working day when air conditioning systems are operating at their maximum and spot prices are higher.

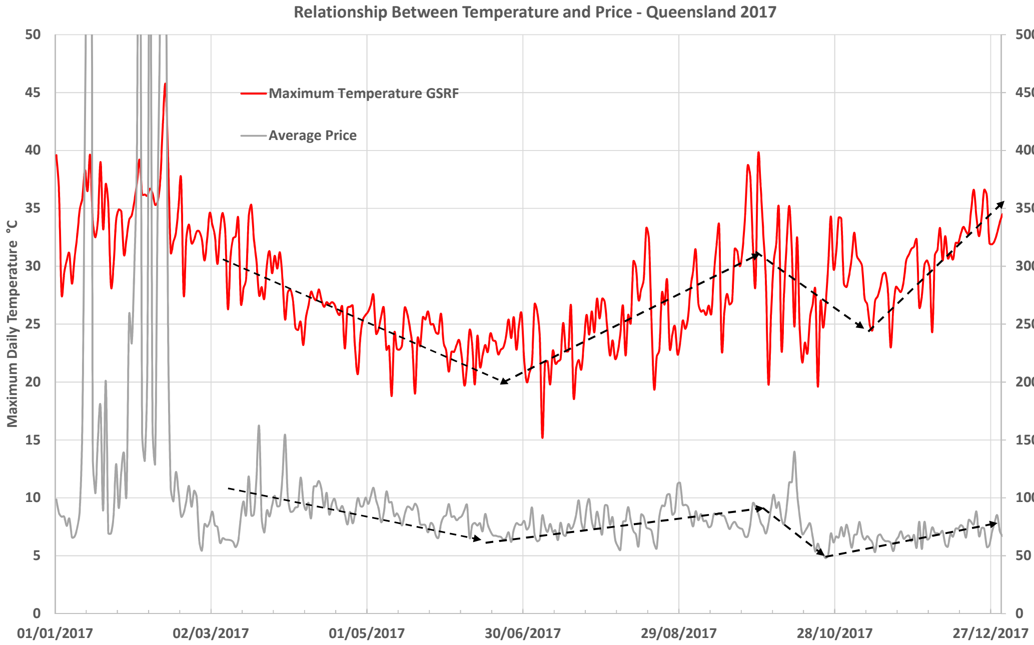


Fig. 6.24. Relationship between temperature and price in Queensland, 2017

Perhaps the most striking feature is the weekly trends that are clearly visible (irrespective of the temperature). This trend illustrates that there is potential for additional income by storing energy during the weekend for sale at higher prices during the week or during peak demands. Fig. 6.25 illustrates the correlation between weekly demand and RRP. The pattern for weekly demand is further highlighted in Fig. 6.26. Moreover, there were clear demand/price spikes at times of the day outside of peak production for FT systems (i.e. midday) and these were exploited by SAT and DAT but not by FT.

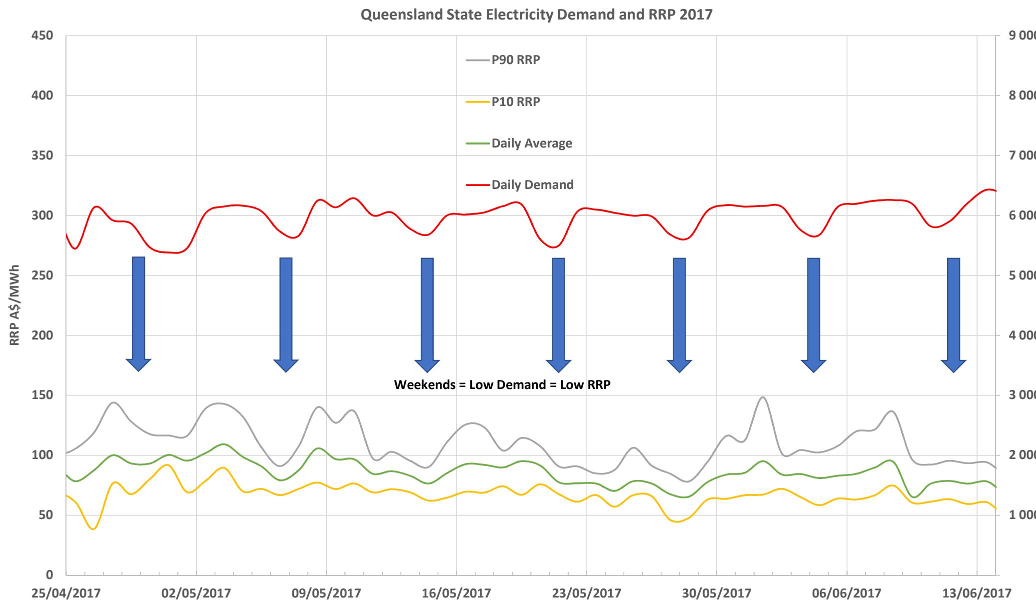


Fig. 6.25. Weekly variation in demand and price in Queensland, 2017

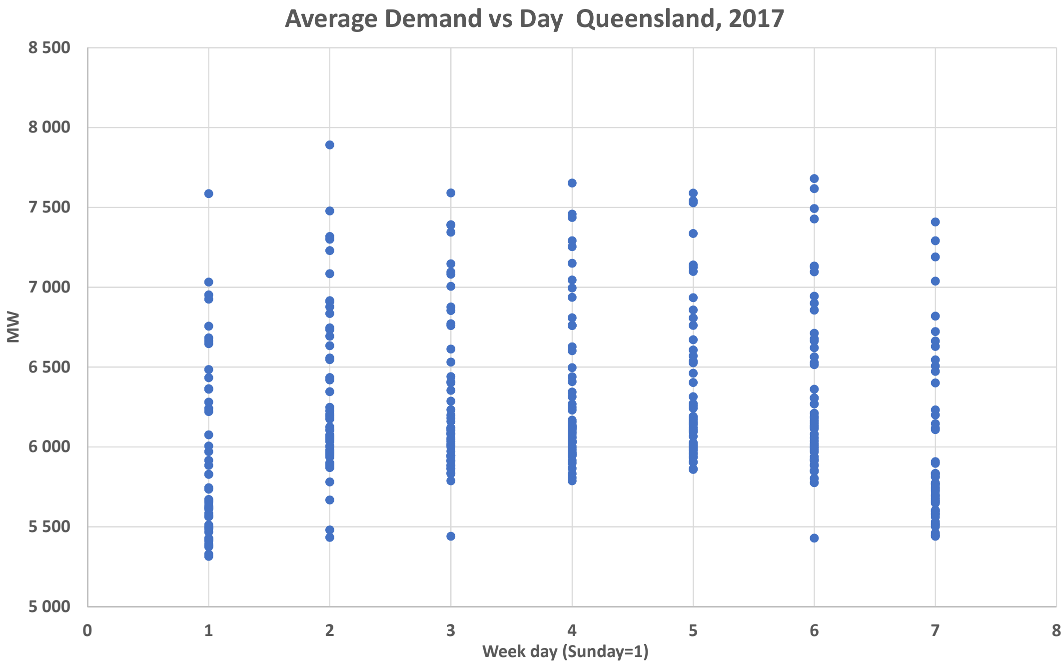


Fig. 6.26. Average demand vs day in Queensland, 2017

6.4 Uncertainty Analysis

Results from the uncertainty analysis concluded that SAT is the obvious choice when subsidies are included. Without subsidies a risk averse investor would favour FT. Despite the capex of DAT generally making its application unreasonable, the inclusion of subsidies along with a likely declining capex could make it competitive with FT and SAT. While annual capacity factor (ACF) and electricity spot price has the greatest impact on the economics for FT and SAT in the case without subsidies, capex is most determining for DAT. However, when including subsidies, ACF is the key cost driver for all three arrays. Results are further presented and discussed for the scenario of excluding and including subsidies.Detailed results from the Monte Carlo analysis are tabulated in Appendix G.

6.4.1 Risk assessment without subsidies

Traditional Tornado plots for NPV, incorporating a +/-20% change in each variable (Fig. 6.27, Fig. 6.28 and Fig. 6.29) show clearly that the DAT system is just too high on capex (as expected) and will not yield positive economics unless the price comes down and / or the electricity price increases. In all cases down time, panel degradation and opex are less important for the overall project economics. However, post investment, the entire focus will be on these three parameters as the farm operator seeks to maximise profits. The top three parameters of importance were capex, ACF and RRP and this appears to be logical. Good maintenance procedures will ensure a high ACF as will good project control (ensuring that things are installed and commissioned properly). Whilst capex and RRP are mostly driven by the external market (supply and demand, less easy to control). Of particular interest is that it is capex and not opex that is currently penalizing the more complicated DAT system, so there is certainly hope for this technology as it is developed further.

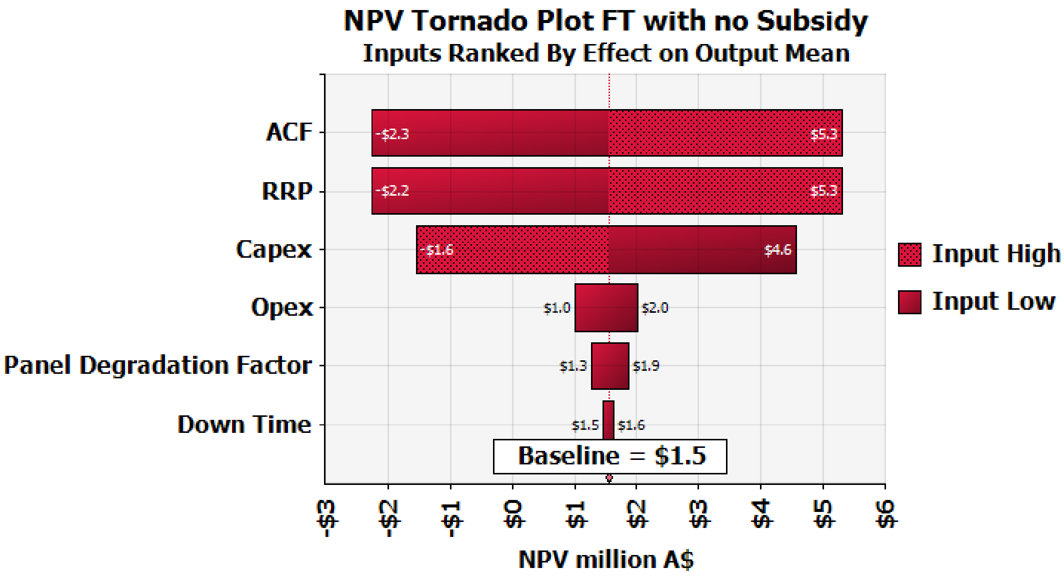


Fig. 6.27. WVSF FT Tornado plot without subsidy

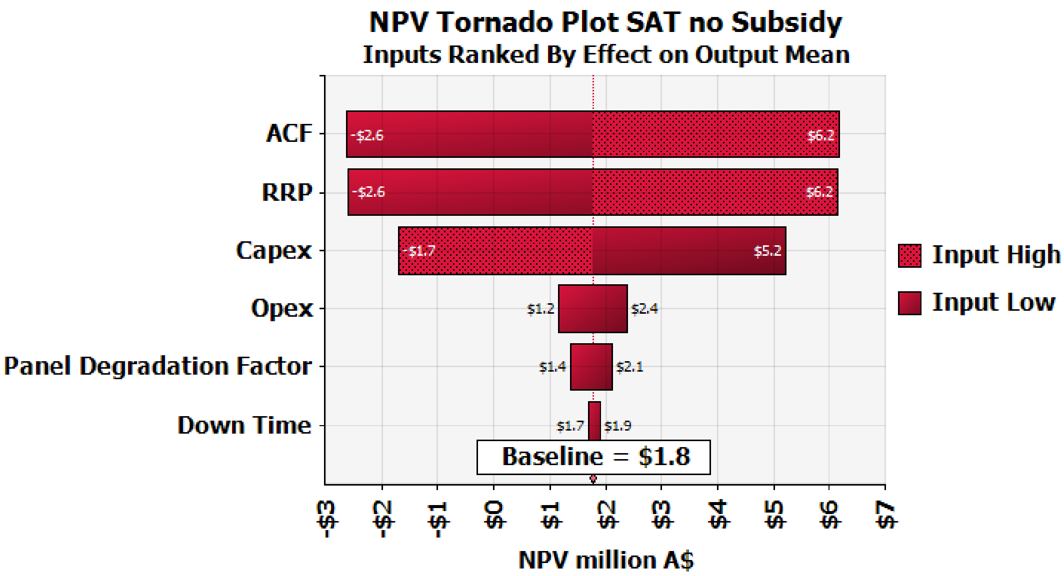


Fig. 6.28. WVSF SAT Tornado plot without subsidy

Differences between the arrays are clearer when NPV is plotted against cumulative probability for each system as shown in Fig. 6.30. As expected DAT falls well into the negative region with no probability of making a profit. However, the FT has better economics than SAT until the 65 percentile is reached. So, a risk averse investor may probably favour for the cheaper and simpler FT system. Given a more positive outlook then the SAT system will yield better economics despite a 10% higher capital exposure. The difference is marginal though. If the derivative of the NPV curves are taken, then they show that if the capex had been equal then the probability is greatest that the DAT can yield a superior result; i.e. it yields a greater volume of power (and income) over the whole year. Complete results for the @RISK simulations without subsidies are included in Table G.1.

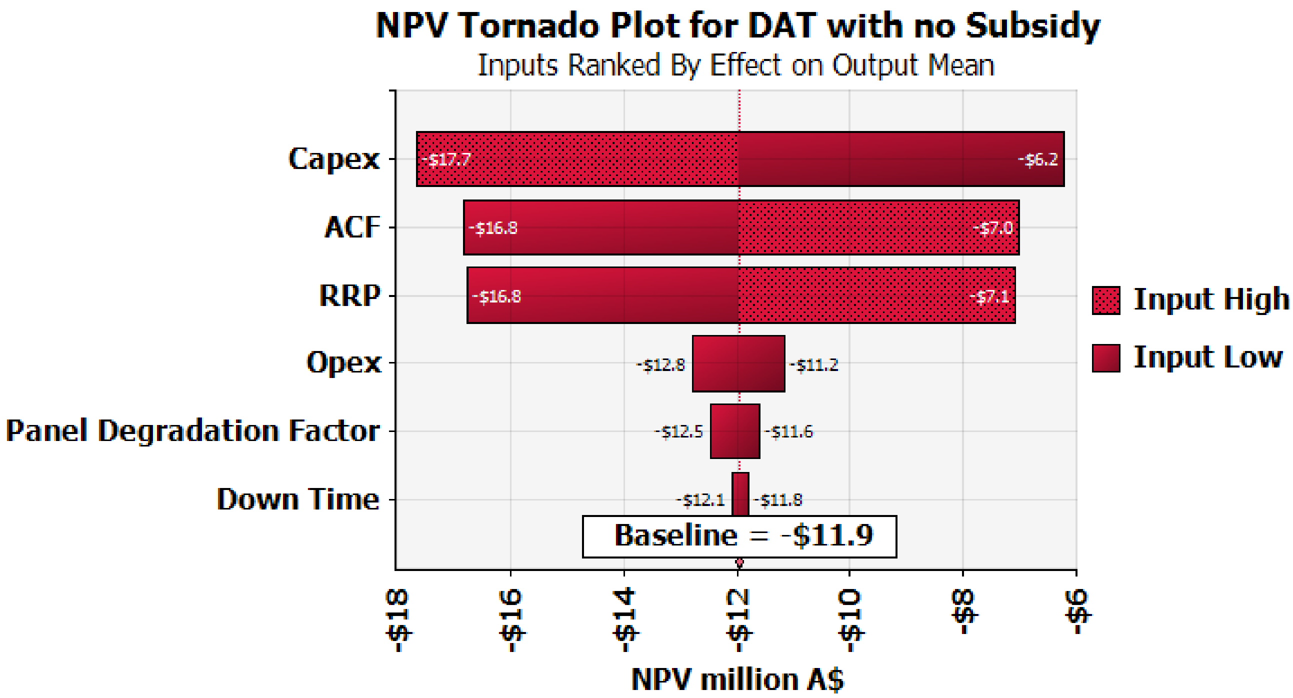


Fig. 6.29. WVSF DAT Tornado plot without subsidy

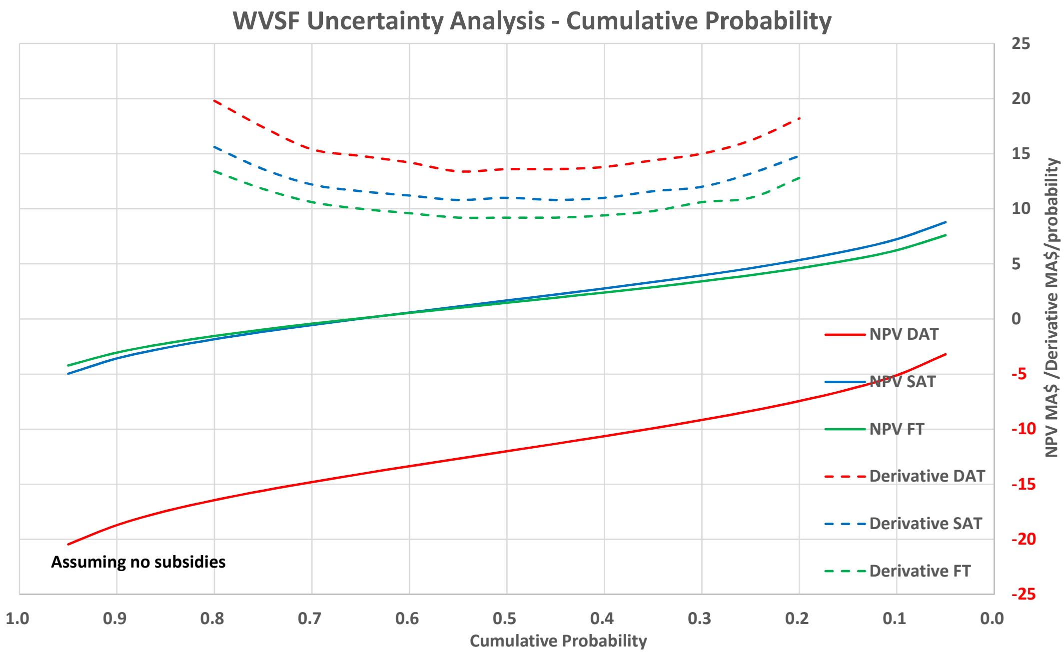


Fig. 6.30. WVSF uncertainty analysis without subsidies

6.4.2 Risk assessment including subsidies

With the 80A$/MWh subsidy the economics become most robust, even for DAT (Fig. 6.31, Fig. 6.32 and Fig. 6.33). The effect of panel degradation, opex and down time remain less important (until start up of course). In all three cases ACF has the greatest impact on the economics and this is one of the reasons why Australia has subsidised development of PV Solar. Developing the most efficient systems with the highest yield (of electricity) will reduce overall unit cost (LCOE) with time (as it has done spectacularly for FT and SAT during the last five years).

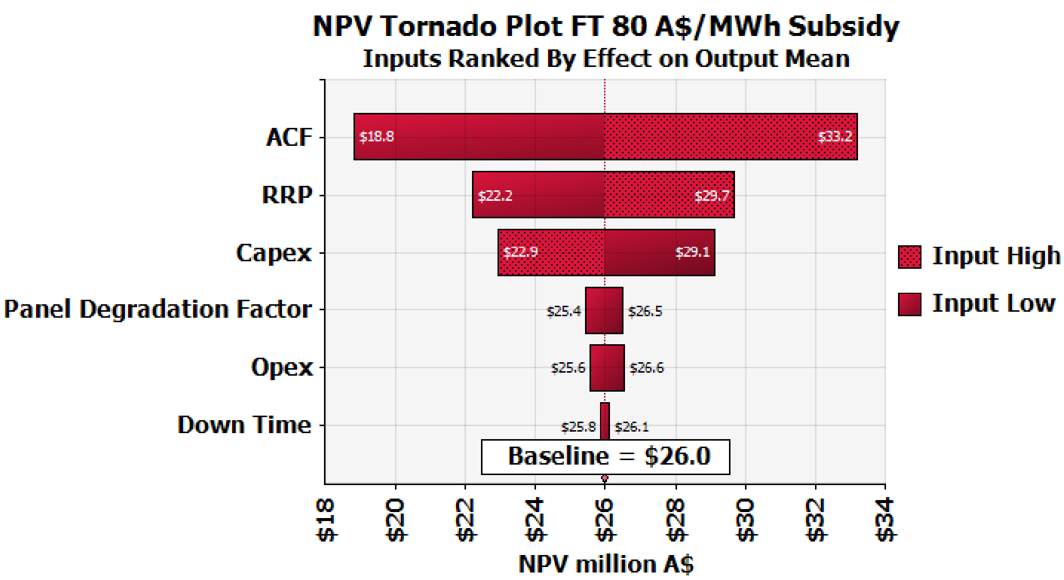


Fig. 6.31. WVSF FT Tornado plot with subsidy

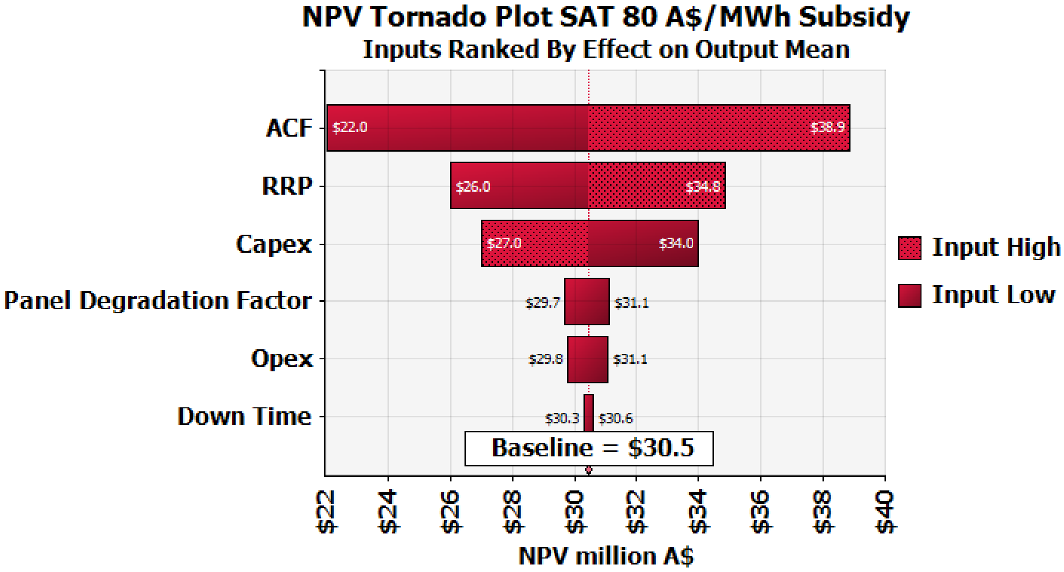


Fig. 6.32. WVSF SAT Tornado plot with subsidy

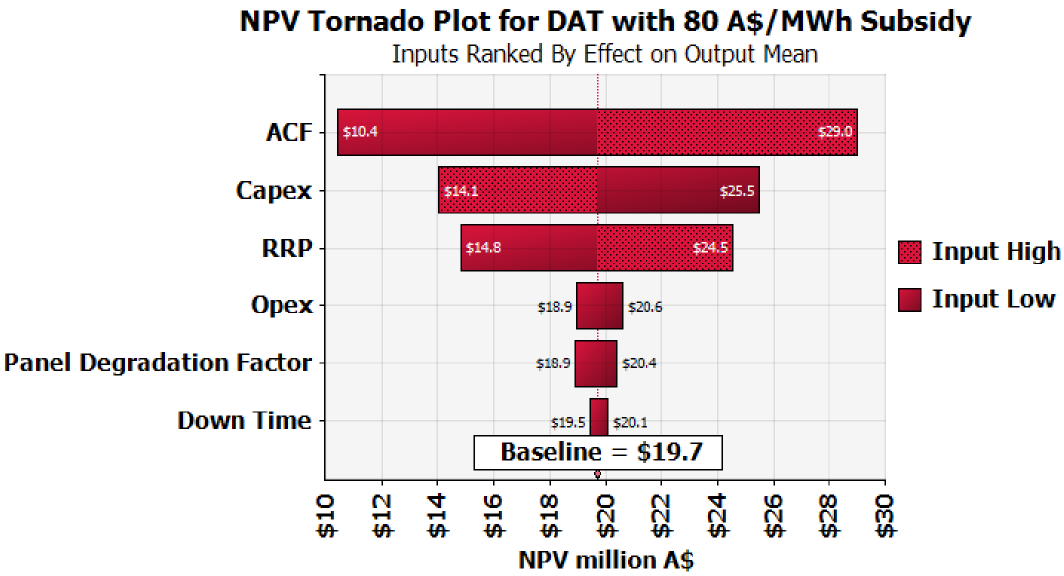


Fig. 6.33. WVSF DAT Tornado plot with subsidy

When the results are plotted against cumulative probability the overall picture is slightly different (see Fig. 6.34). This time all three array types yield solid economics. The capital exposure is still the same as before, however, the SAT array comes out best and is the obvious choice for WVSF, despite any perceptions of risk associated with the tracking system. It leads over the FT because it is more efficient at producing electricity on a daily basis (higher ACF). DAT is still hindered by its high capex, but as the derivative shows, once the issue with capex is sorted, it will have the potential to out perform SAT and FT. It is just not quite there yet and hence SAT is the correct choice for WVSF. Complete results for the @RISK simulations with subsidies are included in Table G.2.

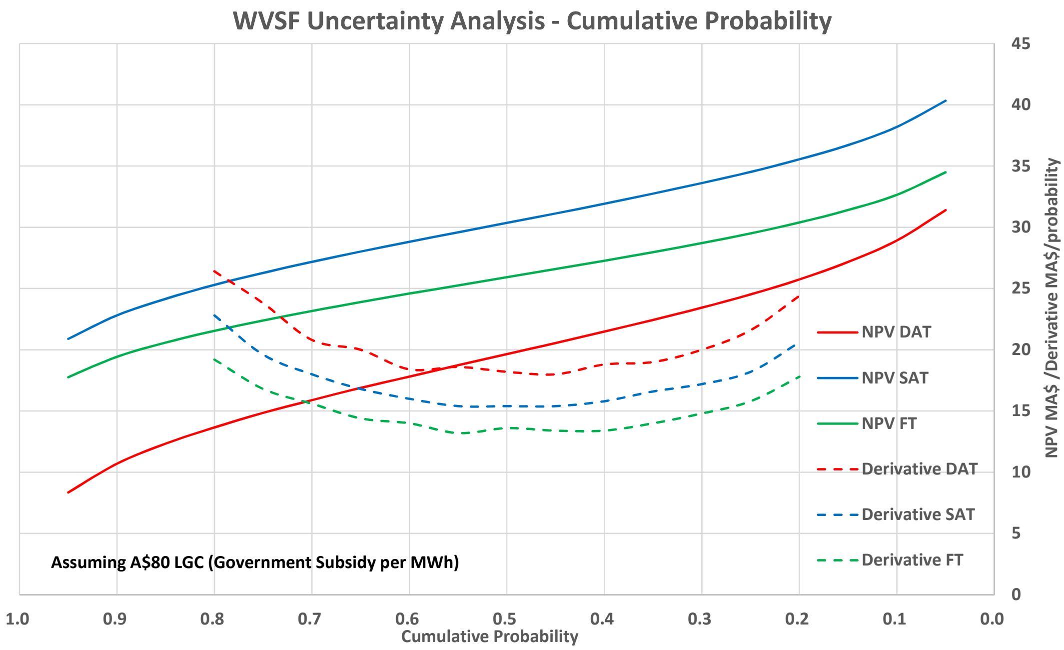


Fig. 6.34. WVSF uncertainty analysis with subsidies

6.5 Overall Performance Evaluation for Wesley Vale Solar Farm

An overall evaluation of the optimal array solution for WVSF has been performed. The results previously obtained created incentives for investigating methods for increasing project value. The fluctuating electricity price along with overproduction indicates a potential for storing excess energy for selling at a higher spot price. The under performance of SAT creates an opportunity for implementing a hybrid PV system which may increase the grid utilization. Finally, the most feasible array deployment for WVSF is suggested.

6.5.1 Storage

Due to grid limitations, any excess electricity produced by the arrays is capped. More specifically, WVSF has a limit of 12.5 MWac while the arrays are designed to deliver 15.6 MWdc to the inverter. Solar farms´ capacity commonly are dimensioned according to grid connection limitations (e.g. GSRF), while a greater DC capacity is installed. With the low panel prices, it can be advantageous to oversize panel capacity over the inverter power. As a result, more power is generated throughout the day, but excess electricity may be cut off during midday. This initiates incentives for investigating solutions for storing energy.

The importance of including storage was emphasized at the Smart Energy Conference & Exhibition 2018, Sydney [78]. Due to the minimal seasonal variations experienced at locations closer to equator, using batteries for storing the surplus electricity for a few hours is practical. In fact, such battery solutions providing a few hours' capacity have already proven to be economic [1]. This might be a feasible solution for GSRF in Queensland. In regions with greater seasonal variation, however, including battery storage to cover weeks or months would be unreasonably expensive. Rather, pumped hydro power could be suitable for seasonal storage. If the deployment of solar PV continues in Tasmania, a combined pumped hydro and solar PV solution is certainly an interesting opportunity to explore.

6.5.2 Hybrid PV system

As one of the major challenges in Australia is limitations in getting grid connection, it is desirable to maximise energy produced given the nameplate AC limitation, i.e. maximize the ACF. As SAT undoubtedly is the favoured array solution in Australia, WVSF is likely to employ this technology. The SAT system provides a significantly higher efficiency than FT. However, the graphs revealed certain drawbacks with SAT during winter, or potential for a hybrid system including FT. This was not only experienced in Tasmania, but also in Queensland which is considered as a lower latitude region. By installing additional FT arrays, the reduced production by SAT (especially at midday) during winter may be compensated for. Despite Tasmania still not being constrained by available grid capacity, the importance of maximizing grid utilization is considered as highly relevant for Australia in general and is further discussed.

A case was examined whereby some FT panels were included in addition to WVSF's nameplate capacity installed with SAT, with the intention of increasing grid utilization. For the purpose of the study, it was assumed that additional land was available. The case started with simulating the performance of WVSF for both FT and SAT with the same 15.6 MWdc capacity, but with a larger inverter so that production was not capped. Then by using Microsoft Excel, the SAT profile and a percentage of a FT profile were added together and then capped when they exceeded 12.5 MWac. The combined income was then calculated by using actual spot prices for Tasmania in 2017 (adjusted to hourly values) and compared with the cost of the additional FT arrays. The process was repeated from 0% to 100% of additional panels by using a macro in Excel.

The results of the simplistic analysis indicate that with no subsidies, adding more FT panels to improve the ACF, whilst keeping the 12.5 MWac inverter is not commercially of interest. If an 80 A$/MWh subsidy is added then some potential is seen although the time to pay back was long (in the order of 8-10 years).

The result disproved the hypothesis that a hybrid PV system could be more appropriate than just SAT, for WVSF. Even when including the subsidy from LGCs, such an investment could not be justified. The income from the incremental increase in generation at midday during winter did not compensated for the increased investment in panels. Despite this result, it should be noted how further reductions in capital costs and increased incentives for maximizing ACF will require the feasibility of hybrid system's to be continuously assessed. Moreover, it is becoming more common to install solar farms at less ideal sites which may include areas with challenging topography or soil conditions. If these areas are not suitable for SAT but possible with FT, the discussed hybrid solution may be commercially interesting. For WVSF, it is recommended that the future use of a hybrid system should be considered in the design and layout. The concept can then be revisited after start up, once actual field experience has been gained.

6.5.3 Final proposal for WVSF

SAT’s impressive results with regards to annual electricity production, together with its economic viability and suitable site topography makes it the preferred solution, even in this higher latitude location. WVSF is well suited for installing SAT as the site has ideal conditions, both being flat, square and with only a slight deviation from true north.

By extrapolating the area required for each array solution at GSRF, it is indicated that the WVSF site is not large enough to facilitate for DAT, given the nameplate capacity, while a SAT system would be appropriate.

As SAT is dominating the large scale market in Australia, it was not unexpected that it also would be the optimal solution for WVSF. However, the feasibility of SAT in Tasmania is more questionable with the state's higher latitude and lower solar irradiance. Higher latitude would generally favour DAT, however, associated capital costs are still too high. While a risk averse investor may have decided on FT, the owner of WVSF has a comprehensive experience with the Australian renewable energy industry, enabling them to select the more expensive SAT option and thereby have greater benefit from LGCs and a higher ACF. It should be noted that the level of subsidies are uncertain after 2020, complicating investment decisions. While it is difficult to predict future levels of subsidies, use of uncertainty analysis can help to de-risk the project.

Importantly, the analysis for WVSF confirmed SAT's superior feasibility in Australia’s higher latitude state. Additionally, the research also revealed the potential for a hybrid solution with FT or even DAT if ACF becomes of more significance and/or electricity prices increase.

6.6 Large Scale Solar PV Potential for Norway

Low electricity prices, ready access to green electricity production and less solar irradiance have prevented development of and incentives for deployment of solar PV in Norway. More specifically, Norway already produces over 95% of its electricity from hydro. However, an increasing interest and demand is occurring. The potential for large scale solar PV was assessed by performing simulations for FT, SAT and DAT in PVsyst for a similar facility to WVSF in Tasmania but placed in Norway. The main findings and considerations include:

- The potential energy yield for large scale solar PV in Norway is significant during summer.
- DAT could offer a remarkable performance once prices come down and regularity improves.
- FT is most likely to be installed initially.
- Floating PV may be competitive with floating offshore wind power and possibly a feasible energy source in the long run.
- The arrays' comparative advantage with regards to geographical location was further validated (DAT for higher latitudes and SAT closer to equator).
- The preferred array solution and tilt angle is greatly dependent on the

objective of the PV investment.

- The potential for PV must be evaluated in accordance to its opportunity cost and social economic benefit.
- There exists a need for further research into ground mounted PV structures under Norwegian conditions.

6.6.1 Status

As elaborated in "Solcellesystemer og sol i systemet", the Norwegian solar PV market is still in an early phase, however, an increasing interest and demand from both industry and the residential sector is occurring [2]. The country's solar industry has large potential, both nationally and globally as well as in several market segments. From 2016 to 2017 the deployment of PV increased by 59%, this being for the commercial and residential sector [2]. The impressive growth rate occurred despite Norway's low electricity prices and limited incentives for investment in solar PV. Small scale rooftop PV is likely to be competitive with end user tariffs, and a significant amount of installations can be expected [64]. Electricity prices are expected to increase, creating further incentives for investment in solar. As the return from feeding the electricity into the grid is lower than utilizing it for self consumption, PV systems are typically installed with the purpose of reducing power costs rather than earning from electricity sales [63]. Norway's large deployment of electrical vehicles creates a market for solar PV and smart energy management (energy storage at off peak rates). Moreover, future energy requirements for buildings are expected to be a driver for the solar market. As explained by Inger Andresen, Professor in Integrated Energy Design at NTNU, Building-Integrated PV (BIPV) offers promising technology for future buildings over the whole of Norway whereby components function as a building materials as well as producing electricity [62].

Interest is also expressed towards hybrid technologies whereby solar PV farms are integrated with existing hydroelectricity plants [2]. The potential for large scale solar PV is further elaborated by Christian Rynning-Tønnesen, President and CEO of Statkraft. "While onshore wind power would outperform any large scale solar PV in Norway today, floating PV may be competitive with floating offshore wind power and possibly a feasible energy source in the long run" [64]. Moreover, the advantage of the energy source is further expressed by Bjørn Thorud, Solar Energy Specialist at Multiconsult. "Compared to constructing new hydroelectricity plants, solar PV offers a quicker development process with ease of scaling" [65]. The potential electricity generation for solar PV integrated with hydro is discussed in Section 8.2.

As elaborated by Thor Christian Tuv, CEO of FUSen, commercial rooftop PV installations typically utilize fixed panels tilted at around 10°, facing east/ west as illustrated in Fig. 6.35 [69]. With the common objective of maximizing area utilization, along with the structure being less exposed to wind loads, this is seemingly the ideal layout. Orienting the panels towards the south, with a greater tilt angle would have increased generation output for an individual panel, but the associated area required to avoid shading makes this less efficient. When placed in an east/west direction they can be roof mounted on aluminium frames using ballast to hold them in place as opposed to screwing them down and compromising the integrity of the roof.

Fig. 6.35. Commercial PV installation in Norway with panels facing east/ west tilted 10° [67]

ASKO, Norway's largest grocery wholesaler, is at the forefront of the commercial PV deployment in the country [67]. For ASKO, the production profile matches the demand perfectly by generating electricity during summer when the need for cooling is greatest. During winter, the panels may be covered by snow when having such a small tilt angle, however, the electricity demand is also lower [68]. ASKO also use solar power to generate hydrogen for operating some of their delivery trucks [2].

There is still limited experience of installing ground mounted PV structures in Norway. Factors of particular importance include:

- Snow loads and the ability to shed snow to clear of the panels.
- Frost heave of supporting piles (resulting in SAT shafts coming out of alignment).
- Wind loads.
- Challenging and varied terrain.
- Desire to not create an impact upon nature and aesthetics .
- Need to capture diffuse irradiance (i.e. the ability to orient horizontally during overcast weather).

6.6.2 Electricity generation analysis for Norway

Simulations of electricity generation were performed in PVsyst with the objective of investigating the potential for solar PV in Norway. The results were then compared with those obtained for WVSF, Tasmania. The analysis involved an evaluation of the three array solutions in the same manner as for WVSF. More specifically, identical input parameters were specified in PVsyst, except for the tilt angle for FT and the geographical location with its associated weather data. This included project size, tracking range, the type and number of modules and inverters and their losses. Optimization of the tilt resulted in an angle of 43°. Due to the limited weather data for Norway offered by PVsyst, data for Stockholm, Sweden, was utilized. As Stockholm is located at a latitude of 59.3° and Oslo at 59.9° along with that the cities have rather similar weather conditions this was considered to be acceptable. The approach used for the simulation in PVsyst and a more detailed explanation of the results can be found in Section 5.4 and Section 6.1, respectively. Detailed summary sheets (simulation parameters, main results and loss diagram) are included in Appendix F.

Solar irradiance

As indicated in Fig. 1.1, the annual global horizontal irradiance is around 1900 kWh/m^2, 1500 kWh/m^2 and 1000 kWh/m^2 for GSRF, WVSF and Oslo, respectively. It can be seen that the solar irradiance is strongly related to latitude, as the cosine of the latitude are roughly proportional with the locations´ irradiance.

The difference in horizontal global irradiance which Oslo and Tasmania are exposed to throughout the year is illustrated in Fig. 6.36. Interestingly, the irradiance level experienced in Oslo from April to August is well above the level in Tasmania during winter. As there are two large scale solar farms to be installed in Tasmania with the intention of generating electricity throughout the whole year, there is certainly potential for harvesting solar energy in Oslo during the above mentioned period. During the winter months, however, the irradiance in Oslo is minimal.

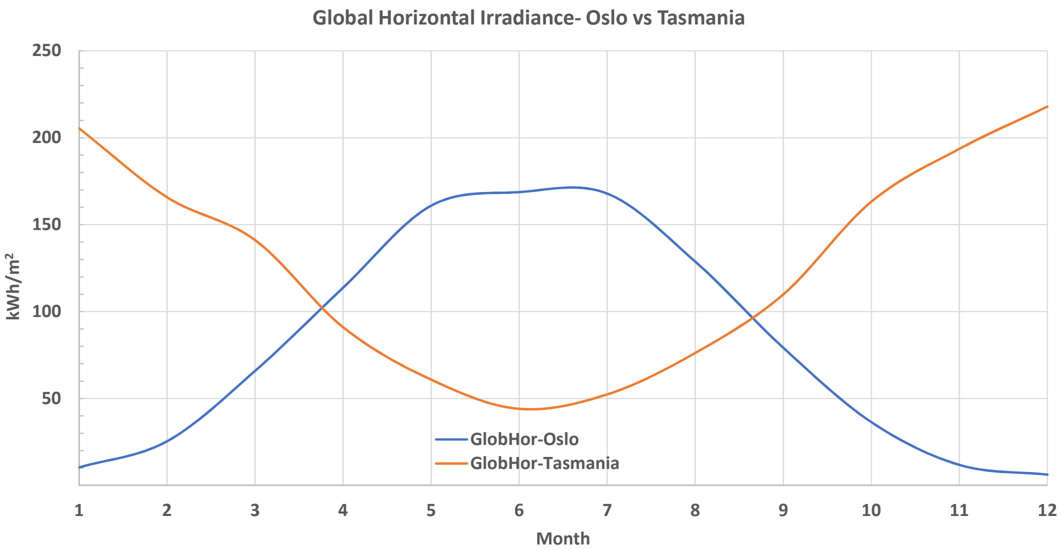


Fig. 6.36. Global horizontal irradiance Oslo vs Tasmania

Annual results

The arrays´ annual performance in Oslo have the same characteristics as in Australia as shown in Fig. 6.37. As previously discussed, DAT maximises production throughout the year, followed by SAT during summer and FT during winter. DAT continuously tracks the sun, SAT is advantageous when the sun is higher in the sky during summer and FT is favourable when the sun is lower in the sky during winter. It should be noted, that excess production (in accordance with the specified 12.5 MWac grid limitation) only occurred for DAT during summer.

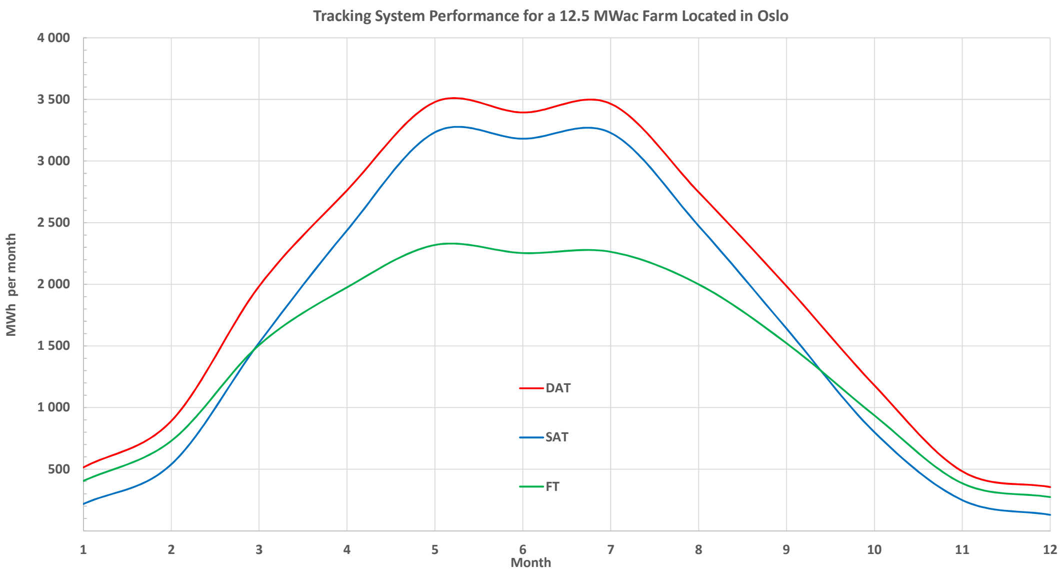


Fig. 6.37. Array performance for a 12.5 MWac farm located in Oslo

Moreover, the arrays' comparative advantage with regards to geographical location was further validated. SAT and DAT in Oslo achieve an increase in energy yield of almost 19% and over 40%, respectively as compared with FT. The increasing benefit of DAT at higher latitudes is demonstrated as it was 25% and 32% for GSRF and WVSF, respectively. SAT, on the other hand, proved to be more advantageous closer to equator, comparably having an increased energy yield of 20% and 19% for GSRF and WVSF, respectively. It should be noted that a minor difference of the values for SAT is likely due to that it generates a decent amount at midday during overcast conditions, not because of its tracking ability. Compared with WVSF, a reduction in annual energy output of 31%, 26% and 23% for FT, SAT and DAT, respectively, was found for the simulated facility in Oslo.

Results for sunny days

During sunny conditions, some differences in the characteristics for the arrays were detected when comparing daily output for Oslo and Tasmania. The daily output during summer, spring/ fall and winter is illustrated in Fig. 6.38, Fig. 6.39, Fig. 6.40 and compared with Fig. 6.5, Fig. 6.6, Fig. 6.7. Norway´s long summer days are accentuated by the additional production hours for the tracking systems. Compared to Tasmania where generation occurs from 05-20 hrs, SAT and DAT produces from 03-21 hrs in Oslo. FT is not capable of exploiting this sunlight. However, whilst the value of the early morning production achieved with tracking may be questionable, when seen in combination with hydroelectric power it is important, because water saved can be used later when demand and spot prices are higher. SAT´s under performance during midday and winter becomes more obvious in Oslo. As expected, Oslo´s higher latitude makes a south tilting FT more favourable as compared to SAT when the sun is lower in the sky. To summarize, the tracking arrays are favourable during summer, while FT´s and SAT´s performance is altered and reduced, respectively, during winter.

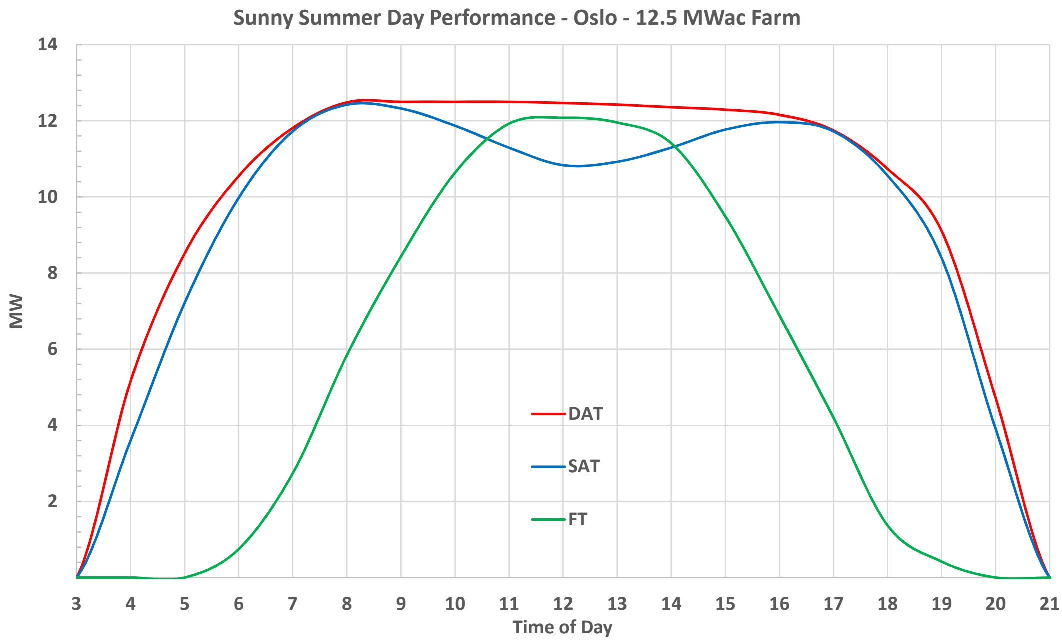


Fig. 6.38. Oslo performance during a sunny summers day

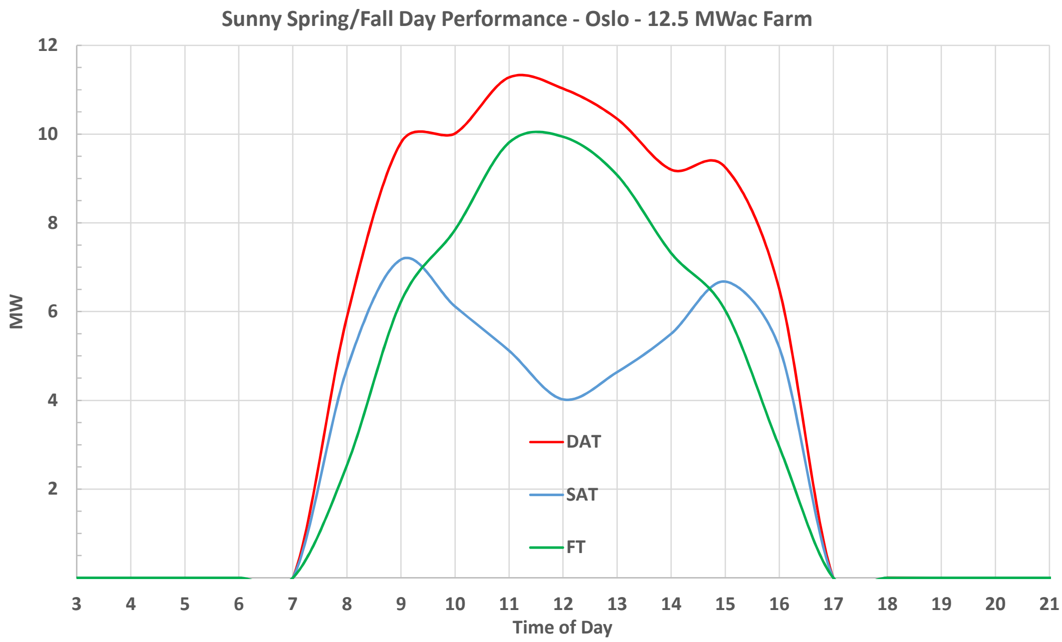


Fig. 6.39. Oslo performance during a sunny spring/fall day

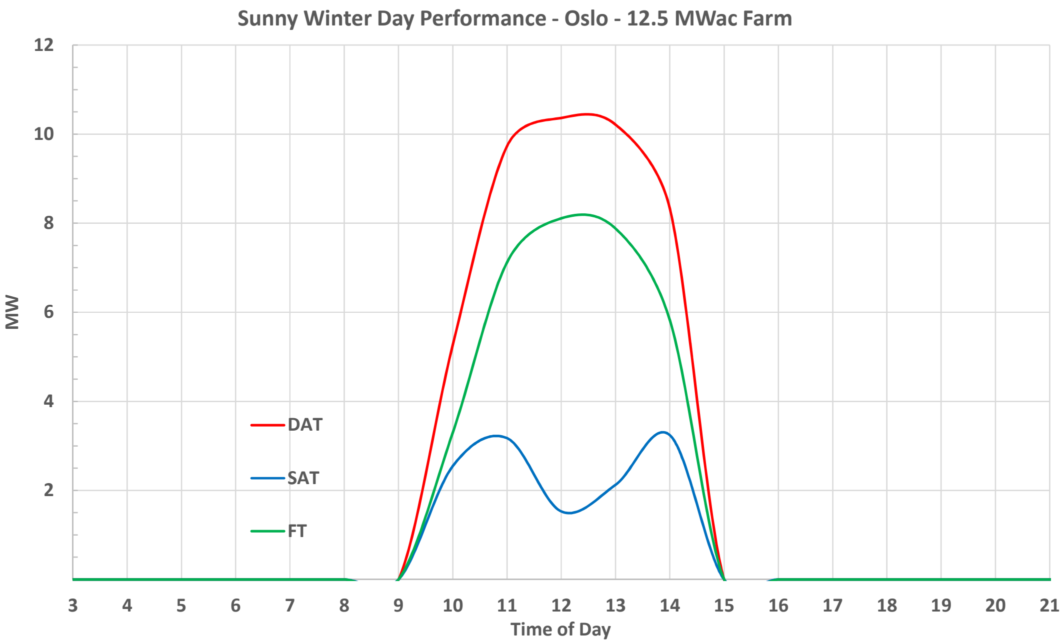


Fig. 6.40. Oslo performance during a sunny winter day

Results for overcast days

For overcast days, similar array characteristics are found for Oslo and Tasmania during summer, while differences are apparent for the remaining months of the year. The daily output during summer, spring/ fall and winter is illustrated in Fig. 6.41, Fig. 6.42, Fig. 6.43 and compared with Fig. 6.11, Fig. 6.12, Fig. 6.13. During summer, the array being most horizontal is most desirable, thereby making FT favourable during the shoulder hours and SAT during midday. The relative advantage of SAT´s horizontal position during midday becomes evident during spring, fall and winter. DAT with its continuous tracking of the sun´s position, however, has a drastically reduced performance, and even zero output during winter, hence the need to track the strongest sunlight and not the position of the sun (direct irradiance). It should be noted how the gain from SAT is due to its horizontal position, not its tracking ability, i.e. simple, flat lying panels would have resulted in the same generation. The difference experienced during overcast weather in Oslo and Tasmania can be interpreted as to what extent direct irradiance is present. While there seemingly still is a decent amount of direct irradiance throughout the year in Tasmania and during summer in Oslo, the diffuse irradiance clearly dominates in Oslo during the rest of the year. The combination of higher latitude and heavy cloud cover causes a high ratio of diffuse radiation and favours horizontal panels. Not to forget, the horizontal global irradiance is in general lower in Oslo, further reducing the potential energy harvesting.

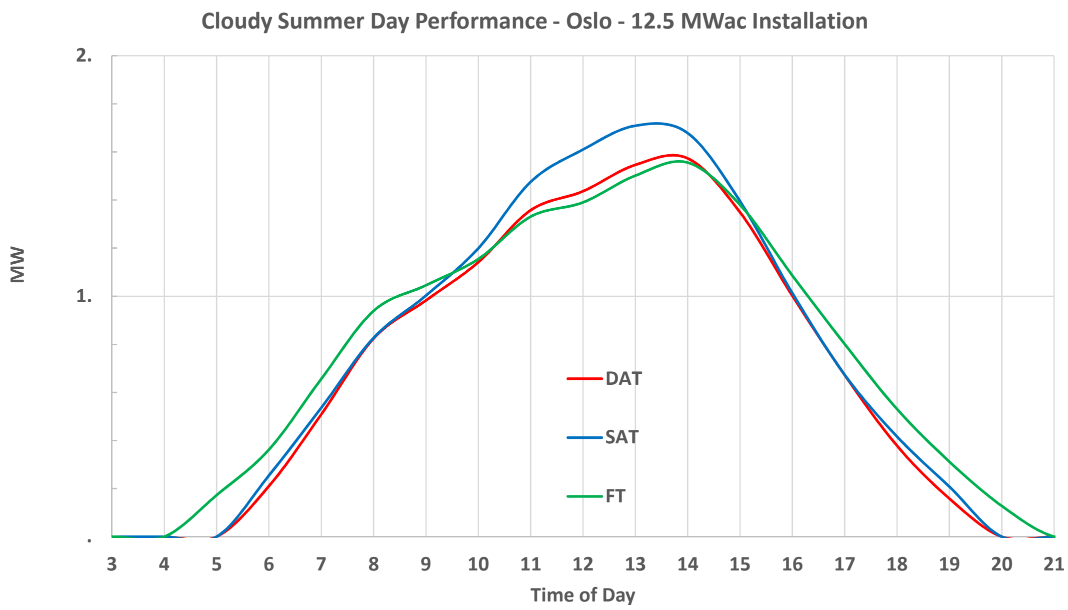


Fig. 6.41. Oslo performance during a cloudy summers day

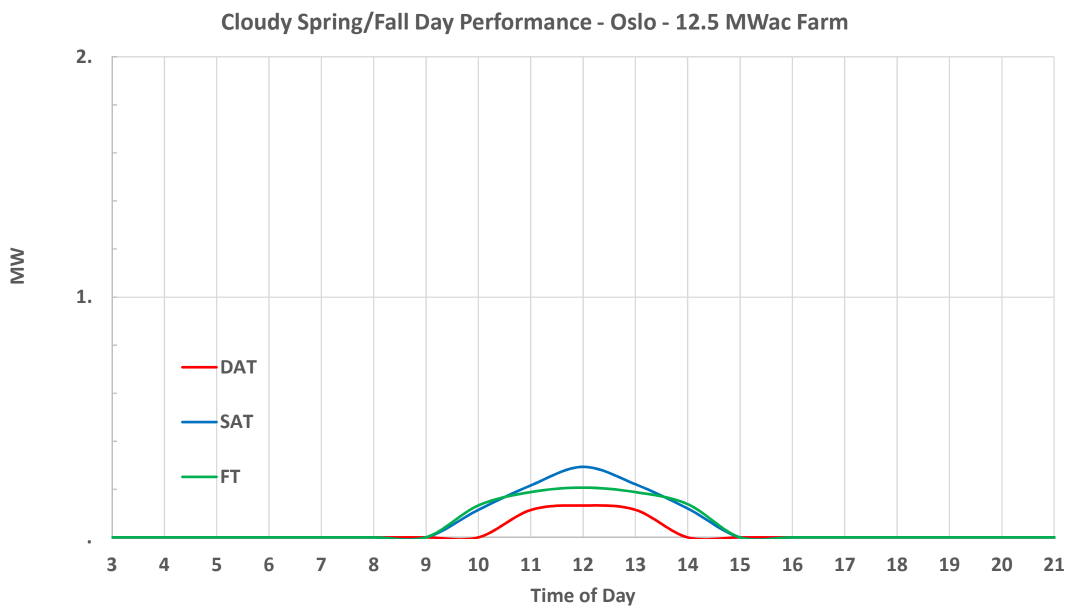


Fig. 6.42. Oslo performance during a cloudy spring/fall day

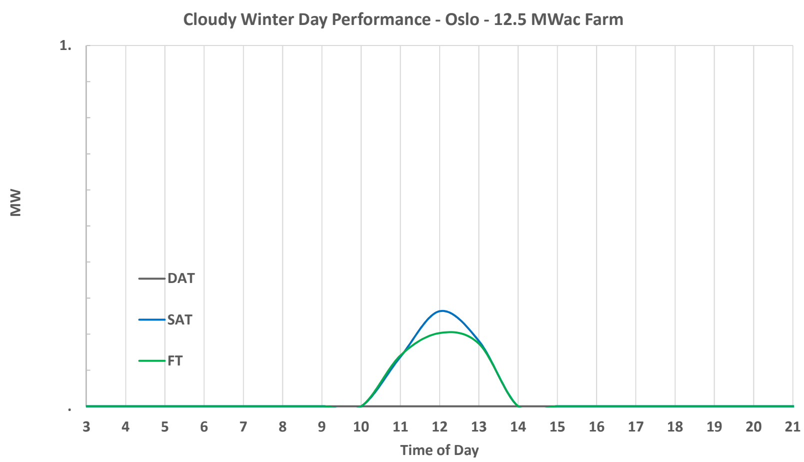


Fig. 6.43. Oslo performance during a cloudy winter day

Identifying potential for Norway
Based on the results obtained, the array solutions are evaluated in accordance with Section 4.2. To indicate the comparative advantage of the arrays along with their yearly potential for energy harvesting, several scenarios are illustrated in Appendix H. The superior potential for energy harvesting during summer is indicated.

As the results in the previous section revealed, the low irradiance during winter limits economic incentives for harvesting solar energy, however, the summer months offer remarkable potential. Favouring summer generation would also eliminate issues related to snow. However, it should be noted how surrounding snow can increase production by including albedo irradiance, especially for vertically installed BIPV [62]. Moreover, the relative income from selling electricity may be altered as prices generally are higher during winter. According to Per Olav Borgsø, Sales Manager at TrønderEnergi, there is limited knowledge of the influence of the albedo irradiance [66]. Further north (where the effect of albedo may be of greater significance) fixed panels generally should be installed with a steeper tilt angle, thereby facilitating capture of more of this associated irradiance. This is an area where more work is clearly required to quantify the potential.

DAT seems to be the ideal solution for Norway, if its associated capital expenditures declines, reliability improves and a tracking algorithm adjusting for overcast weather is implemented. The advantage of DAT´s ability of adjusting for seasonal variations increases with latitude, making Norway an ideal place for their employment. Moreover, the available flat and clear areas in Norway typically are occupied by farming and agriculture, limiting appropriate sites for installing the FT and SAT rows. DAT, however, could be an ideal supplement for such areas, resulting in increased land utilization. Additionally, DAT is suitable for challenging terrain and advantageous in snowy environments. However, the ability of the system to function at low temperatures as well as a significant cost reduction is required. When investing in the more capital intensive DAT systems, it is recommended to include the ability for the system to adjust for overcast weather. By utilizing sensors detecting the strongest light rather then following the direct irradiance, the tracking system can move to a horizontal position and rather optimize the collection of the diffuse light. This is a typical Machine Learning application whereby input from multiple weather stations can be used to optimize the orientation of the DAT arrays.

The preferred array technology for a potential future large scale PV installation in Norway would initially most likely be FT. If a ground mounted farm would be employed, it would probably be rather small (maximum a few MW capacity), and EPC contractors would tend to favour simpler construction options for smaller projects. Moreover, new markets usually begin with FT before maturing enough to employ tracking systems. FT offers both the least capital exposure and greatest reliability. That said, using an experienced EPC contractor (e.g. First Solar or Scatec Solar), together with a recognised international certification company (such as DNV GL) should permit a new player to jump up the learning curve without increasing risk exposure.

.

As expected, the performance of horizontal SAT at higher latitudes is limited and generally not recommended for Norway if the intention is to optimize annual production. However, the tilted single axis tracking, a similar system which includes a tilt angle like FT, could have great potential in Norway. Due to the lack of data, the tilted single axis tracking was outside the scope of this thesis, but such an array technology should be investigated further.

The importance of the objective of the installation is emphasized by Multiconsult's ongoing feasibility study at Svalbard (77.9°N), representing an extreme case for solar PV, as further elaborated by Bjørn Thorud [65]. Despite the high latitude, SAT is being evaluated. Importantly, it should be noted how elevated rows with bifacial panels (capable of capturing light from both sides of the modules) are being considered, thereby facilitating for collecting the albedo irradiance from the snow. In contrast to a FT installation facing south which would have compromised the potential energy gain available throughout the morning, afternoon and evening, SAT can harvest energy throughout the 24 hour days during summer (which is the objective of the farm). DAT has not been considered due to its limited track record and greater requirement for maintenance. Despite a lack of focus on bifacial modules in Australia, this technology is extremely interesting for Norway's snowy regions [8,65]. It should be noted how this case contradicts the previous conclusions drawn regarding tracking and latitude. However, it emphasizes the importance of clearly defining the project objectives and taking account of the advantages and limitations of the specific site location.

It can be concluded that there exists substantial potential for large scale solar PV in Norway during summer, and while FT is most likely to be installed initially, DAT could offer a remarkable energy yield once prices come down and regularity improves. Furthermore, new technology (bifacial modules) may create a new market sector for solar PV.

6.6.3 Considerations

It should be emphasized how the value of a solar PV system needs to be considered in accordance with the opportunity cost. The levelized cost of electricity is suitable for comparing power generation technologies and may provide a valuable indication for countries like Australia where solar PV may be regarded as a major energy source. For countries like Norway, however, the LCOE is somewhat misleading. The potential for PV should be evaluated in accordance to its alternative cost and social economic benefit (e.g. building a new hydroelectric facility, installing more wind parks or importing nuclear or coal power from abroad). In addition to the spot price providing potential earnings, benefits of replacing building material by utilizing BIPV giving the opportunity for residential and corporate consumers to be prosumers, as well as PV for niche markets such as charging of electrical vehicles, is essential to identify. As high costs are expected for upgrading the electricity grid, investing in microgrid solutions may be both a cost efficient and environmentally friendly alternative. Utgard Microgrid, owned by Powel and Trønder Energi, offer software for the design, simulation and analysis of the energy balance of a system including solar, wind and battery storage [60].

Equinor and Scatec Solar are both Norwegian companies at the forefront of large scale solar PV involved in international projects. Scatec Solar offers extensive knowledge throughout the value chain, and develops, builds, owns, operates and maintains solar power plants. Equinor typically invests in countries where they already operate and have local expertise, thereby facilitating an efficient development process [70]. While the companies' expertise has been acknowledged internationally, the associated uncertainty of such investments, for instance the risk associated with exchange rates should be emphasized [70]. An investment in Norway could exclude such issues as well as offer an important social economic benefit for the country.

Moreover, as expressed by both Irma Pienaar, Vice President- Supply Chain and Terje Melaa, Senior Vice President- Technology Solutions, at Scatec Solar along with Richard Erskine, Managing Director at Equinor Technology Invest, the importance of storage solutions should be emphasized [71,72,70]. In a case where large scale solar PV would be installed in Norway, its regularity would not be as predictable as in Australia. However, by integrating solar PV with hydroelectricity, the latter could be regarded as an effective storage solution.

7 CONCLUSIONS

The thesis has evaluated the performance of three array technologies, namely fixed tilt (FT), horizontal single axis tracking (SAT) and dual axis tracking (DAT). The analysis was performed for Wesley Vale Solar Farm (WVSF), a recently approved solar PV project in Tasmania, Australia. The technical performance of the arrays was analysed by using the simulation software PVsyst. The economic viability and key cost drivers were identified and discussed by calculating the Levelized Cost of Electricity (LCOE) and performing uncertainty analysis in @RISK. Furthermore, by identifying trends in electricity demand, the commercial potential was assessed. Geographical characteristics of higher latitude locations were determined by a continuous comparison of the WVSF (41°S) with a solar PV farm located closer to the equator, namely the Gatton Solar Research Facility (GSRF, 27°S) in Queensland, Australia. As this farm includes FT, SAT and DAT with associated real electricity generation data, it also provided validation of the simulated electricity output predicted for WVSF. Based on technical performance and economic viability, an optimal array solution for the WVSF was proposed. Moreover, WVSF can be considered to have similar conditions to Norway with regards to a higher latitude and colder climate. An extrapolation of the results for WVSF was used to evaluate the potential for Norway.

While SAT is dominating the large scale market, the optimal array solution is determined by the project environment and objectives. The site's latitude, solar irradiance, weather, site conditions as well as available area and grid capacity are influencing factors. FT with a smaller tilt angle is ideal when exposed to a higher ratio of diffuse irradiance which may occur due to overcast weather, at higher latitude locations and during winter. SAT is superior closer to the equator. When sunny, it is ideal during the morning and evening, however, if it is overcast weather it is better during midday. For clear sky conditions, DAT always performs best, and its advantage increases with higher latitude. While SAT is most commonly deployed for larger farms, FT and DAT are suitable for both smaller and larger ones. In contrast to SAT, FT and DAT are capable or more challenging geo-technical conditions and site topography, additionally, DAT is more appropriate for combining with farming and agriculture. While the capital exposure increases with the advancement of tracking, the arrays' reliability decreases accordingly. If it is desirable to maximize peak capacity per area, FT is preferable. However, higher energy yield and grid utilization is achieved with tracking and increases along with its complexity.

The tracking solutions' technical performance for WVSF resulted in an increased production of 19% and 32% for SAT and DAT, respectively (over FT). However, it became evident that SAT is just about as productive as DAT during the summer. Throughout the spring and fall FT becomes more efficient relative to the other arrays during midday whilst SAT begins to suffer from being horizontal and its lack of tilt angle at this time. Importantly, SAT and DAT still produce significantly greater amounts of electricity during the shoulder hours of the day, not just because of their orientation but also due to the lower ambient temperatures improving module efficiency. During winter, the most apparent drawback of SAT occurs with its low output during midday, indicating the advantage of having a tilt angle. For overcast days, the tracking systems ability to produce during the shoulder periods becomes absent and the relative performance of FT was superior for all seasons. The real generation data from GSRF (available per minute), revealed the actual electricity production experienced, in contrast to the hourly simulated data obtain for WVSF in PVsyst.

The arrays' feasibility were assessed by evaluating generation output in accordance with the income stream from selling electricity at the spot market, accounting for the fluctuating prices during the day, week and year. Along with discovering trends in electricity prices and demand, it was found that there exists potential for storing electricity and selling at higher prices.

The uncertainty analysis indicated that key cost drivers were dependent on if the project received subsidies or not. While annual capacity factor (ACF) and electricity spot price has the greatest impact on the economics for FT and SAT in the case without subsidies, capex is most determining for DAT. However, when including subsidies, ACF was found to be the key cost driver for all three arrays. While a risk averse investor would favour FT where no subsidies exist, SAT is the obvious choice when they are included. Operating costs did not appear to have a significant impact on project value even for the more expensive DAT technology.

The results for both WVSF and GSRF revealed certain drawbacks with SAT during winter, or potential for a hybrid system including FT. As one of the major challenges in Australia are limitations in getting grid connection, it is desirable to maximise energy produced given the nameplate AC limitation, i.e. maximize the ACF. A case was examined whereby some FT panels were included in addition to WVSF's nameplate capacity installed with SAT, with the intention of increasing grid utilization. The results indicated that the hybrid solution is not commercially of interest. However, it should be noted how further reductions in capital costs and increased incentives for maximizing ACF will require the feasibility of hybrid systems to be continuously assessed. Moreover, it is becoming more common to install solar farms at less ideal sites which may include areas only suitable for FT thereby making a hybrid solution commercially interesting.

SAT's impressive results with regards to annual electricity production, together with its economic viability and suitable site topography makes it the preferred solution for WVSF. The analysis for WVSF confirmed SAT's superior performance, even for the higher latitude location. Additionally, the research revealed the potential for a hybrid solution with FT or even DAT if ACF becomes of more significance and/or electricity prices increase.

There exists substantial potential for large scale solar PV in Norway during summer. DAT is seemingly the ideal solution for Norway, if its associated capital expenditure declines, reliability improves and a tracking algorithm adjusting for overcast weather is implemented. However, for a large scale application in a new market, FT would likely be the preferred solution with its lower costs and proven reliability. Combining solar PV with hydro has clear potential in Norway and is the likely route for large scale farms. To identify the actual benefits of PV in Norway, the electricity production should be evaluated in accordance with alternative costs and social economic benefit, not just through project (NPV) economics.

8 FURTHER WORK

Throughout the research, certain areas of significance became apparent and are further discussed in this chapter. These include the need for quality control, the potential for a hybrid solution of solar PV with existing hydro in Norway and the opportunity for efficient system management by utilizing data analytics.

8.1 Quality Control

The importance of quality control has become evident as many issues have been experienced in Australia. As discussed in Section 2.3, challenges related to the installation, alignment and stability of the piles, electrical installation work and programming of the inverters and tracking systems have occurred. According to Graham Slack, Country Manager for DNV GL Australia, the country is currently experiencing a lot of issues with the tracking systems (SAT) [73]. Despite that being common as for any implementation of new technology, many of the problems which have occurred were avoidable, emphasizing the importance of standard quality control for system components and project execution throughout a PV plants lifetime. The tracking systems, being both newer in deployment as well as being more exposed to faults, are crucial to assess. Importantly, issues with SAT have also been expressed by the owner of O2 Energies, a U.S. company, further emphasizing the importance of quality control [76].

With solar PV still in an early phase in Norway, it would seem wise to utilize experience and expertise from more developed markets to benefit from their practices when implementing new technology. Companies with such experience are well placed for verifying project plans as well as ensuring that it is built properly. According to [74], installation of solar PV systems are offered by many companies in Norway, however, the level of competence is varied. Along with the increasing interest and deployment for solar PV in Norway, a demand for guidance and due diligence will likely follow.

Australia’s emphasis on ensuring a reliable energy supply is resulting in the inclusion of batteries in many solar PV farms. As with any new technology in the industry, standards are crucial for maximizing project value. Currently, there are no agreed international methods for evaluating batteries for PV applications. However, DNV GL recently introduced GRIDSTOR [74], a grid scale energy storage certification. Moreover, the company is about to announce a major project on this very topic for Australia [73].

8.2 Hybrid Solution of Solar PV & Hydro

Combining solar PV and hydroelectric has not yet been performed in Norway, but has been done elsewhere in the world (e.g. Portugal and China). Advantages of combining the sources and in particular having the PV installation floating in Norway include:

- area is already regulated for industrial purposes
- flat
- typically higher up in clean air with the potential for reflected light from snow
- export infrastructure for power already in place
- less scope for interference by animals or humans
- cooling if in direct contact with the water
- reduces evaporation from the lake (more of an issue in hot countries)
- relatively easy to install, short project execution time and scalable

Disadvantages include:

- electronics dislike humidity
- challenging to maintain
- cost of floating elements
- will be covered with snow/ice for several months per year
- mooring system can be overstressed by ice movement
- need to protect the PV panels from external ice forces

Onshore wind turbines are currently meeting much resistance and floating offshore wind turbines are still too expensive to employ in the deep water off Norway. Building additional hydroelectric facilities is possible, but also likely to meet much public resistance. Floating solar PV could therefore represent a simpler option for implementing large scale solar PV in Norway.

Initial simulations with PVsyst (using Oslo meteorological data) suggest that each square kilometre of PV cells would yield about 180 MWac of power with an annual production of over 160 GWh for panels lying horizontal (based upon Appendix F). By including a tilt angle, 200 GWh could be achieved, but that would require a larger area with associated costs. To put this in perspective, Statkraft's Tyssefaldene facility produces 500 MW and yields 2 000 GWh per annum. As Fig. 8.1 shows, the possibility exists to install several (many) square kilometres of solar PV at this site alone, thereby significantly increasing the total output for this facility.

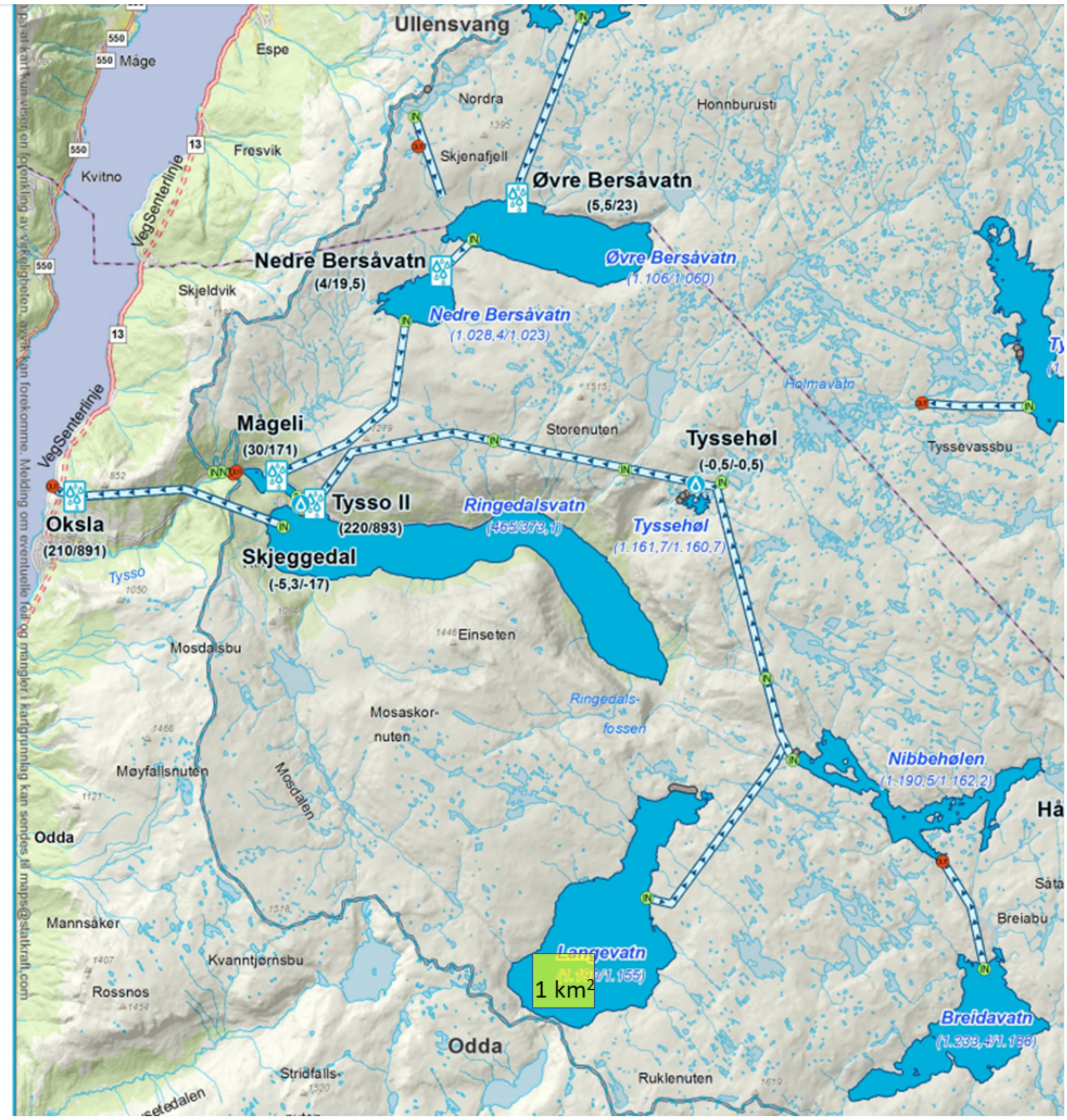


Fig. 8.1. Tyssefaldene hydrcelectric catchment area [77]

8.3 Data Analytics

Utilizing data is becoming essential for ensuring efficient O&M and optimizing project economics. As systems become larger and more complex the importance of integrating data with control systems becomes significant. When more data and experience is gathered, real-time sensing will facilitate for cost savings. Large amounts of data is not sufficient in itself, it must be of high quality and further processed and transformed to give insight, useful information.

In Europe, due to the maturity of the PV industry, there is a highly competitive advanced focus in the O&M market, and Machine Learning (ML) will be used for O&M within 2018 [8]. An elaboration of ML and its potential was written by the author of this thesis and can be made available from NTNU on request (semester thesis fall 2017) [79]. Typical functionality can include:

- Detect and identify failure and further determine if the problem should be assessed or delayed to the next scheduled inspection (i.e. the cost of lost production versus the cost of repairing).
- Optimizing layout of the farm.
- Move tracking arrays to a position to avoid being covered in snow or to remove snow that has built up.
- Self inspection using drones for identifying hot spots on the panels.
- Pattern recognition for learning the electricity spot market to optimize the use of battery systems.

9 REFERENCES

[1] DNV GL 2017a. Energy Transition Ooutlook 2017.

[2] MULTICONSULT & VIAK, A. 2018. Solcellesystemer og sol i systemet.

[3] BP 2018. BP Energy Outlook 2018.

[4] PWC 2014. The Road Ahead Gaining Momentum from Energy Transformation.

[5] NATIONAL RENEWABLE ENERGY LABORATORY 2017. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017.

[6] WITTMER, B. 2018. *RE: Scientific Collaborator, PVsyst.*

[7] SOLAR POWER WORLD. 2016. *Advantages and disadvantages of a solar tracker system* [Online]. Available: https://www.solarpowerworldonline.com/2016/05/advantages-disadvantages-solar-tracker-system/ [Accessed 2018.02.20.].

[8] PWC, RYSTAD ENERGY, FIRST SOLAR, JINKO SOLAR, NEXTRACKER, ARRAY TECHNOLOGIES, SIGNAL ENERGY, AGL, IMPACT INVESTMENT GROUP, DIF, UNIVERSITY OF NEW SOUTH WALES, AUSTRALIAN ENERGY MARKET OPERATOR, EPURON & DNV GL. 2018. *Private Communications with Australian Industry Participants.*

[9] PWC 2017. Utility Scale Solar PV Projects.

[10] AUSTRALIAN ENERGY MARKET OPERATOR. 2018a. Available: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information [Accessed 2018.05.01.].

[11] AUSTRALIAN GOVERNMENT DEPARTMENT OF THE ENVIRONMENT AND ENERGY. 2018. *A better energy future for Australia* [Online]. Available: https://www.energy.gov.au/government-priorities/better-energy-future-australia [Accessed 2018.05.30.].

[12] AUSTRALIAN ENERGY MARKET OPERATOR The National Electricity Market.

[13] SOLARGIS. 2014. *World Map of Global Horizontal Irradiance* [Online]. Available: http://solargis.info [Accessed 2018.05.30.].

[14] EPURON. *Wesley Vale Solar Farm* [Online]. Available: http://epuron.com.au/solar/wesley-vale-solar/ [Accessed 2018.05.30.].

[15] EPURON 2018. Development Application Wesley Vale Solar Farm.

[16] WILD, P. 2016. Comparative production performance of three solar PV technologies installed at UQ Gatton campus.

[17] PENNSTATE. 2018. *Main components of the PV systems* [Online]. Available: https://www.e-education.psu.edu/eme812/node/681 [Accessed 2018.04.20.].

[18] DNV GL 2015. Project certification of photovoltaic power plants.

[19] PVEDUCATION. 2014. *Solar Cells, Modules, and Arrays* [Online]. Available: https://pveducation.com/solar-concepts/solar-cells-modules-arrays/ [Accessed 2018.02.15.].

[20] STANDARD SOLAR. *From Solar Cell to Solar Array* [Online]. Available: https://standardsolar.com.au/solar-panels/ [Accessed 2018.05.30.].

[21] PVEDUCATION. 2018. *PVEducation* [Online]. Available: https://www.pveducation.org/ [Accessed 2018.03.15.].

[22] QUEEN MARY UNIVERSITY OF LONDON The Shockley-Queisser limit.

[23] UNIVERSITY OF NEW SOUTH WALES. 2016b. *Milestone in solar cell efficiency by UNSW engineers* [Online]. Available: https://newsroom.unsw.edu.au/news/science-tech/milestone-solar-cell-efficiency-unsw-engineers [Accessed 2018.02.15.].

[24] ENERGY INFORMATIVE. 2018. *Which Solar Panel Type is Best? Mono- vs. Polycrystalline vs. Thin Film* [Online]. Available: http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/ [Accessed 2018.05.30.].

[25] SOLAR POWER WORLD. 2018b. *What is a solar inverter and how does it work?* [Online]. Available: https://www.solarpowerworldonline.com/2013/04/how-do-solar-inverters-work/ [Accessed 2018.04.22.].

[26] PVSYST. Available: http://www.pvsyst.com/en/ [Accessed 2017.05.05.].

[27] DNV GL 2017b. PV Module Reliability Scorecard Report 2017.

[28] GUDBRANDSEN, A. J. 2018. *RE: Solar PV Farm Visits, Australia.*

[29] SENANI, S. A. 2017. Photovoltaic Module and System Fault Analysis.

[30] PVEDUCATION. 2018. *PVEducation* [Online]. Available: https://www.pveducation.org/pvcdrom/properties-of-sunlight/the-sun [Accessed 2018.04.15.].

[31] CUEVAS, A. 1998. *Solar radiation in the atmosphere* [Online]. Available: http://users.cecs.anu.edu.au/~Andres.Cuevas/Sun/Irrad/Irradiation.html [Accessed 2018.02.03.].

[32] NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. 2018. *Cloud Climatology Global Distribution and Character of Clouds* [Online]. Available: https://www.giss.nasa.gov/research/briefs/rossow_01/distrib.html [Accessed 2018.04.30.].

[33] LIVING ON SOLAR POWER. 2013. *How the Sun Moves Through the Sky* [Online]. Available: https://livingonsolarpower.wordpress.com/2013/03/08/how-the-sun-moves-through-the-sky/ [Accessed 2018.02.02.].

[34] NOTES FROM NOOSPHERE. 2012. *The simple geometry of sun, moon, and star paths* [Online]. Available: http://notesfromnoosphere.blogspot.com/2012/05/simple-geometry-of-sun-paths.html [Accessed 2018.02.03.].

[35] MARSH, A. 2018. *Sun path* [Online]. Available: http://andrewmarsh.com/apps/staging/sunpath3d.html [Accessed 2018.04.04.].

[36] NATIONAL RENEWABLE ENERGY LABORATORY. *Glossary of Solar Radiation Resource Terms* [Online]. Available: http://rredc.nrel.gov/solar/glossary/gloss_g.html [Accessed 2018.02.03.].

[37] RENEWABLE ENERGY WORLD. 2003. *The Sun as an Energy Source* [Online]. Available: https://www.volker-quaschning.de/articles/fundamentals1/index.php [Accessed 2018.03.04.].

[38] MEYER, J. 2015. Solar Electricity Utilization in Finland.

[39] SUNLINK. 2017. *To track or not to track- why a one size fits all approach can limit your optimal solar production*

[Online]. Available: https://sunlink.com/trackervsfixedtilt/ [Accessed 2018.04.04.].

[40] SOLAR POWER WORLD. 2017. *What is a dual-axis solar tracker?* [Online]. Available: https://www.solarpowerworldonline.com/2017/09/dual-axis-solar-tracker/ [Accessed 2018.04.04.].

[41] SOLAR POWER WORLD. 2018a. *Fixed-tilt vs. tracker: Why a one-size-fits-all approach can limit solar production* [Online]. Available: https://www.solarpowerworldonline.com/2018/02/fixed-tilt-vs-tracker-one-size-fits-approach-can-limit-solar-production/ [Accessed 2018.04.05.].

[42] INDEPENDENT POWER SYSTEMS. 2016. *The benefits of a tracker solar system: on and off the grid* [Online]. Available: http://solarips.com/2016/02/like-a-sunflower-solar-pv-panels-track-the-sun/ [Accessed 2018.04.04.].

[43] RENEWABLE ENERGY WORLD. 2015. *Ensuring Your Solar Array Doesn't Get Caught in the Wind* [Online]. Available: https://www.renewableenergyworld.com/articles/print/volume-18/issue-4/features/solar/ensuring-your-solar-array-doesn-t-get-caught-in-the-wind.html [Accessed 2018.04.05.].

[44] MEHRTASH, M., QUESADA, G. & ROUSSE, D. R. 2013. Effects of surroundings snow coverage and solar tracking on photovoltaic systems operating in Canada.

[45] U.S. DEPARTMENT OF ENERGY. 2017. *Let it Snow: How Solar Panels Can Thrive in Winter Weather* [Online]. Available: https://www.energy.gov/eere/

articles/let-it-snow-how-solar-panels-can-thrive-winter-weather [Accessed 2018.04.07.].

[46] NATIONAL RENEWABLE ENERGY LABORATORY 2016. Best Practices in Photovoltaic System Operations and Maintenance.

[47] ALLEARTH SOLAR. *Solar Panels and Snow: The Advantages of Dual-Axis Trackers* [Online]. Available: https://www.allearthrenewables.com/blog/dealers/solar-panels-and-snow-advantages-of-dual-axis-trackers [Accessed 2018.04.20.].

[48] JONES, C. 2018. *RE: Managing Director, IPEX.*

[49] AUSTRALIAN ENERGY MARKET OPERATOR The National Electricity Market.

[50] ABC NEWS. 2018. *Wholesale electricity prices up in Victoria since Hazelwood power station closure* [Online]. Available: http://www.abc.net.au/news/2018-03-29/hazelwood-electricty-prices-climate-pollution-gas-supply/9599998 [Accessed 2018.06.01.].

[51] AUSTRALIAN ENERGY MARKET OPERATOR. 2018b. *Aggregated Price and Demand Data - Historical* [Online]. Available: http://energylive.aemo.com.au/Home/Electricity/National-Electricity-Market-NEM/Data-dashboard - aggregated-data [Accessed 2018.03.20.].

[52] AUSTRALIAN GOVERNMENT BUREAU OF METEOROLOGY. 2018. *Climate Data Online* [Online]. Available: http://www.bom.gov.au/climate/data/ [Accessed 2018.04.22.].

[53] THE UNIVERSITY OF QUEENSLAND. 2018. *UQ Solar Photovoltaic Data* [Online]. Available: http://solar.uq.edu.au/user/reportPower.php [Accessed 2018.04.01.].

[54] NATIONAL RENEWABLE ENERGY LABORATORY. *Simple Levelized Cost of Energy (LCOE) Calculator Documentation* [Online]. Available: https://www.nrel.gov/analysis/tech-lcoe-documentation.html [Accessed 2018.05.30.].

[55] TÜV RHEINLAND PTL LLC. 2017. Risk and economic analysis on two tracker architectures.

[56] RYSTAD ENERGY. 2017. *Australian large scale solar: New year, new cost paradigm* [Online]. Available: http://www.seranalytics.com/single-post/2017/01/05/Australian-large-scale-solar-New-year-new-cost-paradigm [Accessed 2018.05.22.].

[57] RYSTAD ENERGY. 2018. *Radical turnaround in utility-scale solar economics in Australia* [Online]. Available: http://www.seranalytics.com/single-post/2018/04/17/SERA-Newsletter---April-2018-Radical-turnaround-in-utility-scale-solar-economics-in-Australia [Accessed 2018.05.22.].

[58] WILD, P. 2016. The Levelised Cost Of Energy Of Three Solar PV Technologies

Installed At UQ Gatton Campus

[59] UNIVERSITY OF NEW SOUTH WALES. 2016a. *Business Finance* [Online]. Available:http://www.handbook.unsw.edu.au/undergraduate/courses/2016/FINS1613.html

[60] POWEL. Powel Days. 2017.11.09. 2017 Trondheim.

[61] PALISADE. 2018. *@RISK* [Online]. Available: http://www.palisade.com/ [Accessed 2018.06.01.].

[62] ANDRESEN, I. 2018. *RE: Professor, Integrated Energy Design, Norwegian University of Science and Technology.*

[63] SVEIPE, M. R. 2018. *RE: Marketing Manager Mobile, Gudbrandsdal Energi.*

[64] RYNNING-TØNNESEN, C. 2018. *RE: President and CEO, Statkraft.*

[65] THORUD, B. 2018. *RE: Senior Advisor, Multiconsult.*

[66] BORGSØ, P. O. 2018. *RE: Sales Manager, TrønderEnergi.*

[67] TEKNISK UKEBLAD. 2016. *Nå er Norges største solcelle-anlegg blitt nesten tre ganger så stort* [Online]. Available: https://www.tu.no/artikler/na-er-norges-storste-solcelle-anlegg-blitt-nesten-tre-ganger-sa-stort/346914 [Accessed 2018.06.10.].

[68] AALAND, K. 2018. *RE: Director HSE, ASKO.*

[69] TUV, T.C. 2018. *RE: CEO, FUSen AS.*

[70] ERSKINE, R. 2018. *RE: Managing Director-Equinor Technology Invest.*

[71] PIENAAR, I. 2018. *RE: Vice President - Supply Chain, Scatec Solar.*

[72] MELAA, T. 2018. *RE: Senior Vice Precident- Technology Solutions, Scatec Solar.*

[73] SLACK, G. 2018. *RE: Country Manager, Australia, DNV GL - Energy.*

[74] HÅVE, L. E. 2018. *RE: Product Manager- Energy Related Services, Eidsiva Marked.*

[75] DNV GL. *GRIDSTOR Recommended Practice for grid-connected energy storage* [Online]. Available: https://www.dnvgl.com/services/gridstor-recommended-practice-for-grid-connected-energy-storage-52177 [Accessed 2018.06.19.].

[76] OLSEN, J. 2017.*RE: CEO O2 Emc, President, O2 Energies*

[77] STATKRAFT. *Maps over catchment areas in Norway* [Online]. Available: https://www.statkraft.com/energy-sources/hydropower/maps-over-catchment-

areas-in-norway/ [Accessed 2018.06.10.].

[78] SMART ENERGY COUNCIL. 2018. *Smart Energy Conference & Exhibition, Sydney*

[79] GUDBRANDSEN, A.J. 2017. Machine Learning for Improving the Design Process of Topside Layout, Aker Solutions.

A APPENDIX Status of Energy Sources in Australia

The Australian Energy Market Operator (AEMO) quantify and specify the status of the energy sources in the country [10]. The capacity of existing, committed, proposed and withdrawn generation is summarised in Fig. A.1 .

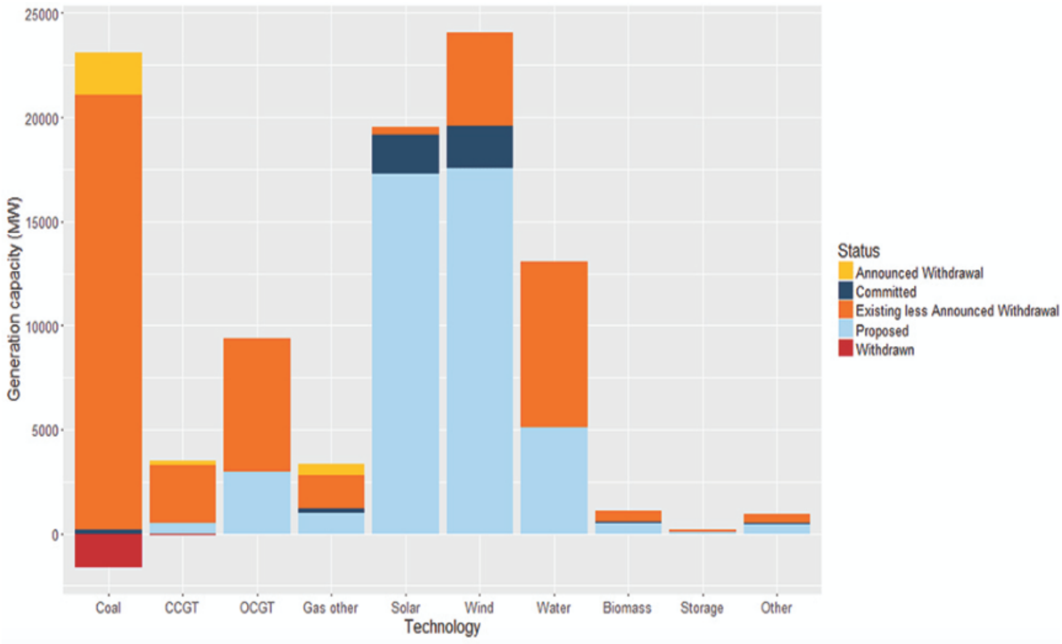


Fig. A.1. Status of energy sources in Australia [10]

Despite Australia still relying heavily upon coal, the strong pipeline of proposed solar PV and wind power becomes evident. Along with coal power plants shutting down, there will be a huge gap to cover [78]. A phasing out of the coal industry in favour of renewables, will create a new employment sector that is natural to fill with skilled workers from the coal mining sector. A similar situation occurred in Norway with the recent down sizing of the oil sector, resulting in a shift in labour force to, for example, Bane Nor for its large railway infrastructure projects.

The expanding PV market in Australia will thus create new jobs and business opportunities; manufacturing of key components as well as non original parts, maintenance/ repair and recycling of decommissioned equipment. A similar situation can be expected to occur in Norway.

B APPENDIX Technical Specifications for WVSF and GSRF

WVSF

Key Data

Fixed tilt array: Fixed tilt of 35°, oriented 0° W of N

Single axis tracking: Horizontal single axis tracking system, oriented 0° W of N with +/- 60° tilt

Dual axis tracking: 340° azimuth / +/- 90° tilt

Common Data

Site longitude: 146°44' E latitude: 41°19' S

Height above sea level: 54 m

Time zone: AEST

Type of installation: Ground mounted

Module make & model: Jinkosolar JKM 360M-72-V

Module technology: Monocrystalline

Number of modules: 43 332

Module Area: 84079 m^2

Nominal DC output: 15 600 kWp

Number of inverters: 5 x 2 500 kWp capped at 12 500 kWp output

Inverter make & model: SMA Sunny Central 2500-EV

Weather data: Meteonorm 7.1 (1990-2008) - Synthetic

GSRF

The Gatton Solar Research Facility (referred to as GSRF) is located just west of Brisbane at the University of Queensland. The full-scale testing facility was opened in Q1 2015 and comprises of 3 types of array, each with identical type and number of panels and inverter:

- Three identical fixed tilt arrays; referred to here as East, Centre and West (FTE,

FTC and FTW. In the main report just one was taken and referred to as FT)
- Single access tracking (SAT)
- Dual access tracking (DAT)
- Battery storage research station (600 kW, 760 kWh)

The GSRF is a collaboration between the University of Queensland, the University of New South Wales, First Solar (a highly regarded US solar panel manufacturer) and AGL PV Solar Holdings Pty Ltd (a major Australian utility provider with interests in large solar farms). The purpose is to improve the understanding of solar technology and its integration into the grid primarily at industrial size.

Key Data

Fixed tilt array: Fixed tilt of 20°, oriented 3° W of N

Single axis tracking: Horizontal single axis tracking system, oriented 3° W of N with +/- 45° tilt

Dual axis tracking: Deger dual axis tracking system (160 x Degertraker 5000HD), 340° azimuth / +/- 90° tilt

Common Data

Site longitude: 152°20' E latitude: 27°33'S

Height above sea level: 88 m

Time zone: AEST

Type of installation: Ground mounted

Module make & model: First Solar FS-395-PLUS (95W)

Module technology: Cadmium telluride (thin film)

Module size: 1200 x 600 mm

Number of modules: 7200

Module Area: 5184 m^2

Nominal DC output: 684 kWp

Number of inverters: 1 x 720 kWp capped at 630 kWp output

Inverter make & model: SMA Sunny Central 720CP TXT

Start-up Date: 27 March 2015

C APPENDIX 20 Year Weather Data

Australian Government Bureau of Meteorological Data (BOM) was used to establish weather data trends for the WVSF and GSRF locations [52] . The PVsyst software uses average ambient temperatures as oppose to the maximum daily temperatures reported by BOM. 2010 was taken as a representative year for comparison (PVsyst versus BOM for GSRF and WVSF). Peak temperatures are better suited for analysis as they connect peaks in demand (air-con usage) with prices. Moreover, maximum temperatures are better for indicating the PV modules efficiency during production hours. For GSRF in 2017, the data is summarised in .

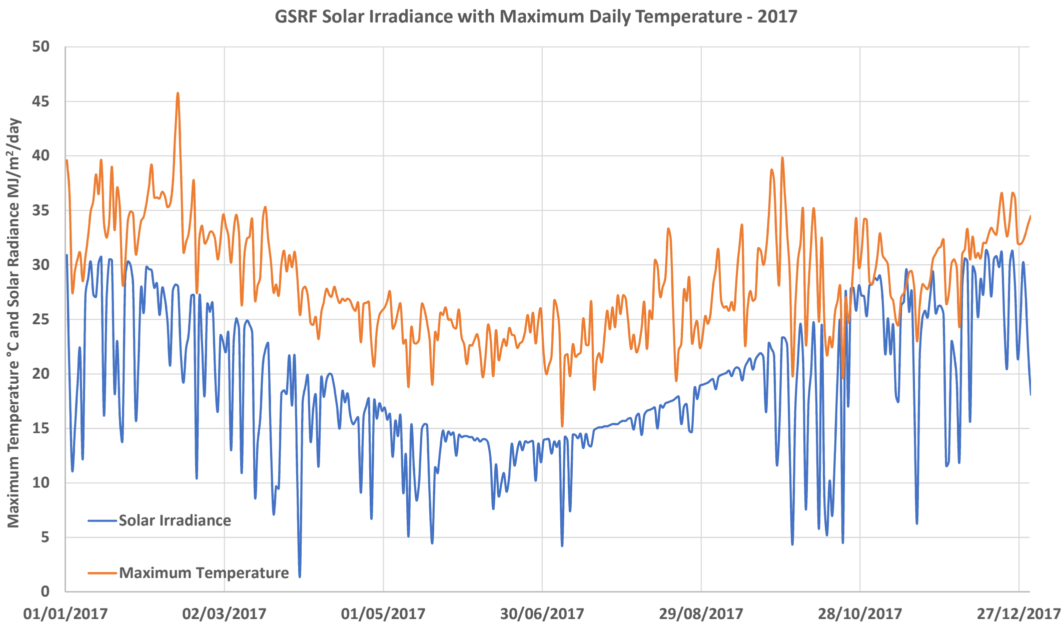


Fig. C.1. GSRF solar irradiance and maximum daily temperature, 2017

The El Niño Southern Oscillation (commonly called ENSO) was raised by GSRF as a possible effect that may need to be considered in PV predictions, but no obvious correlation was found when comparing the effect with 20 years of solar data.

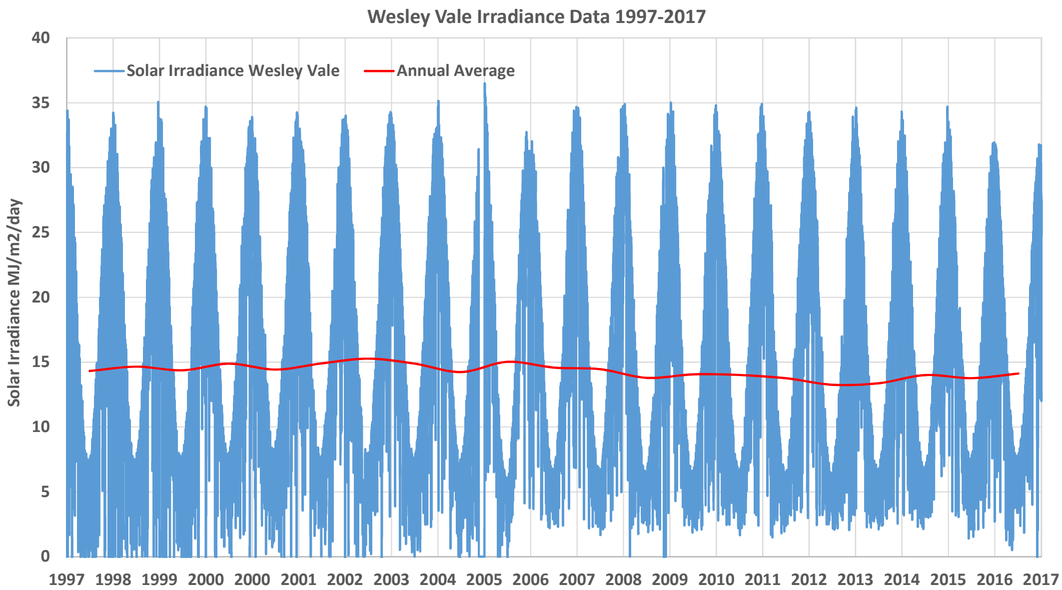


Fig. C.2. WVSF irradiance data 1997-2017

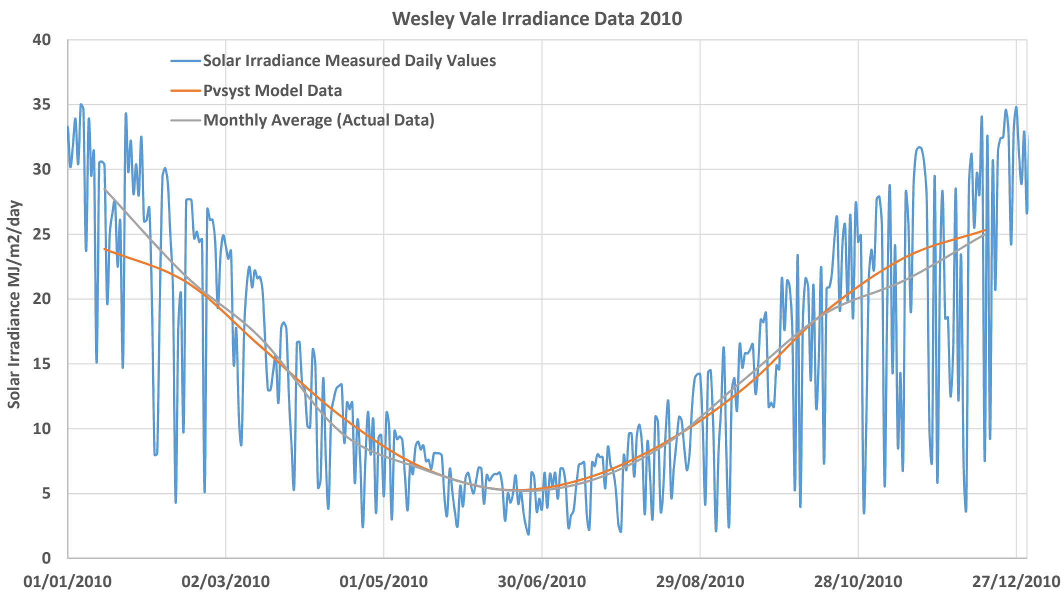


Fig. C.3. WVSF irradiance data 2010

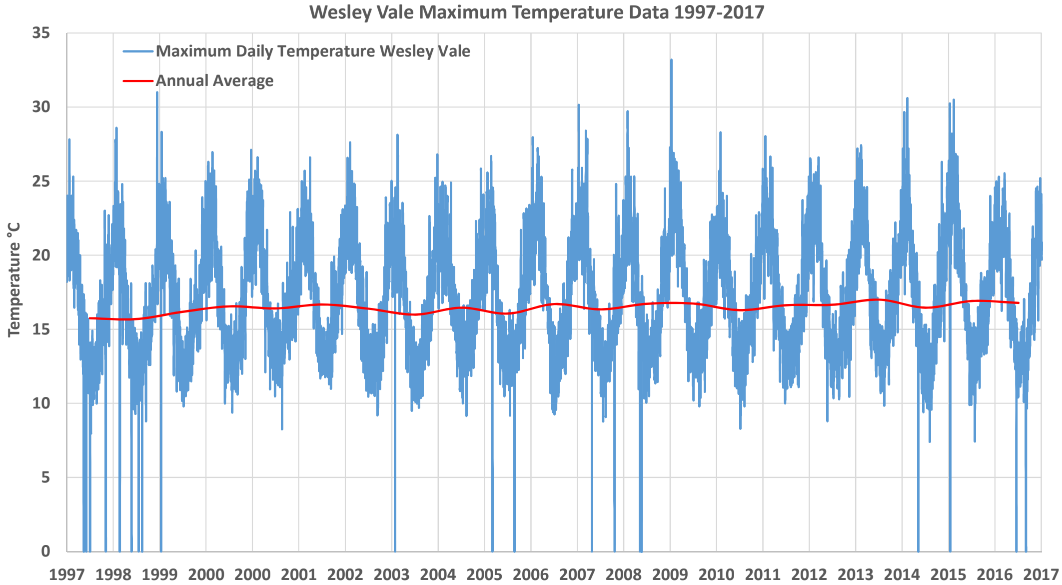


Fig. C.4. WVSF maximum daily temperature 1997-2017

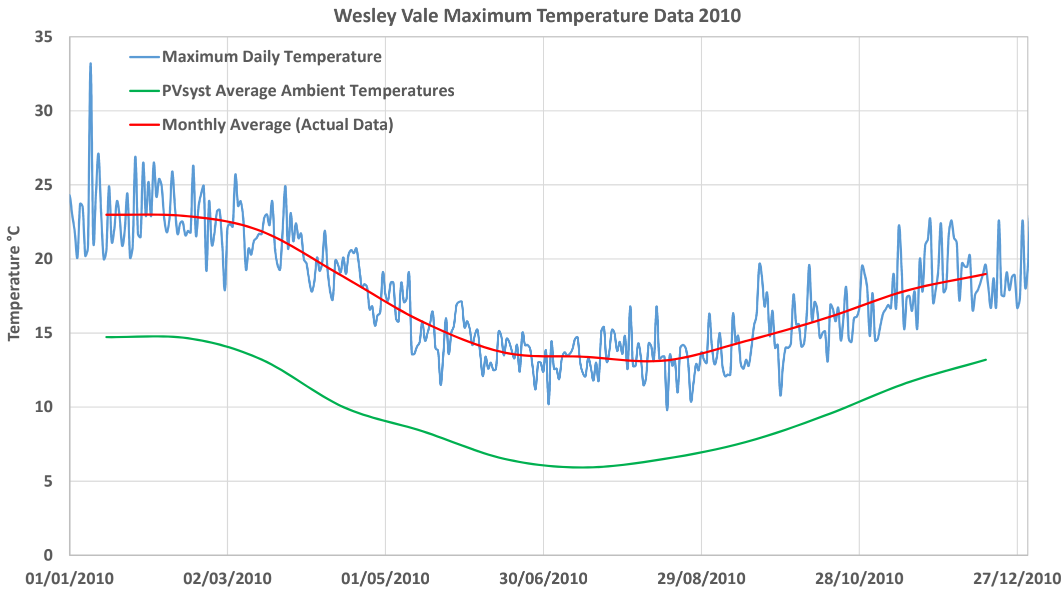


Fig. C.5. WVSF maximum daily temperature 2010

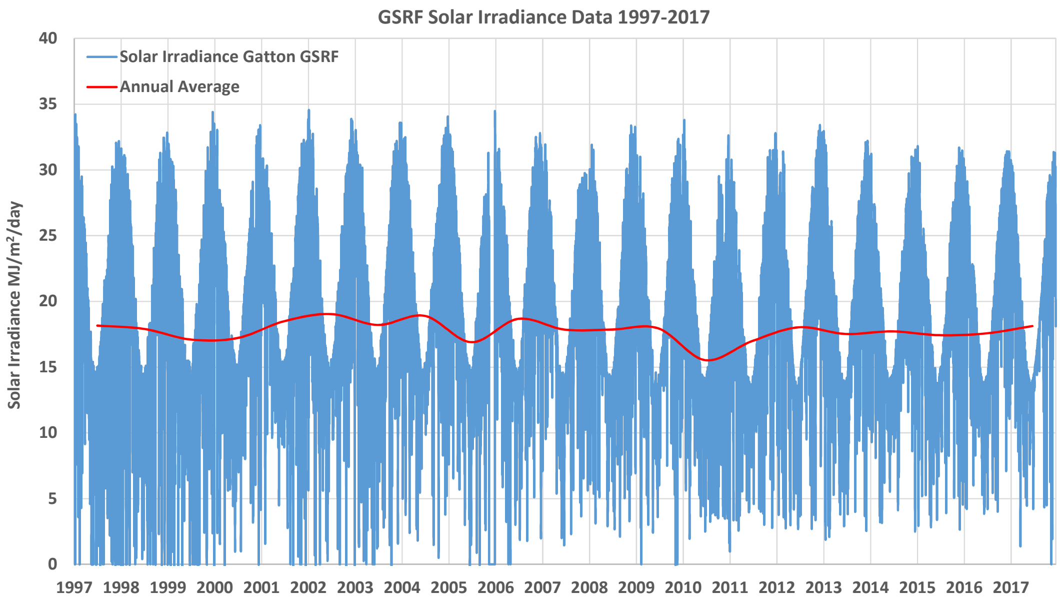


Fig. C.6. GSRF irradiance data 1997-2017

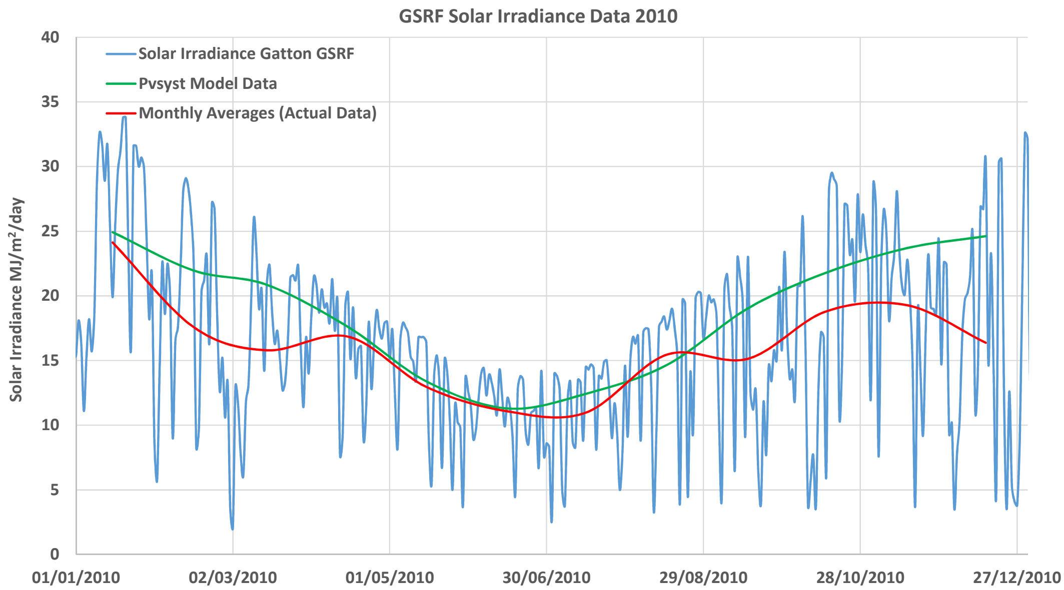


Fig. C.7. GSRF irradiance data 2010

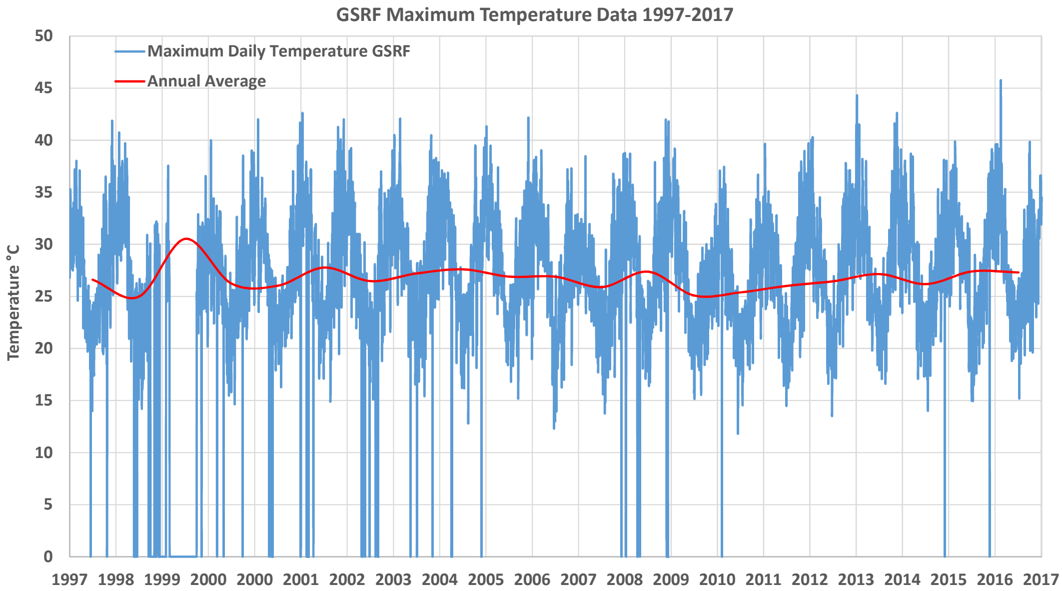


Fig. C.8. GSRF maximum daily temperature 1997-2017

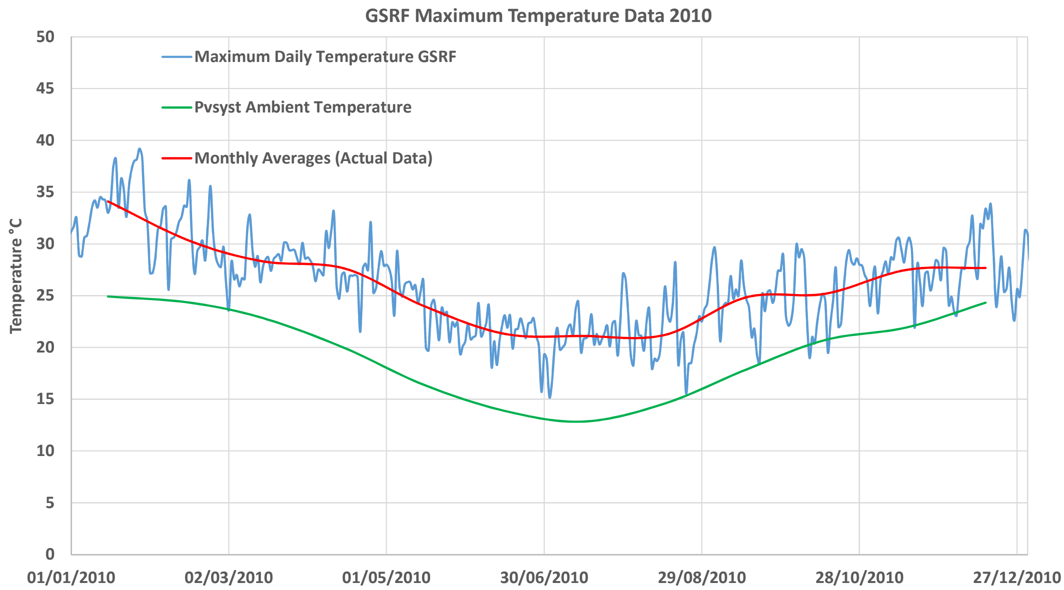


Fig. C.9. GSRF maximum daily temperature 2010

D APPENDIX RRP, Weather and GSRF Data

Raw data for analysis was accessed from three sources:

- Electricity demand and price (RRP) from the website [51]. This data was supplied on a per 30 minute basis, for the whole day on a monthly basis. Data for each State from January 2015 until December 2017 was downloaded and merged into annual files by State in preparation for analysis. The user interface can be seen in Fig. D.1, with an example of the downloaded format shown in .Fig. D.2.
- Weather data was from the Australian Government Meteorological Bureau [52]. This data was supplied on a daily basis, by year for any station in Australia. Irradiance and maximum daily temperature files were downloaded for the WVSF and GSRF locations from 1997 until 2017. The interface window for BOM can be seen in Fig. D.3 and an example of the downloaded data in Fig. D.4
- GSRF generation data from the website [53]. The data was available on an annual bases for the five arrays at Gatton from 2015-2017, see example in Fig. D.5.

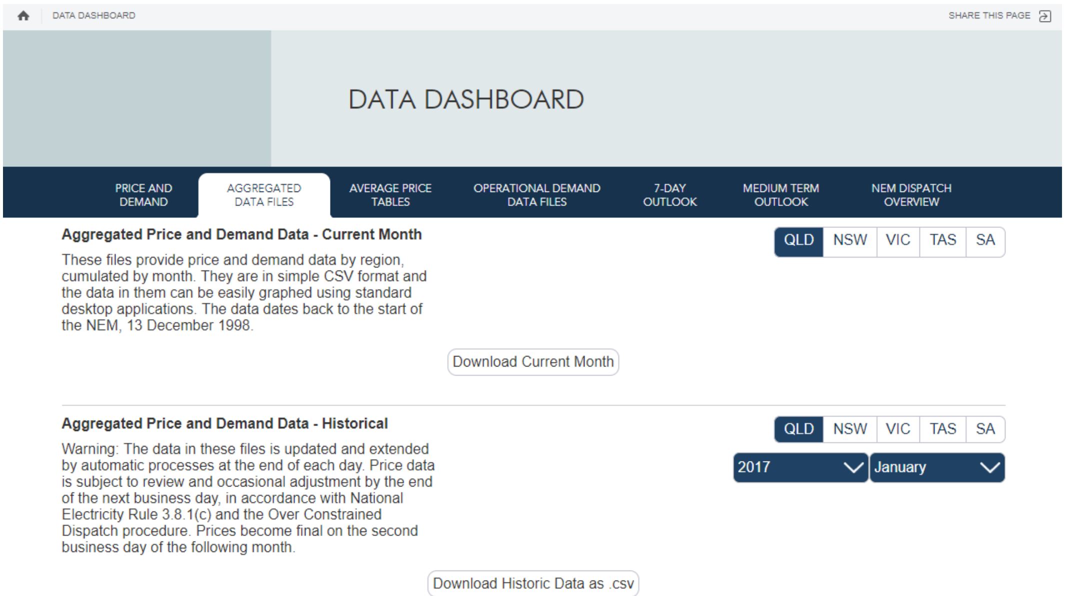


Fig. D.1. Interface page for downloading spot market electricity prices by State for Australia [51]

REGION	SETTLEMENTDATE	TOTALDEMAND MW	RRP A$	PERIODTYPE
QLD1	01/01/2017 00:30	6462.14	186.25	TRADE
QLD1	01/01/2017 01:00	6352.82	83.75	TRADE
QLD1	01/01/2017 01:30	6261.02	64.91	TRADE
QLD1	01/01/2017 02:00	6169.66	53.33	TRADE
QLD1	01/01/2017 02:30	6149.87	64.03	TRADE
QLD1	01/01/2017 03:00	6038.86	57.5	TRADE
QLD1	01/01/2017 03:30	5960.09	52.02	TRADE
QLD1	01/01/2017 04:00	5894.37	54.35	TRADE
QLD1	01/01/2017 04:30	5874.75	59.63	TRADE
QLD1	01/01/2017 05:00	5834.9	57.64	TRADE
QLD1	01/01/2017 05:30	5829.53	55.91	TRADE
QLD1	01/01/2017 06:00	5772.74	47.76	TRADE
QLD1	01/01/2017 06:30	5847.59	47.99	TRADE
QLD1	01/01/2017 07:00	5929.49	47.15	TRADE
QLD1	01/01/2017 07:30	6053.55	46.08	TRADE
QLD1	01/01/2017 08:00	6133.53	46.83	TRADE
QLD1	01/01/2017 08:30	6264.87	48.91	TRADE
QLD1	01/01/2017 09:00	6485.89	54.32	TRADE
QLD1	01/01/2017 09:30	6610.2	60.06	TRADE
QLD1	01/01/2017 10:00	6769.76	57.55	TRADE
QLD1	01/01/2017 10:30	6917.15	79.89	TRADE
QLD1	01/01/2017 11:00	6992.67	292.05	TRADE
QLD1	01/01/2017 11:30	7047.07	99.72	TRADE
QLD1	01/01/2017 12:00	7179.8	214.18	TRADE
QLD1	01/01/2017 12:30	7280.93	298.82	TRADE
QLD1	01/01/2017 13:00	7329.27	98.5	TRADE
QLD1	01/01/2017 13:30	7440.06	82.33	TRADE
QLD1	01/01/2017 14:00	7530.07	104.05	TRADE
QLD1	01/01/2017 14:30	7619.91	108.77	TRADE
QLD1	01/01/2017 15:00	7680.57	119.94	TRADE
QLD1	01/01/2017 15:30	7801.23	101.09	TRADE
QLD1	01/01/2017 16:00	7897.56	185.32	TRADE
QLD1	01/01/2017 16:30	7841	303.85	TRADE
QLD1	01/01/2017 17:00	7996.54	112.73	TRADE
QLD1	01/01/2017 17:30	8042.19	114.06	TRADE
QLD1	01/01/2017 18:00	7933.6	291.35	TRADE
QLD1	01/01/2017 18:30	7903.67	91.54	TRADE
QLD1	01/01/2017 19:00	7975.06	111.76	TRADE
QLD1	01/01/2017 19:30	8030.82	76.03	TRADE
QLD1	01/01/2017 20:00	7981.29	86.72	TRADE
QLD1	01/01/2017 20:30	7883.46	97.03	TRADE
QLD1	01/01/2017 21:00	7686.81	61.69	TRADE
QLD1	01/01/2017 21:30	7568.41	76.11	TRADE
QLD1	01/01/2017 22:00	7343.85	56.34	TRADE
QLD1	01/01/2017 22:30	7154.45	66.53	TRADE
QLD1	01/01/2017 23:00	7065.76	69.23	TRADE
QLD1	01/01/2017 23:30	6763.58	62.71	TRADE

Fig. D.2. Example of demand and spot prices for Queensland, 01.01.2017 [51]

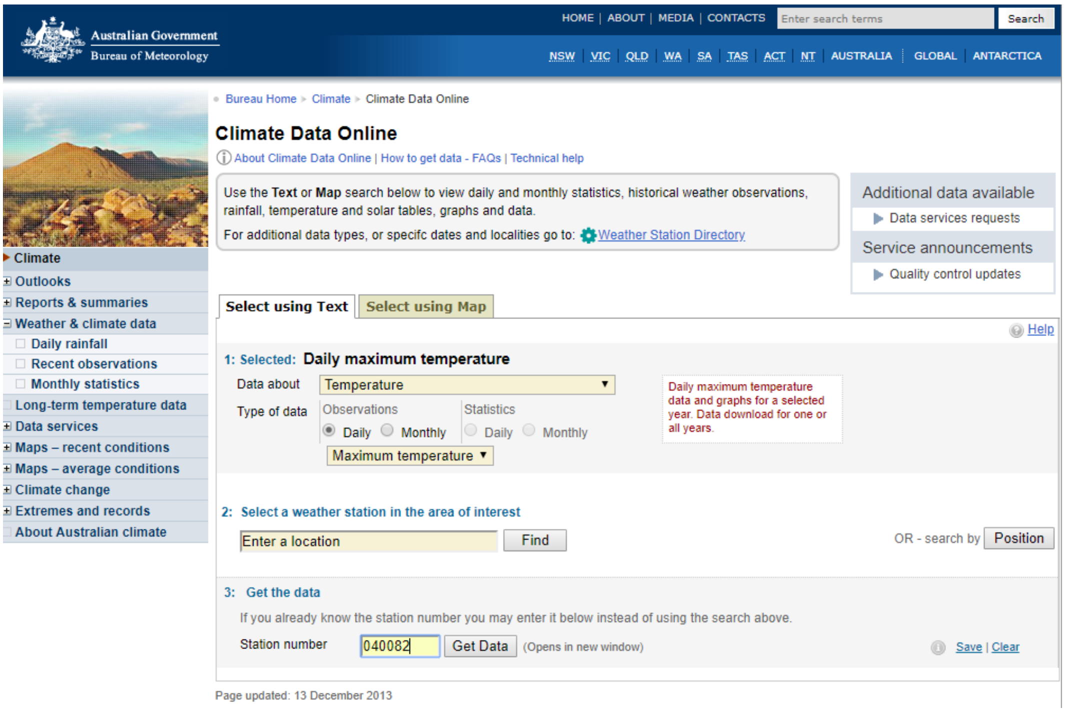
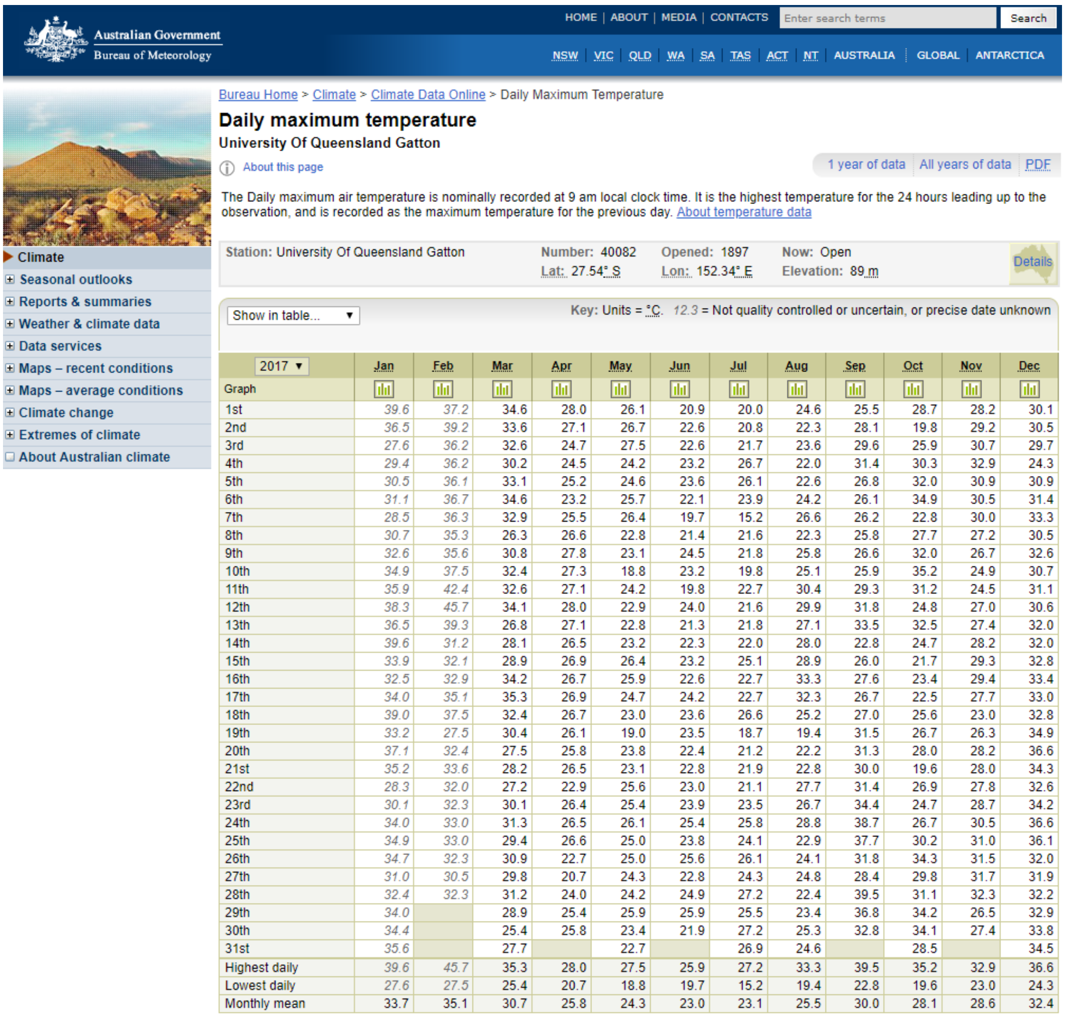


Fig. D.3. Interface window for downloading weather data [52]



2017	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Graph												
1st	39.6	37.2	34.6	28.0	26.1	20.9	20.0	24.6	25.5	28.7	28.2	30.1
2nd	36.5	39.2	33.6	27.1	26.7	22.6	20.8	22.3	28.1	19.8	29.2	30.5
3rd	27.6	36.2	32.6	24.7	27.5	22.6	21.7	23.6	29.6	25.9	30.7	29.7
4th	29.4	36.2	30.2	24.5	24.2	23.2	26.7	22.0	31.4	30.3	32.9	24.3
5th	30.5	36.1	33.1	25.2	24.6	23.6	26.1	22.6	26.8	32.0	30.9	30.9
6th	31.1	36.7	34.6	23.2	25.7	22.1	23.9	24.2	26.1	34.9	30.5	31.4
7th	28.5	36.3	32.9	25.5	26.4	19.7	15.2	26.6	26.2	22.8	30.0	33.3
8th	30.7	35.3	26.3	26.6	22.8	21.4	21.6	22.3	25.8	27.7	27.2	30.5
9th	32.6	35.6	30.8	27.8	23.1	24.5	21.8	25.8	26.6	32.0	26.7	32.6
10th	34.9	37.5	32.4	27.3	18.8	23.2	19.8	25.1	25.9	35.2	24.9	30.7
11th	35.9	42.4	32.6	27.1	24.2	19.8	22.7	30.4	29.3	31.2	24.5	31.1
12th	38.3	45.7	34.1	28.0	22.9	24.0	21.6	29.9	31.8	24.8	27.0	30.6
13th	36.5	39.3	26.8	27.1	22.8	21.3	21.8	27.1	33.5	32.5	27.4	32.0
14th	39.6	31.2	28.1	26.5	23.2	22.3	22.0	28.0	22.8	24.7	28.2	32.0
15th	33.9	32.1	28.9	26.9	26.4	23.2	25.1	28.9	26.0	21.7	29.3	32.8
16th	32.5	32.9	34.2	26.7	25.9	22.6	22.7	33.3	27.6	23.4	29.4	33.4
17th	34.0	35.1	35.3	26.9	24.7	24.2	22.7	32.3	26.7	22.5	27.7	33.0
18th	39.0	37.5	32.4	26.7	23.0	23.6	26.6	25.2	27.0	25.6	23.0	32.8
19th	33.2	27.5	30.4	26.1	19.0	23.5	18.7	19.4	31.5	26.7	26.3	34.9
20th	37.1	32.4	27.5	25.8	23.8	22.4	21.2	22.2	31.3	28.0	28.2	36.6
21st	35.2	33.6	28.2	26.5	23.1	22.8	21.9	22.8	30.0	19.6	28.0	34.3
22nd	28.3	32.0	27.2	22.9	25.6	23.0	21.1	27.7	31.4	26.9	27.8	32.6
23rd	30.1	32.3	30.1	26.4	25.4	23.9	23.5	26.7	34.4	24.7	28.7	34.2
24th	34.0	33.0	31.3	26.5	26.1	25.4	25.8	28.8	38.7	26.7	30.5	36.6
25th	34.9	33.0	29.4	26.6	25.0	23.8	24.1	22.9	37.7	30.2	31.0	36.1
26th	34.7	32.3	30.9	22.7	25.0	25.6	26.1	24.1	31.8	34.3	31.5	32.0
27th	31.0	30.5	29.8	20.7	24.3	22.8	24.3	24.8	28.4	29.8	31.7	31.9
28th	32.4	32.3	31.2	24.0	24.2	24.9	27.2	22.4	39.5	31.1	32.3	32.2
29th	34.0		28.9	25.4	25.9	25.9	25.5	23.4	36.8	34.2	26.5	32.9
30th	34.4		25.4	25.8	23.4	21.9	27.2	25.3	32.8	34.1	27.4	33.8
31st	35.6		27.7		22.7		26.9	24.6		28.5		34.5
Highest daily	39.6	45.7	35.3	28.0	27.5	25.9	27.2	33.3	39.5	35.2	32.9	36.6
Lowest daily	27.6	27.5	25.4	20.7	18.8	19.7	15.2	19.4	22.8	19.6	23.0	24.3
Monthly mean	33.7	35.1	30.7	25.8	24.3	23.0	23.1	25.5	30.0	28.1	28.6	32.4

Fig. D.4. Maximum daily temperatures for GSRF, 2017 [52]

Date	Time		Power (W)	Energy (Wh)
01/01/2017	05:00:00	01/01/2017 05:00:00	0	0
01/01/2017	05:01:00	01/01/2017 05:01:00	0	0
01/01/2017	05:02:00	01/01/2017 05:02:00	0	0
01/01/2017	05:03:00	01/01/2017 05:03:00	0	0
01/01/2017	05:04:00	01/01/2017 05:04:00	0	0
01/01/2017	05:05:00	01/01/2017 05:05:00	0	0
01/01/2017	05:06:00	01/01/2017 05:06:00	0	0
01/01/2017	05:07:00	01/01/2017 05:07:00	0	0
01/01/2017	05:08:00	01/01/2017 05:08:00	0	0
01/01/2017	05:09:00	01/01/2017 05:09:00	0	0
01/01/2017	05:10:00	01/01/2017 05:10:00	0	0
01/01/2017	05:11:00	01/01/2017 05:11:00	0	0
01/01/2017	05:12:00	01/01/2017 05:12:00	0	0
01/01/2017	05:13:00	01/01/2017 05:13:00	0	0
01/01/2017	05:14:00	01/01/2017 05:14:00	0	0
01/01/2017	05:15:00	01/01/2017 05:15:00	0	0
01/01/2017	05:16:00	01/01/2017 05:16:00	0	0
01/01/2017	05:17:00	01/01/2017 05:17:00	0	0
01/01/2017	05:18:00	01/01/2017 05:18:00	0	0
01/01/2017	05:19:00	01/01/2017 05:19:00	0	0
01/01/2017	05:20:00	01/01/2017 05:20:00	0	0
01/01/2017	05:21:00	01/01/2017 05:21:00	0	0
01/01/2017	05:22:00	01/01/2017 05:22:00	34700	96
01/01/2017	05:23:00	01/01/2017 05:23:00	38700	704
01/01/2017	05:24:00	01/01/2017 05:24:00	42800	1408
01/01/2017	05:25:00	01/01/2017 05:25:00	47000	2112
01/01/2017	05:26:00	01/01/2017 05:26:00	51400	2912
01/01/2017	05:27:00	01/01/2017 05:27:00	56100	3808
01/01/2017	05:28:00	01/01/2017 05:28:00	61200	4800
01/01/2017	05:29:00	01/01/2017 05:29:00	65400	5792
01/01/2017	05:30:00	01/01/2017 05:30:00	69300	6912
01/01/2017	05:31:00	01/01/2017 05:31:00	73000	8192
01/01/2017	05:32:00	01/01/2017 05:32:00	76700	9408
01/01/2017	05:33:00	01/01/2017 05:33:00	80300	10816
01/01/2017	05:34:00	01/01/2017 05:34:00	83500	12000

Fig. D.5. Power generation data, an example from GSRF, DAT [53]

The data was processed in Microsoft Excel for analysis using the VLOOKUP function to match the data with different time steps..

E APPENDIX Solar PV Market Trends

“U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017”, published by the National Renewable Energy Laboratory (NREL), elaborates upon large scale solar PV system trends. The decline in costs experienced, the influence of economies of scale and the increased deployment of tracking systems are presented. The values were utilized for obtaining estimates and supporting assumptions for the economic analysis performed in this thesis. Costs are adjusted for inflation and presented as real 2017 USD.

From 2010 to 2017 the PV system cost was reduced by 77% and 80% for the fixed tilt and single axis systems, respectively. This was largely due to a reduction in hardware costs, as module prices decreased with 86% over the time period. From 2016 to 2017 system cost decreased with 29% and 28% for fixed tilt and single axis tracking, respectively. Soft costs, i.e. non-hardware, thus become an increasing proportion of total costs, contributing to 41% of the overall cost for large scale farms. It should be noted how hardware and soft costs are related to each other. As the module efficiency has improved, a system of a given size (nameplate capacity) requires fewer modules thus reducing hardware costs as well as soft costs for installation. The price decline for fixed tilt array and single axis tracking is illustrated in Fig. E.1

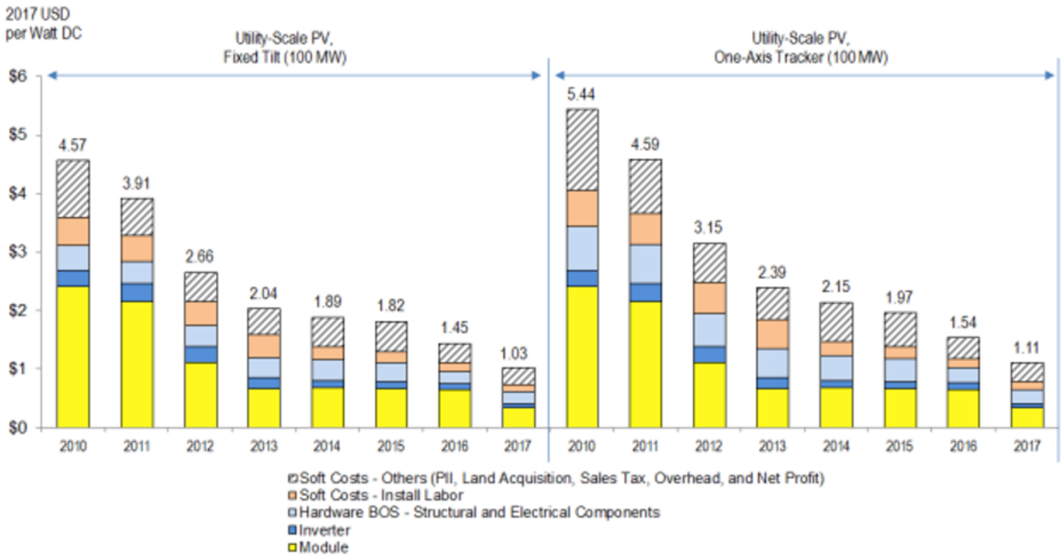


Fig. E.1. PV system installation costs for FT and SAT [5]

By increasing the system size, the system costs are reduced due to economies of scale. Fig. E.2 summarizes the contributions from installation costs and their reduction with increasing system capacity. By scaling up a single axis tracking farm from 10 MW to 100 MW, total costs are reduced by 19%.

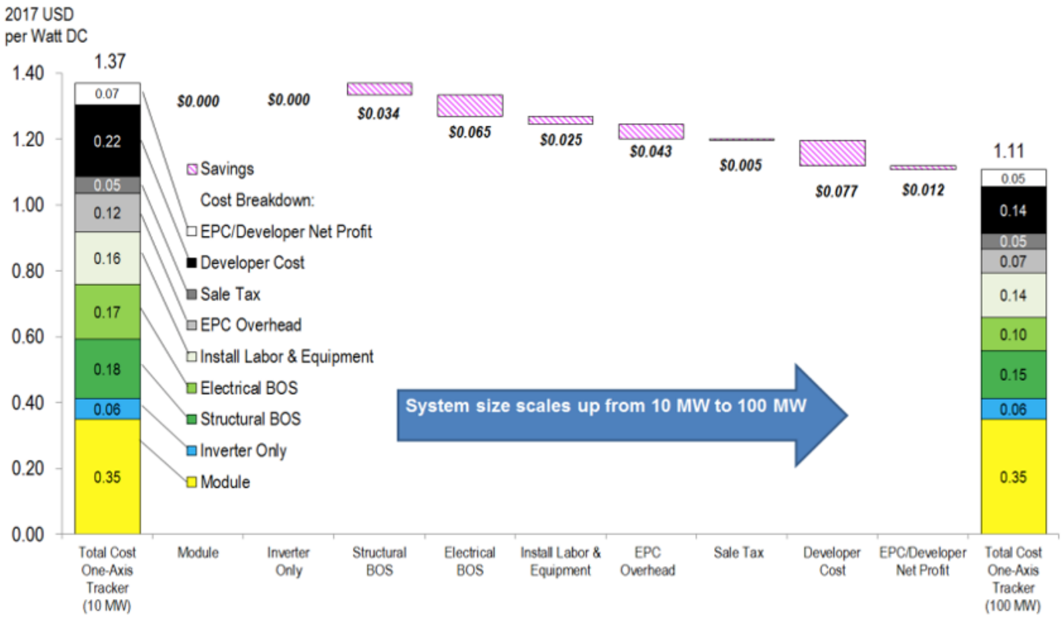


Fig. E.2. Economies of scale of capex for a SAT system [5]

Fig. E.3 indicates the increasing proportion of farms installed with tracking in the U.S. The data for tracking systems include both single and dual axis tracking, however, the majority are for the former. The cumulative tracking system installation increased to 64% in 2016, while 80% of the developed farms same year included tracking.

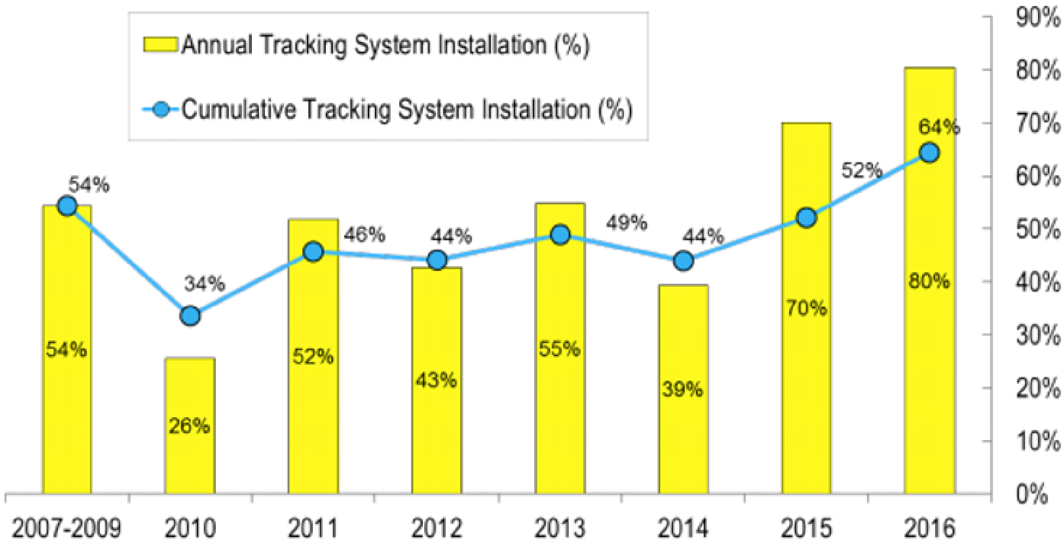


Fig. E.3. Percentage of large scale PV farms installed with tracking systems [5]

F APPENDIX PVsyst Results

PVsyst simulations are summarized in three pages; simulation parameters, main results and a loss diagram. These are included for FT, SAT and DAT for WVSF and Oslo. The result for the FT system at GSRF is also included for completeness. Further explanation of the results can be found in [26].

WVSF Fixed Tilt : Fig. F.1 , Fig. F.2 and Fig. F.3

WVSF Single Axis Tracking: Fig. F.4, Fig. F.5 and Fig. F.6

WVSF Dual Axis Tracking: Fig. F.7 , Fig. F.8 and Fig. F.9

Oslo Fixed Tilt : Fig. F.10, Fig. F.11 and Fig. F.12

Oslo Single Axis Tracking: Fig. F.13, Fig. F.14 and Fig. F.15

Oslo Dual Axis Tracking: Fig. F.16, Fig. F.17 and Fig. F.18

GSRF Fixed tilt: Fig. F.19, Fig. F.20 and Fig. F.21

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project : **WVSF FT**

Geographical Site	**Wesley Vale**		Country	**Australia**
Situation	Latitude	-41.19° S	Longitude	146.44° E
Time defined as	Legal Time	Time zone UT+10	Altitude	54 m
	Albedo	0.20		
Meteo data:	**Wesley Vale**	Meteonorm 7.1 (1990-2008) - Synthetic		

Simulation variant : **WVSF FT**

Simulation date 03/06/18 09h55

Simulation parameters	System type	**No 3D scene defined**		
Collector Plane Orientation	Tilt	35°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module Si-mono	Model	**JKM 360M-72-V**		
Original PVsyst database	Manufacturer	Jinkosolar		
Number of PV modules	In series	23 modules	In parallel	1884 strings
Total number of PV modules	Nb. modules	43332	Unit Nom. Power	360 Wp
Array global power	Nominal (STC)	**15600 kWp**	At operating cond.	14109 kWp (50°C)
Array operating characteristics (50°C)	U mpp	826 V	I mpp	17072 A
Total area	Module area	**84079 m²**	Cell area	74054 m²
Inverter	Model	**Sunny Central 2500-EV**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	778-1425 V	Unit Nom. Power	2500 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	12500 kWac
			Pnom ratio	1.25

PV Array loss factors

Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

Fig. F.1. WVSF FT PVsyst simulation parameters

PVSYST V6.72		17/06/18	Page 2/3

Grid-Connected System: Main results

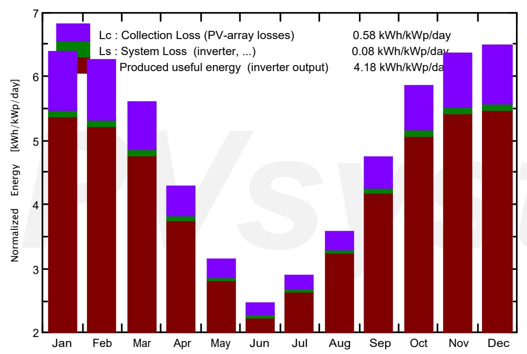
Project : **WVSF FT**

Simulation variant : **WVSF FT**

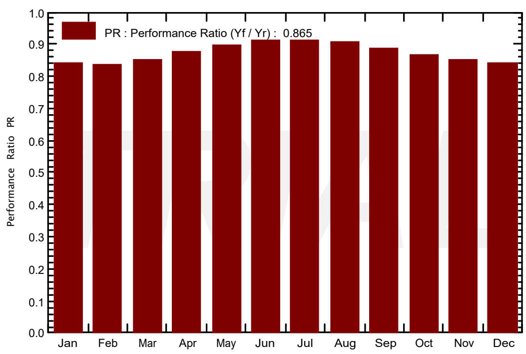
Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	35°	azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**23796 MWh/year**	Specific prod.	1525 kWh/kWp/year
	Performance Ratio PR	86.50 %		

Normalized productions (per installed kWp): Nominal power 15600 kWp



Performance Ratio PR



WVSF FT

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	205.4	89.97	14.73	197.9	187.9	2645	2598	0.842
February	165.8	61.79	14.65	175.3	167.0	2322	2280	0.834
March	141.1	55.89	13.21	173.8	166.1	2350	2308	0.851
April	91.0	36.64	10.01	128.9	123.4	1792	1759	0.875
May	60.8	29.31	8.38	97.4	93.2	1386	1361	0.896
June	44.1	24.82	6.52	73.8	70.5	1072	1053	0.914
July	52.3	24.91	5.93	89.6	85.7	1297	1274	0.911
August	76.2	37.82	6.51	111.2	106.4	1598	1569	0.904
September	109.9	45.42	7.66	141.9	135.8	1999	1963	0.887
October	163.2	67.30	9.44	181.6	173.0	2500	2455	0.867
November	193.6	75.70	11.64	190.8	181.5	2580	2533	0.851
December	217.9	85.07	13.20	201.2	190.9	2691	2643	0.842
Year	1521.4	634.65	10.13	1763.5	1681.4	24233	23796	0.865

Legends:				
GlobHor	Horizontal global irradiation		GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation		EArray	Effective energy at the output of the array
T Amb	Ambient Temperature		E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane		PR	Performance Ratio

PVsyst Evaluation mode

Fig. F.2. WVSF FT PVsyst main results

.

PVSYST V6.72		17/06/18	Page 3/3

Grid-Connected System: Loss diagram

Project : **WVSF FT**

Simulation variant : **WVSF FT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	35°	azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

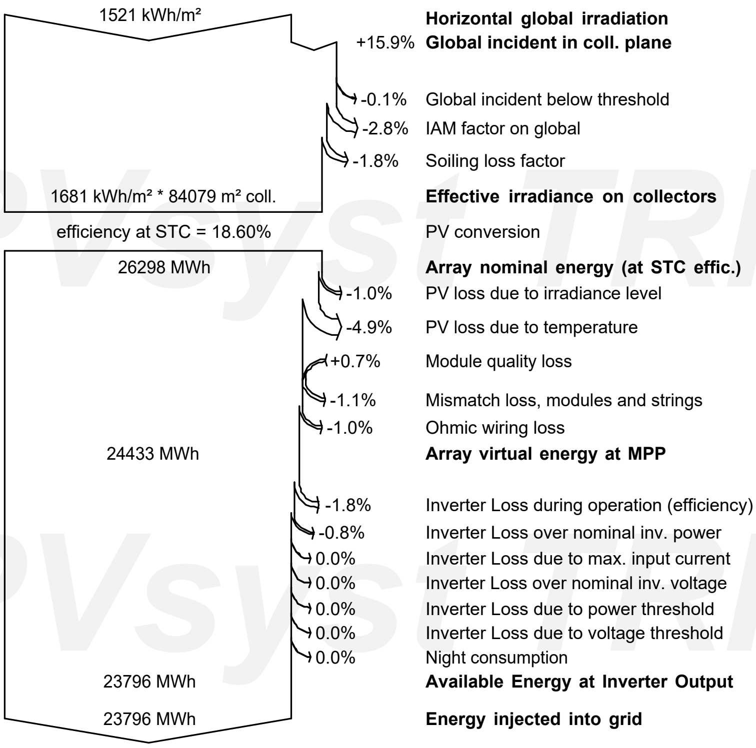


Fig. F.3. WVSF FT PVsyst loss diagram

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**WVSF-SAT**			
Geographical Site	**Wesley Vale**		Country	**Australia**
Situation	Latitude	-41.19° S	Longitude	146.44° E
Time defined as	Legal Time	Time zone UT+10	Altitude	54 m
	Albedo	0.20		
Meteo data:	**Wesley Vale**	Meteonorm 7.1 (1990-2008) - Synthetic		

Simulation variant :	**WVSF SAT**			
	Simulation date	02/06/18 09h17		

Simulation parameters	System type	**No 3D scene defined**		
Tracking plane, tilted Axis	Axis Tilt	0°	Axis Azimuth	0°
Rotation Limitations	Minimum Phi	-60°	Maximum Phi	60°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
PV Array Characteristics				
PV module Si-mono	Model	**JKM 360M-72-V**		
Original PVsyst database	Manufacturer	Jinkosolar		
Number of PV modules	In series	23 modules	In parallel	1884 strings
Total number of PV modules	Nb. modules	43332	Unit Nom. Power	360 Wp
Array global power	Nominal (STC)	**15600 kWp**	At operating cond.	14109 kWp (50°C)
Array operating characteristics (50°C)	U mpp	826 V	I mpp	17072 A
Total area	Module area	**84079 m²**	Cell area	74054 m²
Inverter	Model	**Sunny Central 2500-EV**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	778-1425 V	Unit Nom. Power	2500 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	12500 kWac
			Pnom ratio	1.25
PV Array loss factors				
Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
User's needs :	Unlimited load (grid)			

PVsyst Evaluation mode

Fig. F.4. WVSF SAT PVsyst simulation parameters

PVSYST V6.72		17/06/18	Page 2/3

Grid-Connected System: Main results

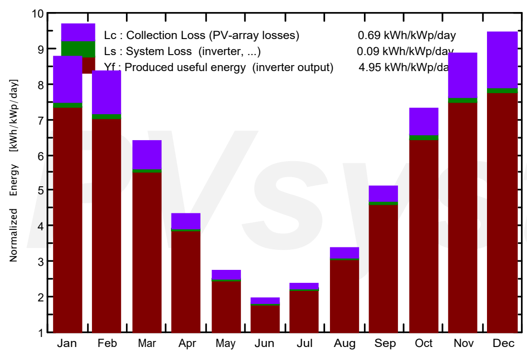
Project : **WVSF-SAT**

Simulation variant : **WVSF SAT**

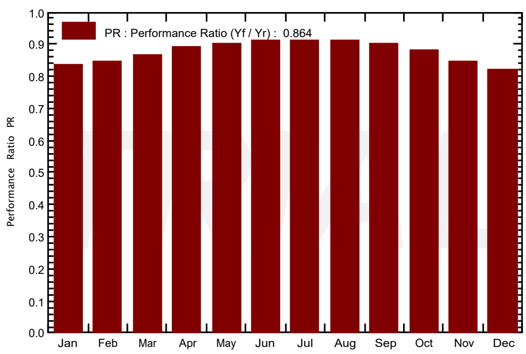
Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**28202 MWh/year**	Specific prod.	1808 kWh/kWp/year
	Performance Ratio PR	86.38 %		

Normalized productions (per installed kWp): Nominal power 15600 kWp



Performance Ratio PR



WVSF SAT

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	205.4	89.97	14.73	271.1	261.1	3611	3546	0.838
February	165.8	61.79	14.65	233.0	224.9	3125	3068	0.844
March	141.1	55.89	13.21	197.5	189.8	2717	2669	0.866
April	91.0	36.64	10.01	130.6	124.9	1849	1816	0.891
May	60.8	29.31	8.38	84.7	80.1	1212	1191	0.901
June	44.1	24.82	6.52	59.6	55.9	862	847	0.911
July	52.3	24.91	5.93	74.3	70.0	1077	1058	0.913
August	76.2	37.82	6.51	104.5	99.3	1514	1488	0.913
September	109.9	45.42	7.66	153.7	147.4	2198	2159	0.901
October	163.2	67.30	9.44	226.3	217.9	3173	3116	0.882
November	193.6	75.70	11.64	265.0	255.7	3555	3490	0.844
December	217.9	85.07	13.20	292.6	282.6	3823	3753	0.822
Year	1521.4	634.65	10.13	2092.9	2009.7	28717	28202	0.864

Legends:			
GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

PVsyst Evaluation mode

Fig. F.5. WVSF SAT PVsyst main results

PVSYST V6.72		17/06/18	Page 3/3

Grid-Connected System: Loss diagram

Project : **WVSF-SAT**

Simulation variant : **WVSF SAT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

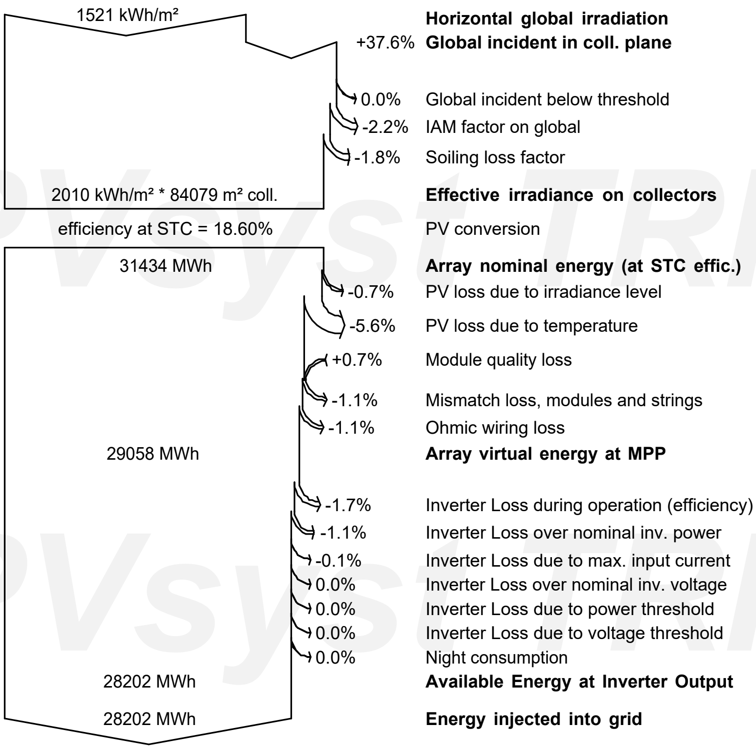


Fig. F.6. WVSF SAT PVsyst loss diagram

.

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project : **WVSF DAT**

Geographical Site	**Wesley Vale**		Country	**Australia**
Situation	Latitude	-41.19° S	Longitude	146.44° E
Time defined as	Legal Time	Time zone UT+10	Altitude	54 m
	Albedo	0.20		
Meteo data:	**Wesley Vale**	Meteonorm 7.1 (1990-2008) - Synthetic		

Simulation variant : **WVSF DAT**

Simulation date 04/06/18 18h07

Simulation parameters	System type	**No 3D scene defined**		
Tracking plane, two axis	Minimum Tilt	-90°	Maximum Tilt	90°
Rotation Limitations	Minimum Azimuth	-170°	Maximum Azimuth	170°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module Si-mono	Model	**JKM 360M-72-V**		
Original PVsyst database	Manufacturer	Jinkosolar		
Number of PV modules	In series	23 modules	In parallel	1884 strings
Total number of PV modules	Nb. modules	43332	Unit Nom. Power	360 Wp
Array global power	Nominal (STC)	**15600 kWp**	At operating cond.	14109 kWp (50°C)
Array operating characteristics (50°C)	U mpp	826 V	I mpp	17072 A
Total area	Module area	**84079 m²**	Cell area	74054 m²
Inverter	Model	**Sunny Central 2500-EV**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	778-1425 V	Unit Nom. Power	2500 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	12500 kWac
			Pnom ratio	1.25

PV Array loss factors

Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

Fig. F.7. WVSF DAT PVsyst simulation parameters

PVSYST V6.72		17/06/18	Page 2/3

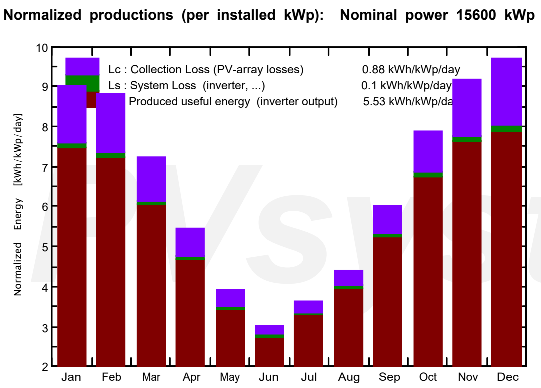
Grid-Connected System: Main results

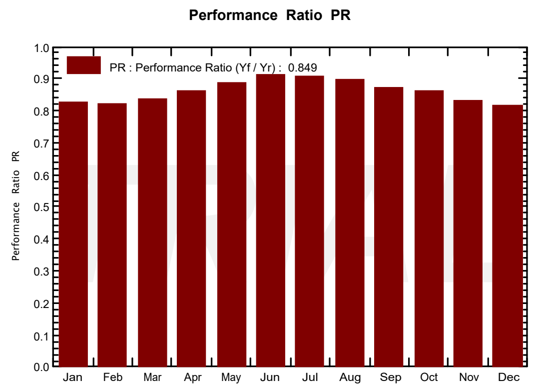
Project : **WVSF DAT**

Simulation variant : **WVSF DAT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	Tracking two axis			
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**31461 MWh/year**	Specific prod.	2017 kWh/kWp/year
	Performance Ratio PR	84.92 %		





WVSF DAT
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	205.4	89.97	14.73	279.4	269.6	3673	3607	0.828
February	165.8	61.79	14.65	246.9	239.0	3217	3158	0.820
March	141.1	55.89	13.21	224.4	217.2	2978	2923	0.835
April	91.0	36.64	10.01	163.7	158.6	2234	2193	0.859
May	60.8	29.31	8.38	120.9	117.0	1701	1669	0.885
June	44.1	24.82	6.52	90.8	87.7	1318	1294	0.914
July	52.3	24.91	5.93	112.8	109.2	1625	1595	0.907
August	76.2	37.82	6.51	136.8	132.2	1952	1917	0.898
September	109.9	45.42	7.66	180.5	174.7	2504	2458	0.873
October	163.2	67.30	9.44	243.7	235.6	3326	3265	0.859
November	193.6	75.70	11.64	274.8	265.7	3634	3567	0.832
December	217.9	85.07	13.20	300.5	290.7	3886	3815	0.814
Year	1521.4	634.65	10.13	2375.0	2297.3	32048	31461	0.849

Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

Fig. F.8. WVSF DAT PVsyst main results

.

PVSYST V6.72		17/06/18	Page 3/3

Grid-Connected System: Loss diagram

Project : **WVSF DAT**

Simulation variant : **WVSF DAT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	Tracking two axis			
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

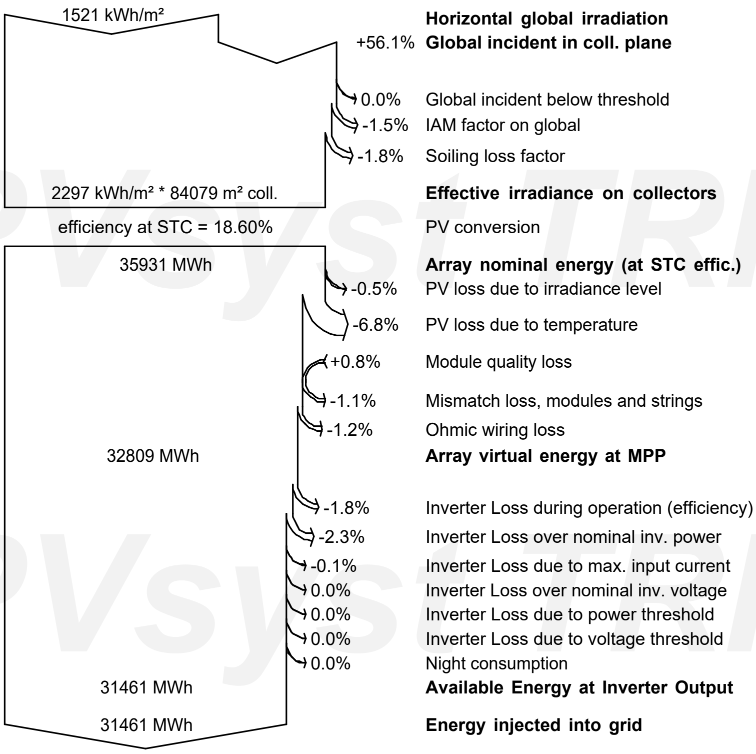


Fig. F.9. WVSF DAT PVsyst loss diagram

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project : **Norway**

Geographical Site	**Stockholm**		Country	**Sweden**
Situation	Latitude	59.35° N	Longitude	17.95° E
Time defined as	Legal Time	Time zone UT+1	Altitude	10 m
	Albedo	0.20		
Meteo data:	**Stockholm**	Meteonorm 7.1 (1991-2010) - Synthetic		

Simulation variant : **Norway FT**

Simulation date 15/06/18 19h07

Simulation parameters	System type	**No 3D scene defined**		
Collector Plane Orientation	Tilt	43°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module	Si-mono	Model	**JKM 360M-72-V**		
Original PVsyst database		Manufacturer	Jinkosolar		
Number of PV modules		In series	23 modules	In parallel	1884 strings
Total number of PV modules		Nb. modules	43332	Unit Nom. Power	360 Wp
Array global power		Nominal (STC)	**15600 kWp**	At operating cond.	14109 kWp (50°C)
Array operating characteristics (50°C)		U mpp	826 V	I mpp	17072 A
Total area		Module area	**84079 m²**	Cell area	74054 m²

Inverter	Model	**Sunny Central 2500-EV**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	778-1425 V	Unit Nom. Power	2500 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	12500 kWac
			Pnom ratio	1.25

PV Array loss factors

Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

Fig. F.10. Oslo FT PVsyst simulation parameters

.

PVSYST V6.72 | 17/06/18 | Page 2/3

Grid-Connected System: Main results

Project : **Norway**

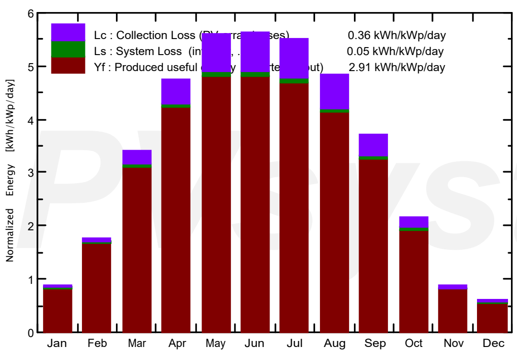
Simulation variant : **Norway FT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	43°	azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

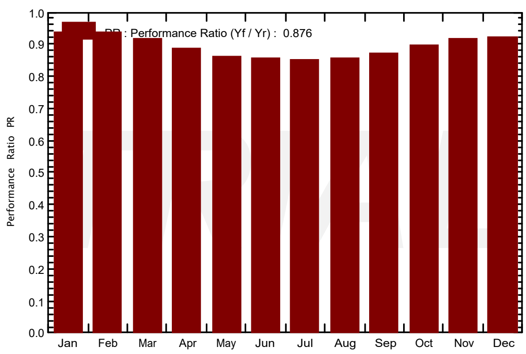
Main simulation results

System Production	**Produced Energy**	**16571 MWh/year**	Specific prod.	1062 kWh/kWp/year
	Performance Ratio PR	87.64 %		

Normalized productions (per installed kWp): Nominal power 15600 kWp



Performance Ratio PR



Norway FT

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	10.3	7.20	-1.10	27.6	26.3	414	405	0.939
February	25.4	15.65	-1.61	49.8	47.6	744	730	0.939
March	65.9	30.59	1.12	105.5	100.7	1536	1508	0.916
April	113.8	50.27	6.56	142.6	135.8	2013	1976	0.888
May	160.9	64.76	11.79	172.9	164.5	2363	2319	0.860
June	168.7	80.37	15.65	168.8	160.4	2295	2254	0.856
July	167.9	80.72	18.89	170.8	162.3	2304	2264	0.850
August	128.8	67.81	17.84	149.7	142.5	2036	2000	0.856
September	79.2	40.79	12.80	111.7	106.4	1550	1522	0.874
October	36.4	19.84	7.69	66.8	63.7	954	936	0.898
November	11.8	8.41	3.50	26.9	25.5	394	385	0.919
December	6.2	4.50	0.75	19.1	18.0	281	274	0.920
Year	975.3	470.89	7.88	1212.1	1153.7	16884	16571	0.876

Legends:				
GlobHor	Horizontal global irradiation		GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation		EArray	Effective energy at the output of the array
T Amb	Ambient Temperature		E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane		PR	Performance Ratio

PVsyst Evaluation mode

Fig. F.11. Oslo FT PVsyst main results

PVSYST V6.72		17/06/18	Page 3/3

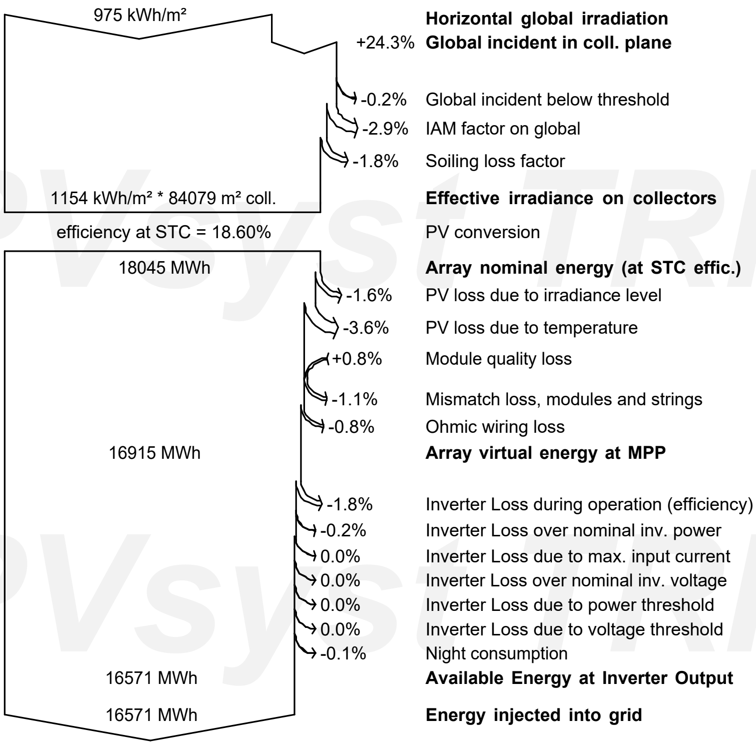
Grid-Connected System: Loss diagram

Project : **Norway**

Simulation variant : **Norway FT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	43°	azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



PVsyst Evaluation mode

Fig. F.12. Oslo FT PVsyst loss diagram

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project : **Norway**

Geographical Site	**Stockholm**		Country	**Sweden**
Situation	Latitude	59.35° N	Longitude	17.95° E
Time defined as	Legal Time	Time zone UT+1	Altitude	10 m
	Albedo	0.20		
Meteo data:	**Stockholm**	Meteonorm 7.1 (1991-2010) - Synthetic		

Simulation variant : **Oslo SAT**

Simulation date 15/06/18 19h15

Simulation parameters	System type	**No 3D scene defined**		
Tracking plane, tilted Axis	Axis Tilt	0°	Axis Azimuth	0°
Rotation Limitations	Minimum Phi	-60°	Maximum Phi	60°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
PV Array Characteristics				
PV module Si-mono	Model	**JKM 360M-72-V**		
Original PVsyst database	Manufacturer	Jinkosolar		
Number of PV modules	In series	23 modules	In parallel	1884 strings
Total number of PV modules	Nb. modules	43332	Unit Nom. Power	360 Wp
Array global power	Nominal (STC)	**15600 kWp**	At operating cond.	14109 kWp (50°C)
Array operating characteristics (50°C)	U mpp	826 V	I mpp	17072 A
Total area	Module area	**84079 m²**	Cell area	74054 m²
Inverter	Model	**Sunny Central 2500-EV**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	778-1425 V	Unit Nom. Power	2500 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	12500 kWac
			Pnom ratio	1.25
PV Array loss factors				
Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

PVsyst Evaluation mode

Fig. F.13. Oslo SAT PVsyst simulation parameters

PVSYST V6.72		17/06/18	Page 2/3

Grid-Connected System: Main results

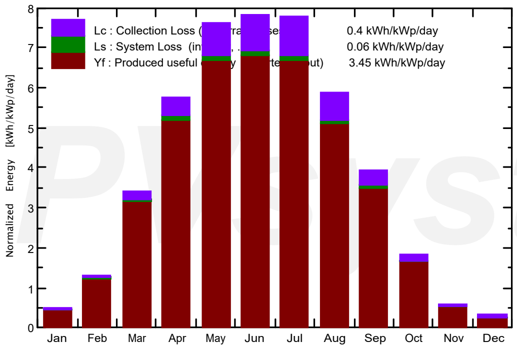
Project : **Norway**

Simulation variant : **Oslo SAT**

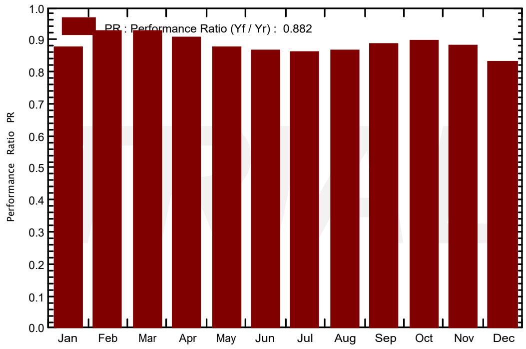
Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**19660 MWh/year**	Specific prod.	1260 kWh/kWp/year
	Performance Ratio PR	88.18 %		

Normalized productions (per installed kWp): Nominal power 15600 kWp



Performance Ratio PR



Oslo SAT

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	10.3	7.20	-1.10	15.9	14.4	224	218	0.878
February	25.4	15.65	-1.61	37.3	34.8	550	539	0.927
March	65.9	30.59	1.12	105.6	100.5	1555	1527	0.927
April	113.8	50.27	6.56	172.4	165.4	2483	2438	0.907
May	160.9	64.76	11.79	236.0	227.3	3292	3234	0.878
June	168.7	80.37	15.65	234.9	225.6	3238	3181	0.868
July	167.9	80.72	18.89	240.7	231.2	3285	3228	0.860
August	128.8	67.81	17.84	182.7	174.9	2517	2474	0.868
September	79.2	40.79	12.80	118.7	113.2	1670	1641	0.886
October	36.4	19.84	7.69	57.1	53.8	816	801	0.899
November	11.8	8.41	3.50	18.1	16.5	256	249	0.882
December	6.2	4.50	0.75	10.0	8.8	135	130	0.832
Year	975.3	470.89	7.88	1429.2	1366.3	20020	19660	0.882

Legends:			
GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

PVsyst Evaluation mode

Fig. F.14. Oslo SAT PVsyst main results

PVSYST V6.72		17/06/18	Page 3/3

Grid-Connected System: Loss diagram

Project : **Norway**

Simulation variant : **Oslo SAT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

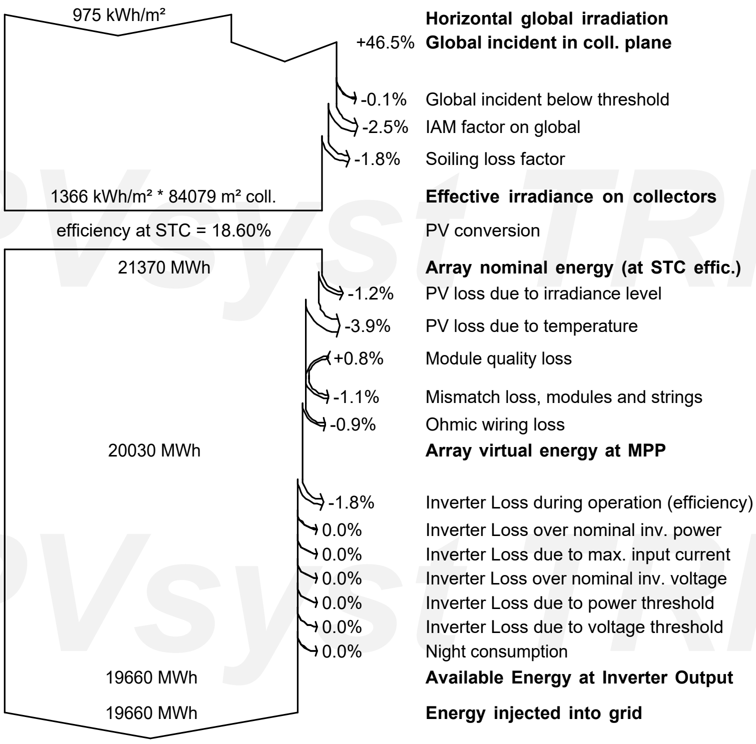


Fig. F.15. Oslo SAT PVsyst loss diagram

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project : **Norway**

Geographical Site	**Stockholm**		Country	**Sweden**
Situation	Latitude	59.35° N	Longitude	17.95° E
Time defined as	Legal Time	Time zone UT+1	Altitude	10 m
	Albedo	0.20		
Meteo data:	**Stockholm**	Meteonorm 7.1 (1991-2010) - Synthetic		

Simulation variant : **Oslo DAT**

Simulation date 15/06/18 19h22

Simulation parameters	System type	**No 3D scene defined**		
Tracking plane, two axis	Minimum Tilt	-90°	Maximum Tilt	90°
Rotation Limitations	Minimum Azimuth	-170°	Maximum Azimuth	170°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module Si-mono	Model	**JKM 360M-72-V**		
Original PVsyst database	Manufacturer	Jinkosolar		
Number of PV modules	In series	23 modules	In parallel	1884 strings
Total number of PV modules	Nb. modules	43332	Unit Nom. Power	360 Wp
Array global power	Nominal (STC)	**15600 kWp**	At operating cond.	14109 kWp (50°C)
Array operating characteristics (50°C)	U mpp	826 V	I mpp	17072 A
Total area	Module area	**84079 m²**	Cell area	74054 m²
Inverter	Model	**Sunny Central 2500-EV**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	778-1425 V	Unit Nom. Power	2500 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	12500 kWac
			Pnom ratio	1.25

PV Array loss factors

Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

Fig. F.16. Oslo DAT PVsyst simulation parameters

PVSYST V6.72		17/06/18	Page 2/3

Grid-Connected System: Main results

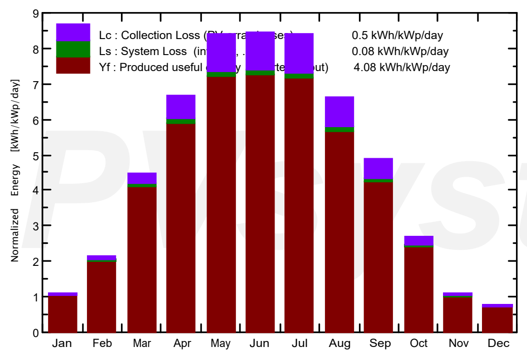
Project : **Norway**

Simulation variant : **Oslo DAT**

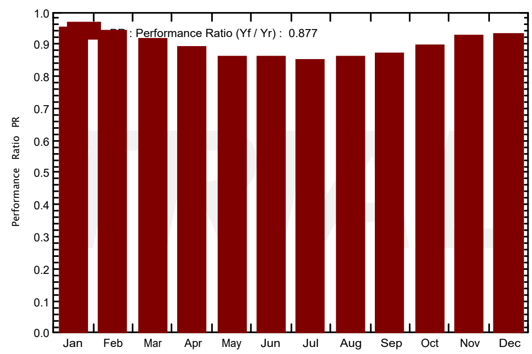
Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	Tracking two axis			
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**23242 MWh/year**	Specific prod.	1490 kWh/kWp/year
	Performance Ratio PR	87.65 %		

Normalized productions (per installed kWp): Nominal power 15600 kWp



Performance Ratio PR



Oslo DAT

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	10.3	7.20	-1.10	34.7	33.4	525	514	0.951
February	25.4	15.65	-1.61	60.6	58.5	909	891	0.943
March	65.9	30.59	1.12	139.1	134.8	2023	1985	0.915
April	113.8	50.27	6.56	199.1	192.7	2814	2762	0.889
May	160.9	64.76	11.79	259.3	251.0	3544	3479	0.860
June	168.7	80.37	15.65	253.3	244.4	3455	3394	0.859
July	167.9	80.72	18.89	260.5	251.3	3526	3465	0.853
August	128.8	67.81	17.84	204.9	197.5	2796	2748	0.860
September	79.2	40.79	12.80	146.3	141.4	2022	1986	0.870
October	36.4	19.84	7.69	84.2	81.5	1203	1180	0.898
November	11.8	8.41	3.50	33.3	32.0	493	483	0.928
December	6.2	4.50	0.75	24.4	23.3	363	355	0.933
Year	975.3	470.89	7.88	1699.8	1641.9	23675	23242	0.877

Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

Fig. F.17. Oslo DAT PVsyst main results

PVSYST V6.72		17/06/18	Page 3/3

Grid-Connected System: Loss diagram

Project : **Norway**

Simulation variant : **Oslo DAT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	Tracking two axis			
PV modules	Model	JKM 360M-72-V	Pnom	360 Wp
PV Array	Nb. of modules	43332	Pnom total	**15600 kWp**
Inverter	Model	Sunny Central 2500-EV	Pnom	2500 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**12500 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

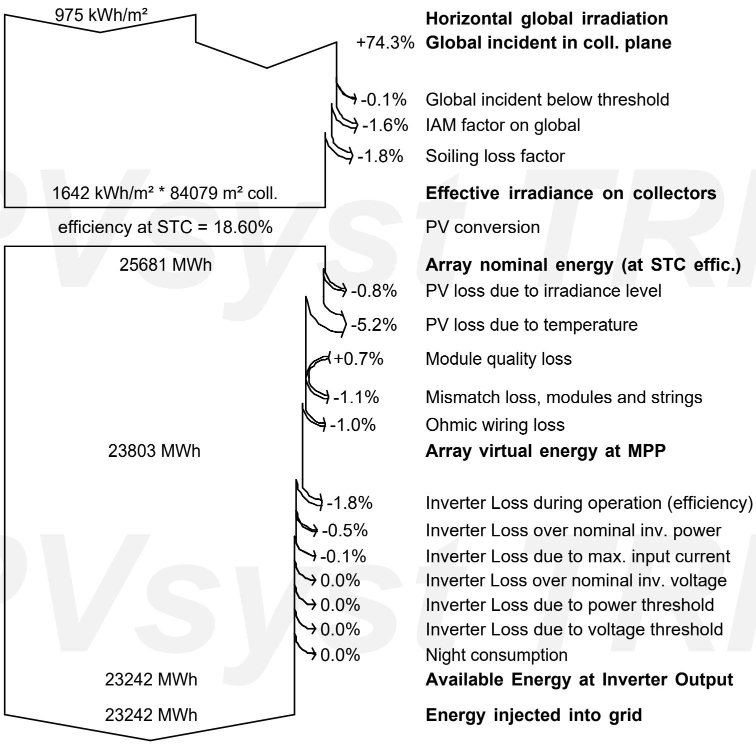


Fig. F.18. Oslo DAT PVsyst loss diagram

PVSYST V6.72		17/06/18	Page 1/3

Grid-Connected System: Simulation parameters

Project : **GSRF**

Geographical Site	**Lawes**		Country	**Australia**
Situation	Latitude	-27.56° S	Longitude	152.34° E
Time defined as	Legal Time	Time zone UT+10	Altitude	98 m
	Albedo	0.20		
Meteo data:	**Lawes**	Meteonorm 7.1 (1990-2008), Sat=14% - Synthetic		

Simulation variant : **GSRF FT**

Simulation date 02/06/18 20h06

Simulation parameters	System type	**No 3D scene defined**		
Collector Plane Orientation	Tilt	20°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module CdTe	Model	**FS-395-PLUS**		
Original PVsyst database	Manufacturer	First Solar		
Number of PV modules	In series	12 modules	In parallel	600 strings
Total number of PV modules	Nb. modules	7200	Unit Nom. Power	95 Wp
Array global power	Nominal (STC)	**684 kWp**	At operating cond.	633 kWp (50°C)
Array operating characteristics (50°C)	U mpp	508 V	I mpp	1248 A
Total area	Module area	**5184 m²**	Cell area	4699 m²

Inverter	Model	**Sunny Central 720CP XT**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	480-850 V	Unit Nom. Power	720 kWac
			Max. power (=>25°C)	792 kWac
Inverter pack	Nb. of inverters	1 units	Total Power	720 kWac
			Pnom ratio	0.95

PV Array loss factors

Array Soiling Losses			Loss Fraction	1.8 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	6.7 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	2.5 %
Module Mismatch Losses			Loss Fraction	0.8 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

PVsyst Evaluation mode

Fig. F.19. GSRF FT PVsyst simulation parameters

PVSYST V6.72		17/06/18	Page 2/3

Grid-Connected System: Main results

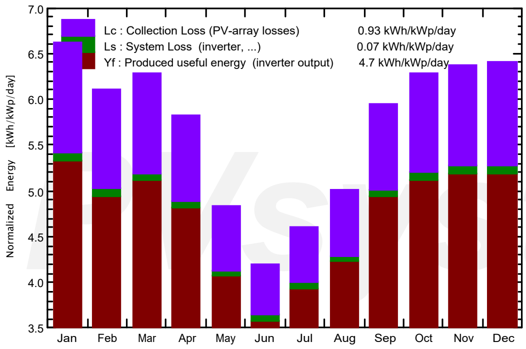
Project : **GSRF**

Simulation variant : **GSRF FT**

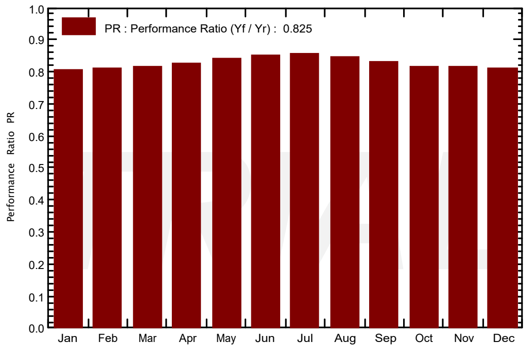
Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	20°	azimuth	0°
PV modules	Model	FS-395-PLUS	Pnom	95 Wp
PV Array	Nb. of modules	7200	Pnom total	**684 kWp**
Inverter	Model	Sunny Central 720CP XT	Pnom	720 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1175 MWh/year**	Specific prod.	1717 kWh/kWp/year
	Performance Ratio PR	82.47 %		

Normalized productions (per installed kWp): Nominal power 684 kWp



Performance Ratio PR



GSRF FT

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	214.6	77.57	24.92	205.3	195.3	114.8	112.9	0.804
February	170.8	68.34	24.33	171.0	162.6	96.2	94.7	0.810
March	179.6	62.97	22.83	194.8	185.7	110.1	108.5	0.814
April	146.7	46.28	19.95	174.7	167.2	100.3	98.7	0.826
May	115.3	39.84	16.41	149.6	142.6	87.5	86.2	0.843
June	94.1	32.99	13.87	126.1	120.2	74.8	73.6	0.853
July	107.0	35.27	12.84	142.9	136.1	84.8	83.6	0.855
August	126.2	41.97	14.59	155.4	148.4	91.1	89.7	0.844
September	158.6	57.21	17.87	178.4	170.4	102.9	101.4	0.831
October	187.7	66.05	20.72	194.6	185.8	110.4	108.7	0.816
November	197.5	81.56	21.93	190.9	181.4	108.1	106.4	0.815
December	212.0	90.02	24.32	198.6	188.5	111.9	110.2	0.811
Year	1910.0	700.09	19.52	2082.3	1984.2	1192.9	1174.6	0.825

Legends:	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

Fig. F.20. GSRF FT PVsyst main results

.

PVSYST V6.72		17/06/18	Page 3/3

Grid-Connected System: Loss diagram

Project : **GSRF**

Simulation variant : **GSRF FT**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	20°	azimuth	0°
PV modules	Model	FS-395-PLUS	Pnom	95 Wp
PV Array	Nb. of modules	7200	Pnom total	**684 kWp**
Inverter	Model	Sunny Central 720CP XT	Pnom	720 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

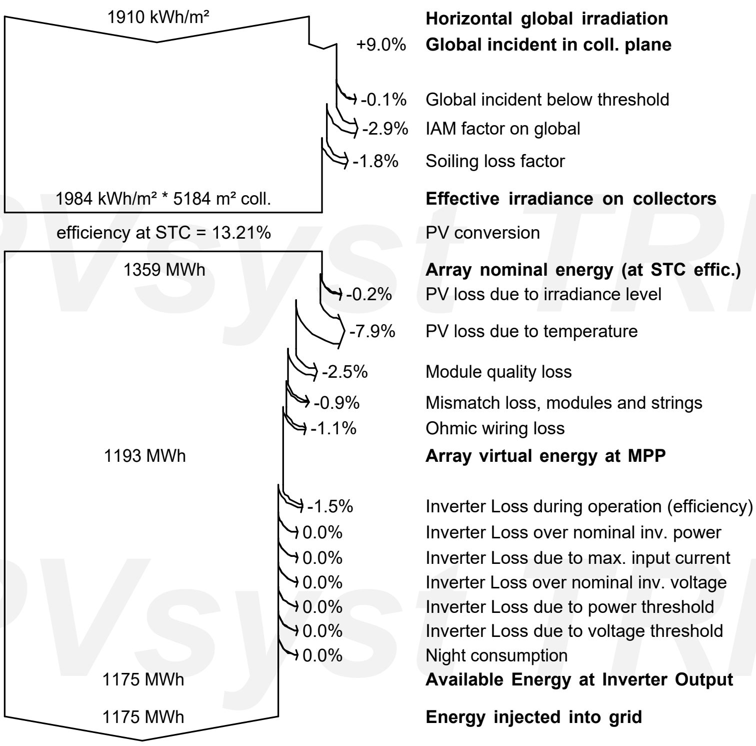


Fig. F.21. GSRF FT PVsyst loss diagram

G APPENDIX Uncertainty Analysis

Table G.1. Tabulated results for the WVSF uncertainty analysis (no subsidies)

@RISK Detailed Statistics

Performed By: Anja Jones Gudbrandsen
Date: 05 June 2018 20:21:33

Name	NPV FT, MA$	NPV SAT, MA$	NPV DAT, MA$	IRR FT	IRR SAT	IRR DAT	LCOE discounted FT, A$/KWh	LCOE discounted SAT, A$/KWh	LCOE discounted DAT, A$/KWh	Time to Payback FT, years	Time to Payback SAT, years	Time to Payback DAT, years	Max Cap Exposure FT, MA$	Max Cap Exposure SAT, MA$	Max Cap Exposure DAT, MA$
Minimum	-$10.78	-$11.75	-$29.41	-0.1%	0.1%	-3.3%	0.058	0.058	0.081	7	6	10	-$26.1	-$29.8	-$48.9
Maximum	$16.00	$18.37	$8.91	13.2%	13.4%	7.6%	0.120	0.119	0.171	40	24	40	-$17.4	-$19.9	-$32.6
Mean	$1.55	$1.76	-$11.94	5.7%	5.7%	1.7%	0.083	0.083	0.118	12.47	12.47	21.58	-$21.8	-$24.9	-$40.8
Std Deviation	$3.59	$4.17	$5.23	1.7%	1.8%	1.4%	0.009	0.009	0.013	2.24	2.29	7.43	$1.8	$2.0	$3.3
5% Perc	-$4.22	-$4.97	-$20.46	3.0%	2.9%	-0.7%	0.069	0.069	0.098	9	9	15	-$24.7	-$28.3	-$46.3
10% Perc	-$3.05	-$3.58	-$18.71	3.6%	3.5%	-0.2%	0.072	0.071	0.102	10	10	15	-$24.2	-$27.6	-$45.3
15% Perc	-$2.22	-$2.62	-$17.44	4.0%	3.9%	0.2%	0.074	0.073	0.105	10	10	16	-$23.7	-$27.1	-$44.4
20% Perc	-$1.55	-$1.84	-$16.45	4.3%	4.2%	0.4%	0.075	0.075	0.107	11	11	17	-$23.4	-$26.7	-$43.8
25% Perc	-$0.96	-$1.16	-$15.58	4.5%	4.5%	0.7%	0.077	0.076	0.109	11	11	17	-$23.0	-$26.3	-$43.1
30% Perc	-$0.43	-$0.55	-$14.81	4.8%	4.8%	0.9%	0.078	0.077	0.111	11	11	18	-$22.7	-$26.0	-$42.6
35% Perc	$0.07	$0.03	-$14.07	5.0%	5.0%	1.1%	0.079	0.079	0.113	11	11	18	-$22.5	-$25.7	-$42.1
40% Perc	$0.55	$0.59	-$13.36	5.3%	5.2%	1.3%	0.080	0.080	0.114	12	12	19	-$22.2	-$25.4	-$41.6
45% Perc	$1.01	$1.13	-$12.69	5.5%	5.5%	1.5%	0.082	0.081	0.116	12	12	19	-$22.0	-$25.1	-$41.2
50% Perc	$1.47	$1.68	-$12.01	5.7%	5.7%	1.7%	0.083	0.082	0.118	12	12	20	-$21.8	-$24.9	-$40.8
55% Perc	$1.93	$2.22	-$11.33	5.9%	5.9%	1.8%	0.084	0.083	0.119	13	13	20	-$21.5	-$24.6	-$40.3
60% Perc	$2.40	$2.77	-$10.64	6.1%	6.2%	2.0%	0.085	0.084	0.121	13	13	20	-$21.3	-$24.4	-$39.9
65% Perc	$2.89	$3.35	-$9.92	6.4%	6.4%	2.2%	0.086	0.086	0.123	13	13	21	-$21.0	-$24.1	-$39.4
70% Perc	$3.42	$3.95	-$9.17	6.6%	6.6%	2.4%	0.088	0.087	0.125	13	13	22	-$20.8	-$23.8	-$38.9
75% Perc	$3.97	$4.61	-$8.36	6.9%	6.9%	2.7%	0.089	0.089	0.127	14	14	22	-$20.5	-$23.4	-$38.4
80% Perc	$4.61	$5.35	-$7.45	7.2%	7.2%	2.9%	0.091	0.090	0.129	14	14	23	-$20.2	-$23.1	-$37.8
85% Perc	$5.33	$6.19	-$6.41	7.6%	7.6%	3.2%	0.093	0.092	0.132	15	15	24	-$19.8	-$22.6	-$37.1
90% Perc	$6.24	$7.24	-$5.11	8.0%	8.0%	3.5%	0.095	0.095	0.136	15	15	40	-$19.4	-$22.1	-$36.2
95% Perc	$7.60	$8.78	-$3.21	8.7%	8.7%	4.1%	0.099	0.098	0.141	16	17	40	-$18.8	-$21.5	-$35.2

Table G.2. Tabulated results for the WVSF uncertainty analysis (with subsidies)

@RISK Detailed Statistics

Performed By: Anja Jones Gudbrandsen
Date: 05 June 2018 20:21:33

Name	NPV FT, MA$	NPV SAT, MA$	NPV DAT, MA$	IRR FT	IRR SAT	IRR DAT	LCOE discounted FT, A$/KWh	LCOE discounted SAT, A$/KWh	LCOE discounted DAT, A$/KWh	Time to Payback FT, years	Time to Payback SAT, years	Time to Payback DAT, years	Max Cap Exposure FT, MA$	Max Cap Exposure SAT, MA$	Max Cap Exposure DAT, MA$
Minimum	$9.80	$10.47	-$4.62	8.7%	8.5%	4.0%	0.057	0.057	0.081	3	3	5	-$26.1	-$29.8	-$48.9
Maximum	$44.74	$51.69	$45.01	25.4%	26.1%	16.8%	0.120	0.118	0.170	9	9	15	-$17.4	-$19.9	-$32.6
Mean	$25.99	$30.45	$19.73	15.8%	16.1%	9.7%	0.083	0.083	0.118	5.58	5.50	8.62	-$21.8	-$24.9	-$40.8
Std Deviation	$5.08	$5.89	$6.99	2.4%	2.4%	1.8%	0.009	0.009	0.013	0.86	0.85	1.29	$1.8	$2.0	$3.3
5% Perc	$17.76	$20.89	$8.35	12.1%	12.3%	6.9%	0.069	0.069	0.098	4	4	7	-$24.7	-$28.3	-$46.3
10% Perc	$19.43	$22.81	$10.70	12.9%	13.1%	7.5%	0.072	0.071	0.102	5	5	7	-$24.2	-$27.6	-$45.3
15% Perc	$20.59	$24.16	$12.34	13.4%	13.6%	7.9%	0.074	0.073	0.105	5	5	7	-$23.7	-$27.1	-$44.4
20% Perc	$21.55	$25.30	$13.66	13.8%	14.0%	8.2%	0.075	0.075	0.107	5	5	8	-$23.4	-$26.7	-$43.8
25% Perc	$22.39	$26.28	$14.85	14.1%	14.4%	8.5%	0.077	0.076	0.109	5	5	8	-$23.0	-$26.3	-$43.1
30% Perc	$23.17	$27.18	$15.89	14.5%	14.7%	8.7%	0.078	0.077	0.111	5	5	8	-$22.7	-$26.0	-$42.6
35% Perc	$23.89	$28.02	$16.89	14.8%	15.0%	9.0%	0.079	0.079	0.113	5	5	8	-$22.5	-$25.7	-$42.1
40% Perc	$24.59	$28.82	$17.81	15.1%	15.3%	9.2%	0.080	0.080	0.114	5	5	8	-$22.2	-$25.4	-$41.6
45% Perc	$25.25	$29.59	$18.74	15.4%	15.6%	9.4%	0.081	0.081	0.116	5	5	8	-$22.0	-$25.1	-$41.2
50% Perc	$25.93	$30.36	$19.65	15.7%	16.0%	9.6%	0.083	0.082	0.118	6	5	9	-$21.8	-$24.9	-$40.8
55% Perc	$26.60	$31.13	$20.55	16.0%	16.3%	9.9%	0.084	0.083	0.119	6	6	9	-$21.5	-$24.6	-$40.3
60% Perc	$27.27	$31.92	$21.49	16.3%	16.6%	10.1%	0.085	0.084	0.121	6	6	9	-$21.3	-$24.4	-$39.9
65% Perc	$27.97	$32.75	$22.44	16.7%	16.9%	10.3%	0.086	0.086	0.123	6	6	9	-$21.0	-$24.1	-$39.4
70% Perc	$28.71	$33.61	$23.44	17.0%	17.3%	10.6%	0.088	0.087	0.125	6	6	9	-$20.8	-$23.8	-$38.9
75% Perc	$29.50	$34.52	$24.52	17.4%	17.6%	10.9%	0.089	0.089	0.127	6	6	9	-$20.5	-$23.4	-$38.4
80% Perc	$30.39	$35.55	$25.74	17.8%	18.1%	11.2%	0.091	0.090	0.129	6	6	10	-$20.2	-$23.1	-$37.8
85% Perc	$31.41	$36.71	$27.17	18.3%	18.6%	11.6%	0.093	0.092	0.132	6	6	10	-$19.8	-$22.6	-$37.1
90% Perc	$32.65	$38.20	$28.92	18.9%	19.2%	12.0%	0.095	0.095	0.136	7	7	10	-$19.4	-$22.1	-$36.2
95% Perc	$34.49	$40.33	$31.40	19.9%	20.2%	12.7%	0.099	0.098	0.141	7	7	11	-$18.8	-$21.5	-$35.2

H APPENDIX PVsyst Results for 12.5 MWac Farm in Oslo

This appendix contains the results from PVsyst for the "WVSF" placed in Oslo, Norway. The performance of FT, SAT and DAT are compared with each other and versus WVSF in Tasmania. Particular emphasis is placed on understanding the overall energy yield per annum and also how the power output varies throughout the year for both sunny and cloudy days.

Fig. H.1

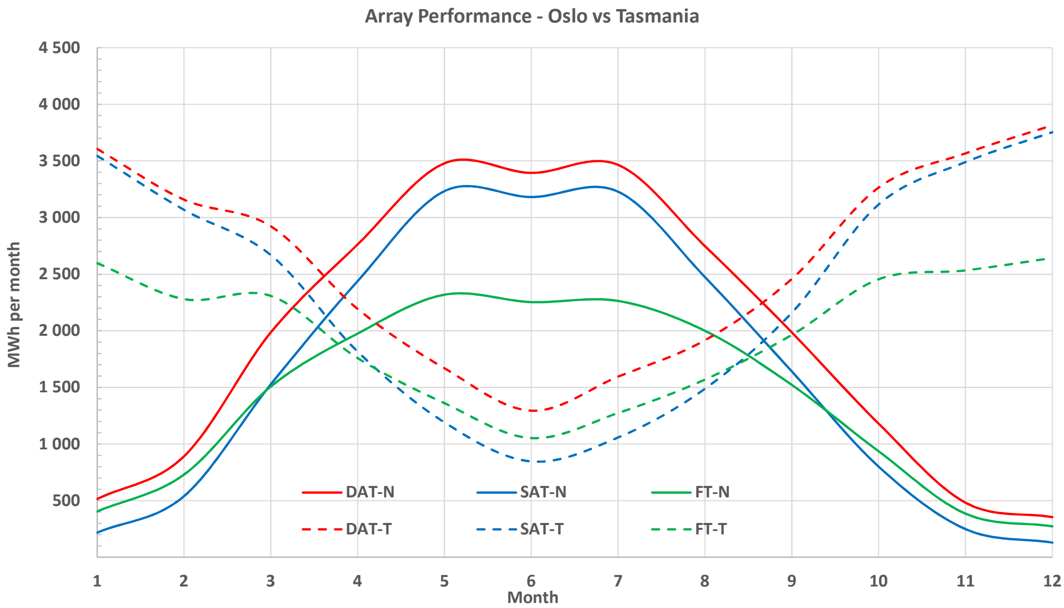


Fig. H.1. Array system performance Oslo vs Tasmania

Fig. H.2

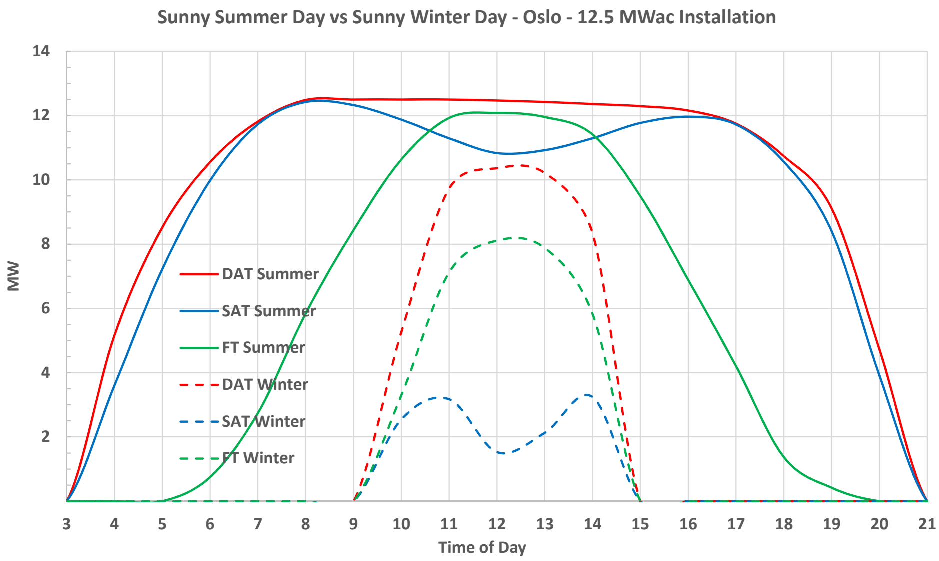


Fig. H.2. Sunny summer day vs sunny winter day Oslo 12.5 MWac

Fig. H.3

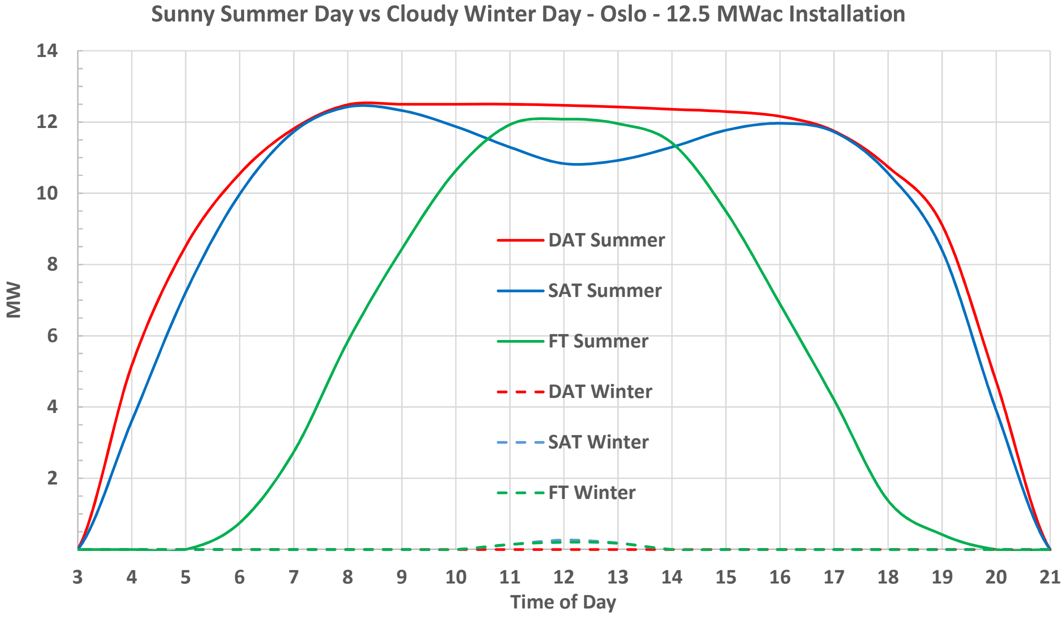


Fig. H.3. Sunny summer day vs cloudy winter day Oslo 12.5 MWac