SHORT-TERM SOLAR FORECASTING FOR MICROGRIDS

Thesis is submitted in partial fulfillment of the requirements for a masters in Renewable & Sustainable Energy at Murdoch University

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Submitted on May 2019

Declaration

I declare that this thesis is my original work and does not contain any material that has ever been submitted in any forum before except where reference has been labeled. This dissertation meets the basic standards of citation and referencing to the best of my knowledge and has been submitted with the approval of my supervisor.

Dedication

I dedicate this work to God for His guidance and grace to date.

To my wife Lynneth and our children Kimutai and Cheptoo, thank you for your patience, love and support all throughout my studies.

To my mother Anne, father Ezekiel and sister in-law Nancy. Without your support I wouldn’t have come this far.

Acknowledgements

The past ten months have been an exciting journey, dedicated to the final step in finishing my master in Renewable and Sustainable Energy at Murdoch University writing this thesis. I would like to express my sincere gratitude to those who helped me during this period.

I acknowledge and appreciate the guidance, patience and knowledge input of my supervisor Dr. Martina Calais throughout the entire thesis study. Your understanding has humbled me.

My gratitude goes to the entire staff and my colleagues of the department of energy studies whose participation made this study a reality. It is my hope that you will enjoy reading this research. May you be richly blessed.

Abstract

This thesis explores the need and application of short-term solar forecasting (STSF) in microgrids. Among several solar forecasting methods, a justification for the choice of sky imaging tools as a preferred method for STSF in microgrids is provided.

The rapid increase in the uptake of solar PV in the electricity grid has shown a convergence in research in the fields of solar forecasting and management of the electricity grid. This energy transition from fossil fuel powered generation to renewable energy generation characterised by consumer-controlled energy generation and the emergence of smart grid has created a surge in demand for real time solar PV forecast information. The relationship between short-term solar forecasting information and microgrid PV generation fluctuation is analysed together to identify areas for the application of STSF technique in microgrid management.

To achieve this, the various solar forecasting methods are discussed with a view of identifying suitable techniques for microgrid applications. Sky imaging is identified as a preferred method thus the operation principle of a sky imaging tool is explained followed by analysis of capabilities of several tools/products available in the market. A summary chart showing the capabilities of WobaS, Steady eye, Instacast and CloudCAM STSF tools is presented in a table.

Three case studies are selected to demonstrate the need and application of STSF under the following scenarios:

- Case 1: Uncontrollable distributed energy resource for this case solar PV, together with centrally located fossil fuel powered power plant with no STSF tool in use.
- Case 2: Centrally located and controllable solar PV plant, a central fossil fuel power plant and energy storage using STSF tool.
- Case 3: Virtual power plant using STSF tool.

Through this approach the need, application and associated benefits of STSF is clearly shown. The benefits in cost savings for the combination of STSF with battery storage is demonstrated. Overall this thesis connects STSF and microgrid management.

Glossary

PV – Photovoltaic.

VRER – Variable Renewable Energy Resource

CSP – Concentrated solar power.

STSF – Short term solar forecasting**.**

GHI – Global Horizontal Irradiance.

DNI – Direct Normal Irradiance.

GTI – Global Tilted Irradiance.

IPC – Interprocess Communication.

SCADA - Supervisory control and data acquisition.

WobaS - “Wolkenkamera-basierte Betriebsstrategien für Solarkraftwerke”

NTP -Network Time Protocol.

MAE – Mean Absolute Error.

FTP - File Transfer Protocol.

HTTP - Hypertext Transfer Protocol.

MODBUS – Serial communication protocol.

TCP – Transmission Control Protocol.

ARENA - Australian Renewable Energy Agency.

USB - Universal Serial Bus.

GPS -Global Positioning System.

JPEG - Joint Photographic Experts Group

HDR – High dynamic range

USI - University of California, San Diego Sky imager

MB – Megabyte

IEEE - Institute of Electrical and Electronics Engineers

APVI – Australian PV Institute

HP – Horizon Power

CO2 – Carbon dioxide.

NWIS – North-West Interconnected System

GSS – Grid Support System

DNSP - Distribution Network Service Provider

DREDs - Demand Response Enabled Devices

AFLC - Audio Frequency load Control

TCP - Transmission Control Protocol

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Chapter 1 - Background of the Thesis

1.1 Introduction

The growth of solar photovoltaic (PV) electricity generation has increased in recent years due to a number of factors such as favourable government renewable energy policies, concern about climate change caused by greenhouse gas emissions and reduced photovoltaic equipment costs among others (Newton and Newman 2013). Unfortunately this energy resource is variable and the fluctuating power it produces causes a complication in the management of any electricity grid compared to the conventional power plants such as fossil fuel powered generation.Some conventional power plants energy generation can be adjusted to meet the energy demand at any particular time while the variable renewable energy resource (VRER) for this case solar PV is weather dependent. The temporal and spatial availability of this VRER at any particular time to meet a certain load is dependent on prevailing weather conditions. It is therefore becoming increasingly important to forecast the solar energy output to maintain smooth operation and management of electricity grid supplied by VRER (Jakoplić et al. 2018). This project adresses what solar forecasting is and why it is needed in relation to distributed energy generation in brief and relate it to a microgrid situation. The focus will then shift to short term solar forecasting (STSF) in relation to its importance to microgrid energy management. A description and analysis of existing short term solar forecasting tools (STSFT) will be done to show their capabilities. A description of the STSFT tools analysed based on their capabilities will be presented in a chart and a brief analysis of the findings is presented. Chapter three of the project will focus on case studies on the need and application of STSFT highlighting the benefits. Finally a discussion and conclusion of the whole project will be presented.This chapter provides background information on the project, the motivation behind it, aims and objectives. The research questions will also be explained in this chapter. The methodology used will be provided together with the limitations.

1.2 Motivation and Background

To provide quality electricity supply, utilities need to ensure that there is a near match between electricity being supplied and consumed at any time. Imbalance between supply and demand causes system stability issues which may lead to power outages, damage to equipment and high operation costs. To be able to balance these two elements forecasting becomes necessary. Utilities over a long period of time have been able to control electricity supply to a large extent because almost all the grid connected generation were large and centrally controlled. The demand on the other hand was managed by providing a safety margin over and above the peak demand thus generation capacity was oversized in a way to ensure the peak demand was met. During these time periods utilities and generation plants were state owned in many jurisdictions, conventional methods of energy generation such as fossil fuels and hydropower were used and there was not much focus on profit making then. This therefore meant state budgets covered long term development of the grid and associated generation which was based on conservative load forecasts.

With emerging technologies coupled with entry of several market players in energy generation and distribution, a lot of changes have been witnessed in the modern grid. There has been rapid growth in renewable energy generation, formation of electricity market for trading and emergence of smart grids. The grid is moving towards an automated system with bidirectional flow of energy which calls for real time information for effective operation. This may be a challenge to achieve regarding a system with a high penetration of solar PV due to the variability of the resource. A report by Australia Renewable Energy Agency(ARENA) indicated that due to these developments electricity network operators are trying to balance demand and supply in periods ranging from seconds to years and scheduling of generators is made against forecast demand(ARENA 2016).

Microgrids are not exempted from these changes as they are characterised by weak networks which pose further challenges for high penetration of variable solar PV generation. Drops in solar PV production occasioned by cloud movements must be compensated by generator ramp up to meet the demand load and this requires large spinning reserves associated with higher costs apart from system stability and security issues. Utilities in such areas have other options to manage the variability of solar PV which include use of curtailment, smart inverters, battery storage and limiting hosting capacities. These approaches are costly, some wasteful and limit the growth of renewable energy generation and the benefits that come with it especially reduction of greenhouse gas (GHG) emissions. These challenges therefore call for variable renewable energy generation forecasts to mitigate the effects of high solar PV penetration into the electricity grid for purposes of grid management(Sayeef et al. 2012). The goal is to make solar PV a dispatchable resource like other conventional generation resource and remove the stigma associated with it.

1.3 Aims and Objectives

The aim of this thesis is to support the proposition that short-term solar forecasting can contribute to power system management of microgrids and allow for an increase in solar PV generation through a literature review and presentation of case studies as proof. This will be achieved through close look into three objectives below:

- To determine the impact of irradiance fluctuation on microgrids with considerable solar PV penetration
- To demonstrate the need and application of STSF on microgrids with focus on the work already done in this field.
- Analysis of short-term solar forecasting tools (STSFT), their capabilities and applications on microgrids.

A clear understanding on the application and benefits associated with short-term solar forecasting will be demonstrated by analysing current microgrid case studies using the technology.

1.4 Research questions

In view of these developments in the present-day electricity grid, this thesis will focus on three research questions:

- Can short-term solar forecasting contribute to power system management and allow for an increase in PV generation?
- If yes, which methods and tools are currently in use?
- What are the STSFT capabilities and where have they been applied?

These research questions can be answered by:

- Investigating and analysing the impacts of solar PV generation on micro grids.
- With focus on specific case studies demonstrate application of various STSFT.
- Formulate a table of STSFT indicating their key capabilities.

1.5 Methodology

This thesis uses case study and literature review approaches. A literature review is important in that it provides a theoretical foundation for this study and can substantiate the presence of the research problem. It enables us to identify what has been written on this topic and determine the extent of research in this field and check if it reveals any interpretable trends or patterns. This was then used to broaden our understanding of the topic in question by comparing the findings of several scholars. The empirical findings from the literature review relating to the research questions can then be aggregated to support what is happening in practice. This helps us develop a theoretical framework for analysis of the specific research questions earlier developed which required more investigation (Paré et al. 2015). The steps involved include the understanding of solar forecasting and why it is needed according to a number of scholars. The next stage was to identify solar forecasting methods and narrow down to short term solar forecasting and its applications. Microgrid definition and electric system faults are highlighted and identify areas where short term solar forecasting can be applied in solving them. Capability requirements of a short-term solar forecasting tool are developed and several STSFT currently available in the market are analysed and summarised in a chart. This information will be based on a literature review. Data sources for the literature review included books, research journals, data sheets from product manufacturers, relevant web pages of utility companies such as Horizon Power among others.

The case study approach is used in this thesis because it is an effective methodology of investigating and understanding complex issues in real life scenarios and used by researchers to address a wide range of research questions (Mills et al. 2017). One of the limitations of this thesis is the lack of theoretical data in this research area and a case study approach fills the gap. The advantage of case study approach is that, it provides practical knowledge to clearly demonstrate the findings of the literature review and answer the research questions and this is one of the reasons why the method was chosen.

1.6 Limitations of the thesis

The research for this thesis has been confined to literature review and case study approach. This is partly because STSF is an emerging technology and there are limited existing projects which can be used to provide meaningful data for analysis. Some of the tools available are at the trial stage therefore may not be easy to find utilities which have a fully running one. The research mainly relied on existing literature and STSF tool manufacturers' data sheets. This narrowed my critical analysis of the topic from available research as most articles were written by a small group of researchers due to lack of extensive research in this field. This constricted the scope and understanding of the topic. The data sheets may have been biased since they are sales material and focused on positives making it quite difficult to know the shortcomings of the tools.

The case studies chosen were quite challenging to find as indicated in one of the reports that there was no other case study in the world they were aware of to compare their findings with. This means the few cases to choose from may not provide enough information to make a conclusion, the advantage is that some of the cases are very recent which brings relevance to the thesis. There was also a limitation of time and scepticism by the tool manufacturers to provide more information on their tools whenever requested to do so.

Chapter 2 - Short Term Solar Forecasting (STSF)

In this section a brief introduction of solar PV forecasting is done. Its relevance to a solar PV dominated distributed energy generation network is demonstrated and related to a microgrid situation which is the focus of our study. The second part will provide the background of short-term solar forecasting and why it is needed in microgrids. The last part will be on analysis of several short-term solar forecasting tools currently available in the market and their evaluation in terms of their capabilities.

2.1 Solar forecasting, solar PV energy generation and microgrids

2.1.1 Solar forecasting

Traditionally solar forecasting was for meteorological purposes. A number of studies were done based on what some refer to as many facets of the sky or climate regimes and their relationship with solar energy(Brownson 2013). There have been attempts to determine the sun's radiant power in relation to its interaction with the earth's atmosphere and surface, which has brought a convergence between solar energy generation and climate studies(Vignola, Michalsky, and Stoffel 2016). To understand this better, it would be appropriate to define some critical solar radiation terminologies that are going to be used quite frequently in this thesis.

- Direct normal irradiance (DNI): is the solar beam radiation that reaches the earth's surface directly in line from the solar disc without being reflected or scattered.
- Diffuse horizontal irradiance (DHI): is the scattered solar radiation reaching the earth surface. The scattering is due to clouds, aerosols, and other atmospheric constituents.
- Global horizontal irradiance (GHI): is the total hemispheric solar radiation on a horizontal surface that is sum of DNI, DHI and ground reflection or albedo(Markvart and Bogus 2000). Pictorial representation of these terminologies is as presented in fig 2.1

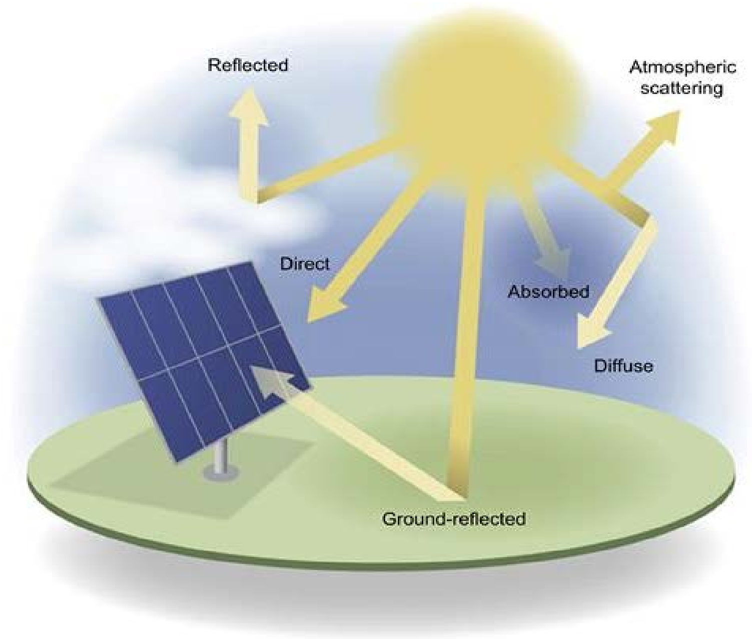

Fig 2.1 Solar radiation in the atmosphere (Kleissl 2013).

Studies done by research groups have a shown a near direct or linear relationship between GHI (W/m^2) and PV power (Watts) from solar PV modules as graphically presented in fig 2.2 below under tests done by the National Renewable Energy Laboratories (NREL) (Richardson et al. 2019).

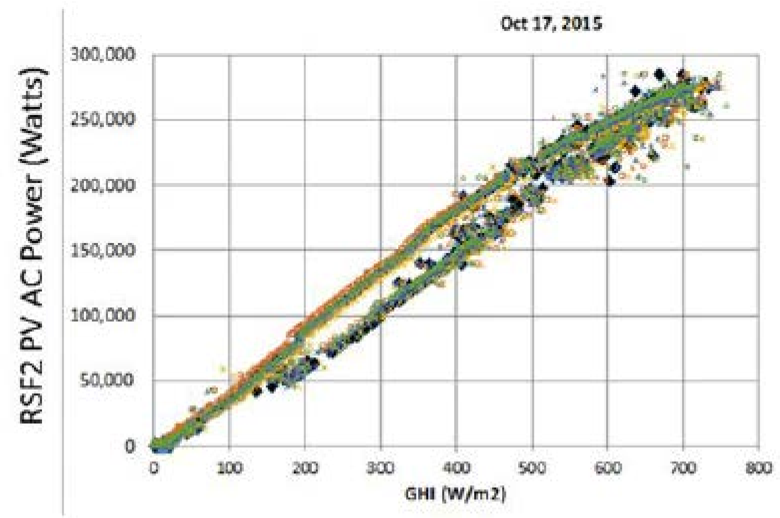

Fig 2.2 Relationship between GHI (W/m^2) and PV power (Watts) determined at NREL (Richardson et al. 2019).

From this demonstration, it shows that any interference with GHI affects PV power output. This therefore means that by forecasting GHI we can forecast the power to be generated by a PV panel. It is also important to note that PV systems, which are generally non-concentrating technologies, require global horizontal irradiance data that is the sum of DNI, DHI and albedo for its forecasts. Research has shown that errors in DNI due to change in sky conditions is reflected by diffuse irradiance increase (Kleissl 2013).

2.1.2 Solar PV energy generation

In the recent past, electricity energy generation was done in a controlled manner to match the demand with some reserve capacity to meet peak load demand as stated earlier in this thesis. Therefore, it was quite possible to plan future grid infrastructure development and maintenance based on conservative load forecasts. This was an expensive approach but was necessary to maintain grid stability, which is key to reliable electricity supply. The grid has undergone rapid transformations occasioned by rising maintenance costs, emergence of smart grid and high uptake of renewable energy generation for our case solar PV. This situation has presented grid operation and planning with challenges, in that electricity consumers have suddenly become producers and the utility operators have very little control over their energy generation. It is becoming increasingly difficult for the utilities to balance demand and supply at a time due to high levels of renewable energy generation in the network. Some customers have installed software technologies that enable them to monitor their electricity usage enabling them to minimise charges and maximise returns based on the applicable unit rates and this behaviour affects the management of the grid (West et al. 2014). This electricity revolution calls for accurate real time information on renewable energy generation and solar PV forecasting can be part of the solution in such a situation. There have been arguments for and against renewable energy generation and one main issue has been the variability of the resource. Solar forecasting application is one of the solutions mentioned that can be used to ensure that grid reliability and stability is maintained under high penetration of low carbon energy (Guerrero-Lemus and Shephard 2017).

The rapid change in electricity grid dynamics is creating demand for solar forecasting by several players in the market, one of them being utility operators. One major challenge associated with increased penetration of renewable energy is the inability for utility operators to tell the actual load of an electric system at a particular time. When electricity consumers are generating energy using solar PV on rooftops, utilities cannot easily quantify that energy, it may only be noticed due to the variability of the solar resource. When the solar resource is not available, consumers begin to draw energy from the grid and this change may sometimes be very rapid and create power ramps on the network. These ramps can be either up or down and may cause frequency stability issues to electricity network, which its frequency regulation will need to handle. Large grids are protected from the fluctuations because they are strong and have frequency regulation services as opposed to microgrids.

To make solar PV generation grid friendly many utilities have come up with solutions that help lessen the impacts of its variability, use of smart inverter functionalities such as ramp rate control is one of them unfortunately most existing inverters may not have these functionalities. Large-scale PV systems can employ active power control mechanisms through voltage current control strategy (Janssen and Krishnaswami 2016) and the inverters can limit voltages to set levels thus ensuring grid stability. Utilities with no such services use power curtailment approach that is, limit PV power output to contain the frequency issues, which is not desirable as it cannot handle power drops unless there is sufficient reserve (Chen, Du, and Wen 2017). Numerous studies have indicated that if the energy fluctuation issues caused by variability of the renewable energy resource are not managed, the resulting grid stability challenges have the potential of causing major system shutdowns (Boemer et al. 2011).

Under this energy transition from unidirectional to bidirectional energy flow, research indicates that solar PV systems combined with other technologies can provide its own technical services for grid stability. This, depends on the level of PV penetration on the network from low levels experiencing low reverse power flows to high penetration levels witnessing frequency and voltage issues. A report by the international energy agency (IEA task 14) indicates that the future grid with mixed generation using inverters and battery storage if well designed with proper regulation can offer some theoretical technical services as shown in fig 2.3 (Stetz et al. 2014).

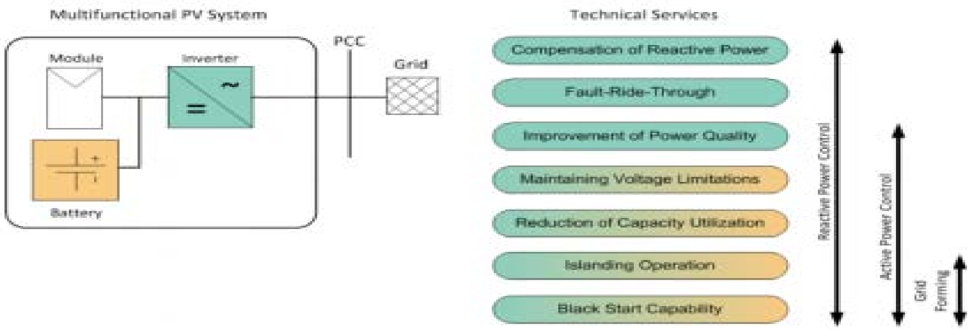

Fig 2.3 Theoretical PV-Battery technical services. Source: (Stetz et al. 2014)

2.1.3 Microgrids

Microgrids lack adequate stabilizing back up which large grid have because of their isolation, size and limited redundancy. A microgrid by definition is "a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes"(IEEE 2017). The microgrid system stability is vulnerable when working under islanded modes due to the lack of technical services support from the large grid. Sophisticated microgrids use Microgrid Energy Management Systems (MEMS) for balancing the generation, load, energy storage and PV output and this requires accurate information especially on the variable PV output to efficiently run the system. The majority of the microgrids currently do not have the capability to predict solar PV energy generation. Horizon Power's 2018 WA microgrid inquiry report indicates that hosting capacities, that is limiting the amount of installed solar PV energy in the grid, are used to manage the technical effects associated with high solar PV penetration. Some utilities operating microgrids have altogether stopped uptake of new solar PV energy generation as they find solutions to this problem (Horizon power 2018).

These methods tend to manage system technical issues and may compromise other benefits such as energy affordability and greenhouse gas emission reduction. Solar forecasting in combination with MEMS can provide a chance to overcome such limitations. Thus, it is becoming increasingly evident that solar forecasting application can provide information on solar PV prediction for microgrids, which will allow higher solar PV penetration through reduction of PV output curtailment and hosting capacity levels. Several microgrid case studies later in this thesis will further demonstrate this.

2.2 Background of short-term solar forecasting

The new electricity market scenario with high penetration of renewable generation in the energy mix is creating interest in solar forecasting. The interest groups range from utilities, investors and even governments because of the interest of having affordable, reliable and environmentally friendly energy supplies. Solar PV is not a dispatchable energy resource due to its variability and utilities have a problem with that because it compromises the quality of electricity supply. The available technologies of making this energy resource dispatchable, such as use of battery storage to absorb all the solar energy during peak sun hours and deliver to the grid when needed are costly now and if deployed will make this energy generation uncompetitive on cost compared to fossil fuel powered generation plants. Having enough capacity reserve to cover for load demand when solar PV is not available is another option, but the costs of installation and maintenance are high which leads to overall rise in electricity costs. Solar forecasting can complement this by providing information, which can be used for real time solar PV energy generation, energy storage management and scheduling of generators in anticipation of any solar PV energy variation. This in a way makes solar PV dispatchable depending on the accuracy of data and forecast horizon therefore resolving problems associated with solar variability and grid integration (Sayeef et al. 2012). There are several solar forecasting methods currently available in the market to provide this information. These forecasting methods are classified according to forecast horizons or timescales from minutes to days ahead and the area of forecast from local area to global as described in section 2.21. The method to employ depends on the purpose of the information.

2.2.1 Solar Forecasting Method Classification

As stated earlier, load forecasting is critical for any electricity system management in both the past and the present scenarios. To meet the forecasted load, variable energy generation calls for generation forecasts and this information is of use to both utility operators and consumers. There are several methods currently in use, they are classified in terms of area of coverage, and time horizon of the forecasts. Some of the methods are:

- Sky imaging.
- Numerical Weather Prediction (NWP).
- Satellite imaging.
- Statistical methods.

The sky imaging method covers timescales of (0-30) minutes for an area of around 1 km, this method converts the cloud position data to deterministic models, that is, the output is determined by the input parameters with no randomness involved. Numerical weather prediction (NWP) uses mathematical models of the atmosphere to predict the irradiance for timescales of between 2 hours to several days covering several kilometres. Satellite imaging on the other hand operates on the timescales of 15 minutes to 6 hours covering very many kilometres that is global scale. Finally, statistical methods provide forecasts of up to several days (Kleissl 2013). This thesis is mainly concerned with a method which can provide accurate forecasts in the short term and for reasonably small area coverage to match microgrid characteristics. The forecast horizon targeted therefore will be in the range of seconds to around 30 minutes ahead. The world meteorological organisation (WMO) considers this type of forecast under nowcasting, a detailed description of the present weather with forecasts covering a period of 0 to 6 hours ahead and is suitable for small area coverage (WMO 2017). The forecast methods with the corresponding forecast horizons are as per table 2.1 below.

Forecast Method	**Forecast Horizon**
Sky imaging	Few seconds to 30 minutes
Satellite Imaging	15 minutes to 6 hours
Statistical	Zero to several days
Numerical weather prediction (NWP)	2 hours to several days

Table 2.1 Forecast methods and associated forecast horizons

The first three methods can somehow meet the requirements for this study however, available research information cannot qualify all these methods as being fit for short term solar forecasting. There are arguments that satellite and NWP methods lack the temporal and spatial resolution for small scale applications while statistical methods cannot predict changes in cloud movement (Schmidt et al. 2016, Jakoplić et al. 2018). This therefore makes sky imaging a preferred method for short term solar forecasting applications.

This forecasting information can be used in meeting a variety of electricity grid needs such as:

- Network operation – manage voltage and frequency fluctuations occasioned by variability in solar PV generation. These fluctuations usually occur in very short time periods generally seconds this therefore a forecast method applied should match this requirement. Generator scheduling can also use forecast information and generator sizes to be made available are prepared based on solar PV generation forecast this can be in the range of minutes to days.
- Regulation purposes – utilities have set technical requirements that solar PV generators must follow. Different utilities have varying allowed ramp rates, such as is the case in Hawaii of ± 2 MW/minute(Martins et al. 2019) and penalties apply for bridge of these regulations. If the STSF accurately predicts a certain amount of drop in solar PV generation, other methods such as energy storage and inverter control are activated in time to inject power in the grid allowing the drop in solar PV to operate within accepted ramp rates level. As stated above this happens in the timescale of minutes and informs the type of solar forecasting method to apply.

- Energy market purposes – the STSF information can assist owners of solar farms to estimate the expected earnings in relation to electricity spot prices in the energy market as per predicted solar PV generation. This can occur from a few hours to days.

The 2018 WA microgrids inquiry report indicate that voltage and frequency fluctuation technical challenges associated with solar PV generation fluctuation is hindering further PV penetration. A case of Horizon Power having set specific solar PV hosting capacities for some microgrids is mentioned in the report. These solar PV effects on the grid fall under regulation and network operation and occur at time periods of few seconds to minutes. Some research done on nowcasting and forecasting of solar irradiance for solar PV grid integration proposes ground measurements for this case with sky imaging as the best approach for intrahour forecasts (Schroedter-Homscheidt et al. 2009). It is therefore reasonable to conclude to some extend that sky imaging STSF technique is a suitable forecasting method for microgrids. A graphical summary of the various methods of forecasting is as shown in fig 2.4 below. This summary is borrowed from several research articles and the blue circle indicates the area of interest for this study.

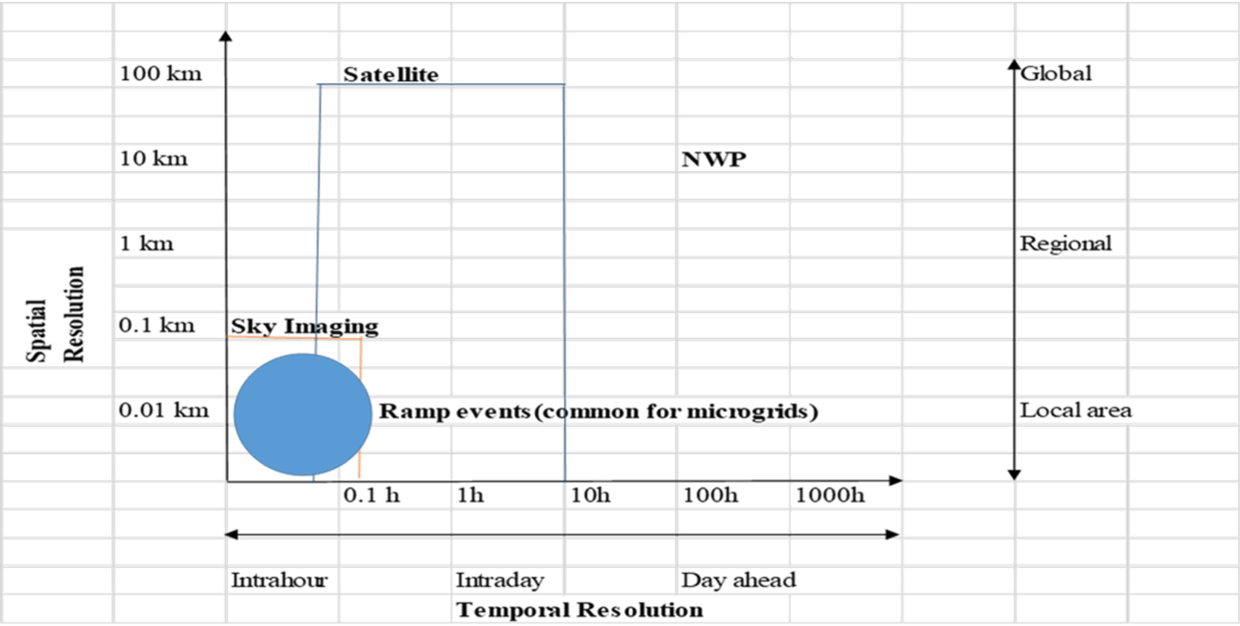

Fig 2.4 Solar forecasting methods and associated spatial and temporal resolution.

Adapted from (Diagne et al. 2013)

2.3 Short term solar forecasting tool evaluation and product description

Clouds are the major causes of variability in surface solar radiation, therefore, to forecast short-term solar irradiance it is important to detect clouds and determine their motion across the sky. A few tools have been developed and are available to handle this unavoidable irradiance variability and uncertainty in its prediction.

2.3.1 Short term solar forecasting tools (STSFT)

Weather conditions are generally dynamic and nonsequential especially about cloud conditions and this makes solar irradiance forecasting difficult. A certain area for example, can experience a high degree of solar variability on a cloudy day due to passing clouds. However, solar energy variability consolidation for the same area over several days will show less variability and becomes insignificant as the time scales increase. The same applies to area of coverage from a single location to an entire region (Perez et al. 2016). This is an indication that the short-term variability in solar energy resource for a given area is critical for solar PV energy generation. STSF tools therefore make a major contribution in helping to forecast solar irradiance conditions in the short term. In this solar forecasting field, several techniques are available, each technique offering different accuracies, having different requirements and operating on varying forecast horizons as indicated earlier in this thesis. This analysis will focus on sky-imaging tools since single instruments deployed can provide high-resolution cloud distribution and track cloud motion, which builds the basis for this forecasting and is a preferred method as explained earlier. Sensor networks can be used but need to be closely spaced in an area of interest to capture cloud movement from point a to b which makes it costly and space consuming compared to sky-imaging (Marquez and Coimbra 2012).

2.3.2 Components of sky imaging tools - STSFT

Sky imagers were initially built for capturing meteorological conditions such as cloud cover. Solar energy irradiance was not critical as such, thus the finer details such as obstruction of the sun in the very short term was not important. Today sky-imaging tools can provide information on local conditions such as amount, classification and composition of cloud cover. It can also tell the direction of movement of the cloud including the temporary characteristics of each cloud and cloud layers and this information is necessary for STSF (Kleissl 2013). A basic sky imager mainly uses a camera. The camera however does not work on its own as it is combined with other solar and cloud assessment equipment such as a pyrheliometer for DNI measurement, ceilometer for cloud height measurement and pyranometer for GHI measurement. The sky imaging tools demonstrate varying capabilities depending on the components incorporated and speed of data computation and some of its components include:

- **Fish eye lens camera -** can map a hemisphere to a flat surface for a limited area due to its visual distortion. There are two methods of capturing the sky image, either by use of a fisheye lens camera pointing the sky or a spherical mirror to reflect the sky hemisphere into a downward pointing camera. The ability to adjust the exposure integration times and area/region of interest is a critical capability of a given STSF tool (Urquhart et al. 2015).Cameras have image sensors that detect and convey data used to make an image or picture also referred to as photodetectors. Examples include semiconductor charge-coupled devices (CCD) and complimentary metal-oxide semiconductors (CMOS). The pixel level of the image obtained is important. Images generated need to be suitable for cloud detection and motion processing (Urquhart et al. 2015).

- **Irradiance sensors and assessment equipment –** Solar PV output is determined by existing weather conditions, which make up the level of solar resource available and solar PV system efficiency. Reference cells can be used to measure irradiance by comparing energy in and energy out in a PV module, pyranometers to quantify the sunshine energy (GHI), pyrheliometer for DNI and ceilometer for cloud height measurements. Inbuilt GPS for geolocation, ambient temperature and humidity sensors also add into the system (Meydbray et al. 2012).

- **Data processing and acquisition software –** Information captured by the camera is processed, a minicomputer system can be embedded in the STSF tool. This computer will perform several operations such as camera control and system configuration. It also processes the images derived from the camera to come up with cloud maps and finally irradiance and production forecasts. This processing is based on the specific STSF tool processing algorithm and final data is made available to the customer through the SCADA or internet connection (Liandrat et al.)

- **Enclosures –** solar forecasting tools are exposed to harsh environmental conditions such as high temperatures, dust and wet conditions. These tools are sensitive to such conditions and enclosures are therefore designed to protect them and this may include use of light external colours to reduce shortwave absorption, temperature and relative humidity sensors to monitor the environmental conditions (Kleissl 2013).

2.3.3 Sky imaging tool operation principle

The tool operates basically in three steps, image analysis, irradiance analysis and finally irradiance/power forecast.

Image analysis

The camera takes images of the sky at set time intervals. To detect clouds, the red-blue-ratio (RBR) method is used, the red channel is divided by the blue channel to determine whether the light comes from cloud (value close to 1) or blue sky (close to zero) and clouds are determined using a threshold that is set for each instrument as explained in chow et al. and Yang et al. (2011; 2014). Objects in the field of view are masked and cloud and shadow mapping done based on cloud height and the position of the sun. Multiple cameras help to determine the cloud height. Due to difference in cloud conditions, cloud classification is done using the set algorithm since irradiance forecast is different for cumulus and stratocumulus clouds (Tapakis and Charalambides 2013). A sample of sky images taken are shown in fig 2.4 below on 27 October 2015, at NREL site. Sky imager takes eight images at 2-minute interval, at 12:31 the sky around the sun is clear, clouds are moving in from the left. At 12:35, the cloud begins to block the sun and by 12:37, the sun is fully occluded, and this continues up to 12:44 when the cloud has passed and GHI is available again (https://doi.org/10.3390/su9040482).

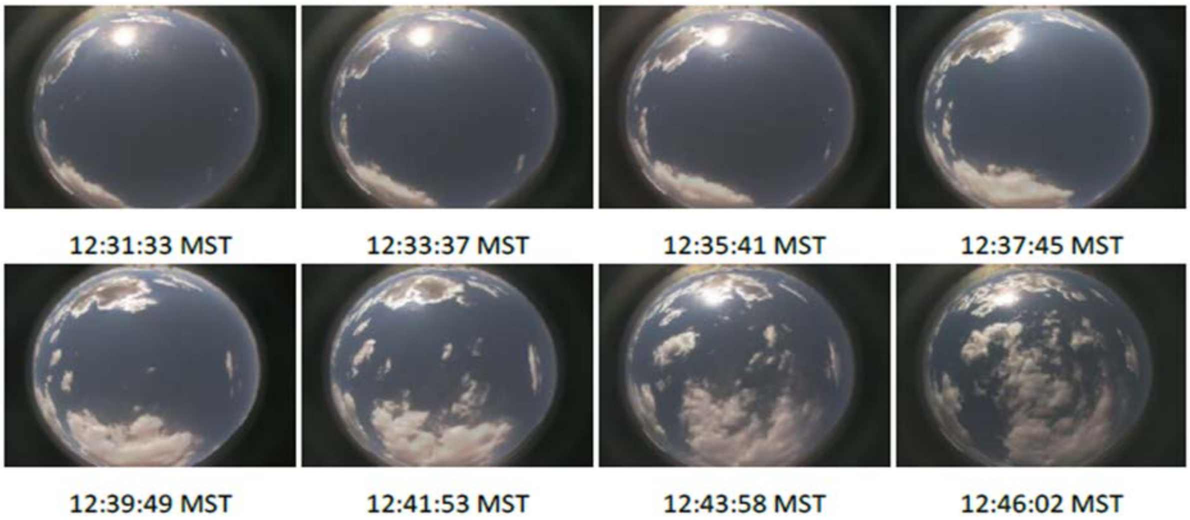

Fig 2.4 Sky imager shadow event. Source:(Richardson et al. 2019)

Irradiance analysis

The transformation of cloud shadow maps into irradiance maps is based on the clear sky data or pyranometer measured clear sky indices information. The clear sky index is the ratio of measured GHI and clear sky data GHI.

$k = GHI_{meas} / GHI_{Clear}$

A histogram is then plotted for different values of k which has two peaks, one for clear sky and the other for overcast conditions. The two peaks are assigned K_{hist} values and the irradiance is calculated as $GHI = K_{hist} \times GHI_{clear}$ and this data is used to create irradiance maps. Different approaches are used to determine the irradiance as is explained in (Schmidt, Kalisch, and Lorenz 2015).

Irradiance/power forecast

Cloud motion information is required for irradiance forecast. This is determined by application of optical flow algorithm, that is the obvious pattern created by a moving object between an observer and a scene (Wood-Bradley, Zapata, and Pye 2012).Cloud edges are used to track the clouds and the algorithm yields cloud motion vectors (CMVs) to determine cloud movement scenes, this process will not be discussed in detail in this thesis but more information is available in (Bouguet 2001). Irradiance forecast is obtained by transferring the still cloud field with the CMVs and subsequent calculation of cloud shadow and irradiance maps is done as explained above in irradiance analysis section. The relationship between GHI and solar PV can be used to determine power forecasts. Other factors such as present air mass and linke turbidity factor are also considered. The principle of operation of a sky imaging tool is as summarised in fig 2.5 below.

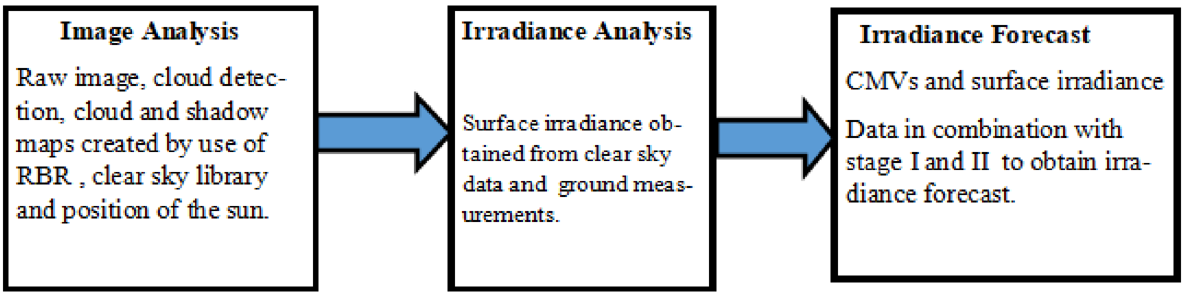

Fig 2.5 Sky imager operation. Adapted from: (Schmidt et al. 2016)

STSF tools capabilities depend on the image processing algorithms used, obstruction of the sky image referred to as occlusion, spatial and temporal resolution. The image can be a compressed JPEG file or a high dynamic range (HDR) image, JPEG loses information due to image compression and reduced dynamic range, which is not desirable but affordable as used in Commonwealth Scientific and Industrial Research Organisation (CSIRO) sites in Newcastle and Canberra, Australia (West et al. 2014). HDR image format has a no information loss thus high accuracy but the technology is expensive. Occlusion leads to missing data due to the shadow band not from the clouds but other objects obstructing the irradiance and it affects tool accuracy. Camera pixels determines spatial and intensity resolution, high pixel levels provide for better spatial resolution, which is desirable but achieved at a cost. The University of California, San Diego Sky imager (USI) uses an HDR system (Urquhart et al. 2015).

Tools which can download and process high MB data at very short intervals equal to the time the camera images are captured, and a new forecast is generated are desirable, this however requires them to have high frame rates that are not easy to achieve. Some tools down size the image to increase processing speed and overcome the challenge (West et al. 2014).

Microprocessors and relay cards serve the purpose of power cycling inbuilt computers in the STSF tools in case the computers fail to start and this capability is critical for remote sites which are not maned and lack regular inspection (Urquhart et al. 2015). There has been advancement in the development of sky imaging tools due to the changes in use from atmospheric sciences to solar energy forecasting applications. This has resulted in various versions of the tools that employ several components. These state of the art STSF tools have the sky image filming components using a variety of cameras some sky facing while others down facing. The irradiance assessment instruments, temperature and humidity sensors, cloud height measurement and inbuilt GPS systems form another set of components of the tool. In built computer system with software for data processing and analysis from the two earlier set of components is also a critical part of modern tool. The output from the computer is the irradiance and finally solar PV energy forecast which is available to the customer via the SCADA system or product manufacturer server depending on the manufacturers' tool being used. This is as summarised in fig 2.6 below

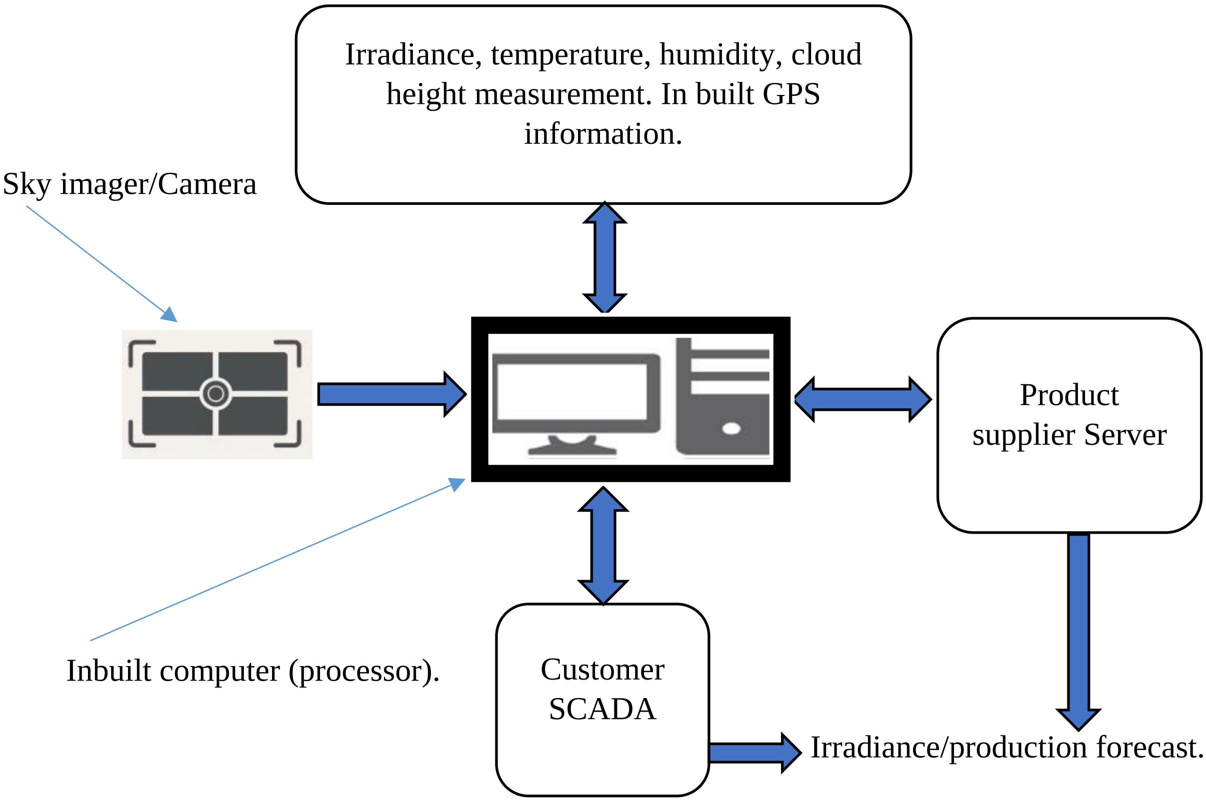

Fig 2.6 STSF standard tool set up.

The above STSF tool shows transformation over time as the requirements on solar forecasting change and grow. The current STSF tools have a sky camera, additional system control hardware and software components with unique and varying capabilities to capture and process data and this provides for a difference in their abilities or strengths. This variety of tools have therefore brought about development of several STSF products as research institutions and companies compete in providing better solutions.

2.3.4 STSF Product description.

A number of research groups and companies have developed forecasting products and tools which can detect and track cloud movements thus forecast cloud shadow events and solar irradiance where required for solar energy production use (Schmidt et al. 2016). These products used for short term solar forecasting are mainly based on sky imagers because they can provide great spatial and temporal resolution forecasts within an hour which is of interest in this study (Chow et al. 2011). There are few products/tools commercially available in the market due to limited research and interest in this field in the past. The STSF products/tools that we have been able to identify so far include:

- Steady Eye by Steady sun.
- InstaCast by Reuniwatt.
- WobaS by Concentrating Solar Power Services and DLR.
- CloudCAM by Fulcrum3D.
- TSI-440 Automated Total Sky Imager by Yankee Environmental Systems.
- Magellan solar smoother by Magellan power.

These products have undergone performance testing and are currently available in the market while some are in use for short-term solar forecasting (STSF) applications in several solar PV energy generation sites. They have different capabilities making them suitable for distinct applications due to the features provided by the different components incorporated. Their capabilities are the focus of the evaluation of these tools and include items such as:

- Forecast area.
- Spatial resolution.
- Temporal resolution.
- Irradiance forecast parameters such as GHI, DNI and GTI.
- Forecast horizon
- Camera type, image resolution and cost.
- Data acquisition and transmission.
- Commercial availability and demonstrated application.

In the following section, we shall consider the attributes of four of these products which have been used and tested in a number of sites currently.

i. WobaS

WobaS is one of the STSF tools based on sky imaging. It uses 180-degree cameras to capture sky images for irradiance forecasts. There are one, two or four camera versions depending on data availability for cloud positions, heights and motion vectors. The 4-camera version provides exact calculation of cloud positions, heights and motion vectors compared to one camera version. This tool uses four regular surveillance cameras Mobotix Q24-3 MP and Q25-6 MP image resolution level, taking sky images at intervals of 30s. The clouds are sectioned, geo-positioned and their shadow maps estimated. This process involves comparing the camera-derived sky images with the clear sky library (CSL) images using the image pixel. This is done while considering present air mass and Linke Turbidity factor (clean and dry atmospheres required to produce the same attenuation of the extra-terrestrial solar radiation that is produced by the real atmosphere) based on the weather. The 3-D position and shapes of the clouds are determined through volume element (Voxel) carving that is the process of using multiple cameras views to derive 3-D images as shown in fig 2.7 below.

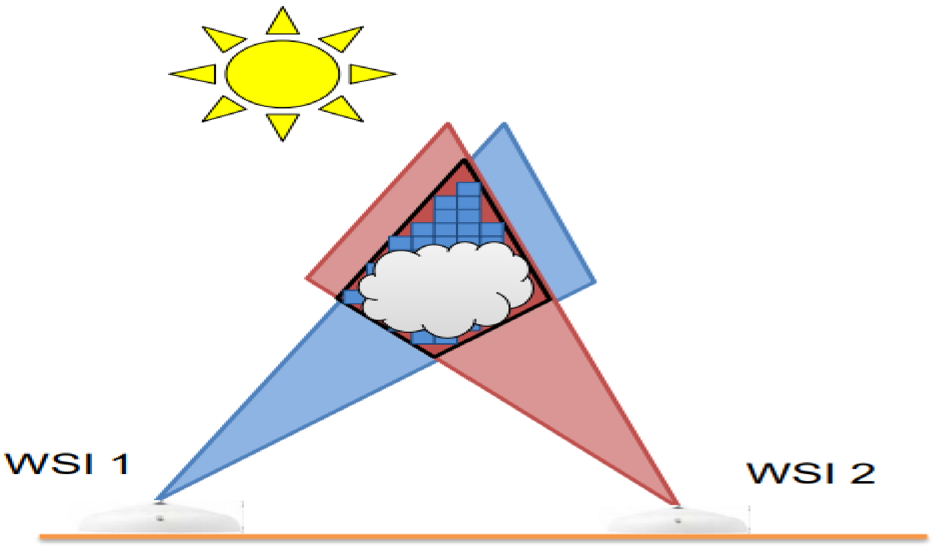

Fig 2.7 Voxel carving (Kuhn et al. 2018).

The cloud images are tracked over several set periods, by doing so cloud velocities and directions are obtained which forms the basis for cloud prediction. It is then possible to tell the position of the cloud shadows on the ground based on the position of the sun and ground topography and this tool can forecast 15 minutes ahead. Irradiance measurements done, help to ascertain the cloud transmittances, which makes it possible to convert shadow maps into irradiance maps. These irradiance maps are used to calculate predicted solar PV energy output, which is our major concern in this study. This STSFT can use ground measurement or modelled irradiance data and the operational block diagram is as shown in fig 2.8 below:

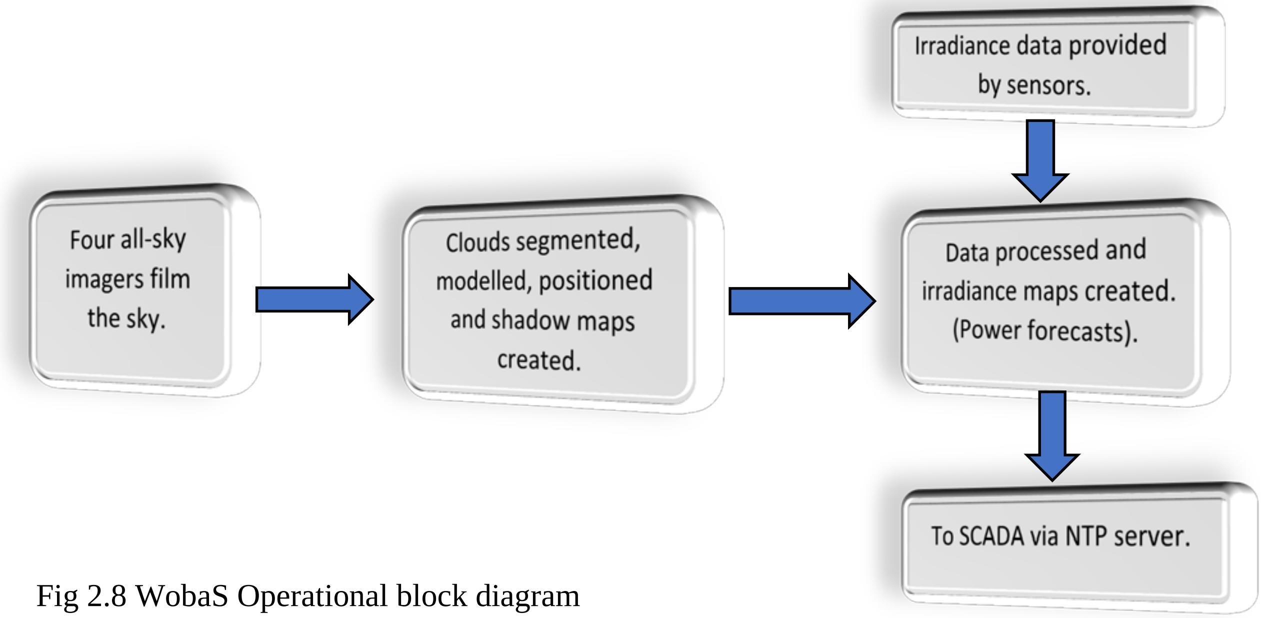

Fig 2.8 WobaS Operational block diagram

This tool can provide predictions for GHI, DNI and GTI covering an area up to 8x8 km^2 with spatial and temporal resolutions of 25 m^2 and 30 seconds respectively. The components used include; sky cameras, pyranometer, LIDARs (light detection and ranging), shadow cameras, pyrheliometers and cloud speed sensor used as additional. Four regular surveillance cameras Mobotix Q24 or Q25 are utilised, as they are easy to use, cheap and reliable under harsh weather conditions. These cameras are of low cost approximately 800 €, easy to operate and reliable. The cameras are synchronised by NTP server, which can be connected to the internet for data transmission. This product is in use in a CSP plant in Spain and at the Plataforma Solar de Almeria (Kuhn et al. 2018). A summary of the tool capabilities is as shown in table 2.2 below.

Description	**Capability**
Forecast area	Up to 8x8 km^2
Temporal resolution	30s
Spatial resolution	25 m^2
Forecast Horizon	15 minutes
Components	4 sky cameras- Mobotix Q24-3 MP and Q25-6 MP image resolution. Pyranometers and pyrheliometer with LIDARs.

Table 2.2 WobaS 4-Camera version capabilities.

ii. Steady Eye

This is a STSF product offered by Steady sun. It employs a 180° sky-facing camera and by use of its image processing algorithms, it can forecast cloud movement for an area of 4 km² with power generation forecasts up to 60 minutes. The working principle of this product is like other STSF products in that, the camera takes hemispherical images of the sky at regular intervals, shadow and cloud maps are created by the cloud detector and motion field instruments using steady sun algorithm. This information is processed together with the irradiance sensors data using the Steadysun algorithm to provide the solar production forecasts. Local / on-site data processing and forecasts production is done, and the tool operates as a stand-alone or by internet connection. Uses WAN configuration for an area with internet connection and an upload speed of 2 Mbps is achievable through the steadysun server to the customer SCADA. A site without permanent internet connection will collect the data from the steadysun server by use of IPC system on site to the customer SCADA. The components in use include a Super Wide (SW) lens X series camera, pyranometer, silicon reference cell and steadysun data processor. The product is as shown in fig 2.9 below:

Fig 2.9 Steady sun SW-X series all-sky imager.

Source:(Steadysun 2018).

A block diagram for the forecast generation is as shown below:

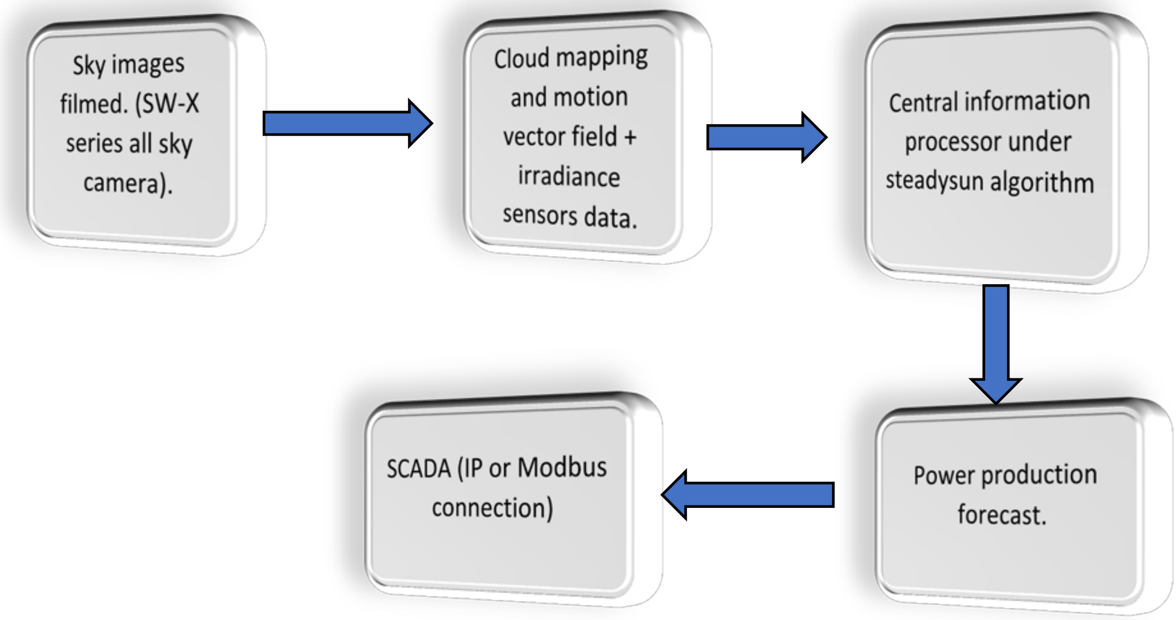

Fig 2.10 Steady eye operational block diagram

Uses IP or Modbus connection for data acquisition to SCADA The tool is commercially available and deployed in a PV plant in Switzerland (Steady sun 2016). A summary of the tool capabilities is as shown in table 2.3 below:

Description	**Capability**
Forecast area	4 km^2
Temporal resolution	10s
Spatial resolution	Local area coverage
Forecast Horizon	60 minutes
Components	Super Wide (SW) lens camera, pyranometer, silicon reference cell, data processor.

Table 2.3 Steady eye sky imaging tool capabilities.

iii. InstaCast

This is one of the Reuniwatt's STSF products. It consists of a down facing long-wave infrared thermal camera facing a hemispherical convex mirror, enabling provision of wide-angle images of the sky. The sky imager operates in steps, first the camera acquires sky images at a high frequency of less than one minute, the images are processed to differentiate the clouds from the sky and sun glares. Cloud maps are generated through geometric calibration to assign the pixels in relation to the position of the sun this is followed by radiometric procedure to convert the raw pixels into luminance pixels. This is then compared to the clear sky library images and a radiative transfer model (inversion) is applied to obtain cloud maps. The irradiance sensors provide irradiance information and by using Reuniwatt processing algorithm the irradiance and production forecasts are obtained.

Temperature, humidity and irradiance sensors are some of the components, which form part of the tool. A minicomputer working as a control unit for image acquisition, processing and network communication to a remote server with a relay card for restarting of the camera is also used. Information processing is done locally on site and can be transmitted to customer via the internet (Liandrat et al.). The product can provide 180° view for an area of approximately 12.5 km^2 and predicts GHI, DNI and GTI with one-minute updates and 30-minute time horizon forecasts. It has output power and drops forecasts variables and data acquisition is via multi-protocol FTP, HTTP, MODBUS-TCP systems. It can withstand harsh climatic conditions of -40 to +60°C.This product is available commercially and recently deployed for a microgrid in Oiapoque, Brazil (Reuniwatt 2018).

Fig 2.11 Reuniwatt InstaCast Sky Insight infrared sky imager.

Source: (Reuniwatt 2018)

A block diagram for the forecast generation is as shown below:

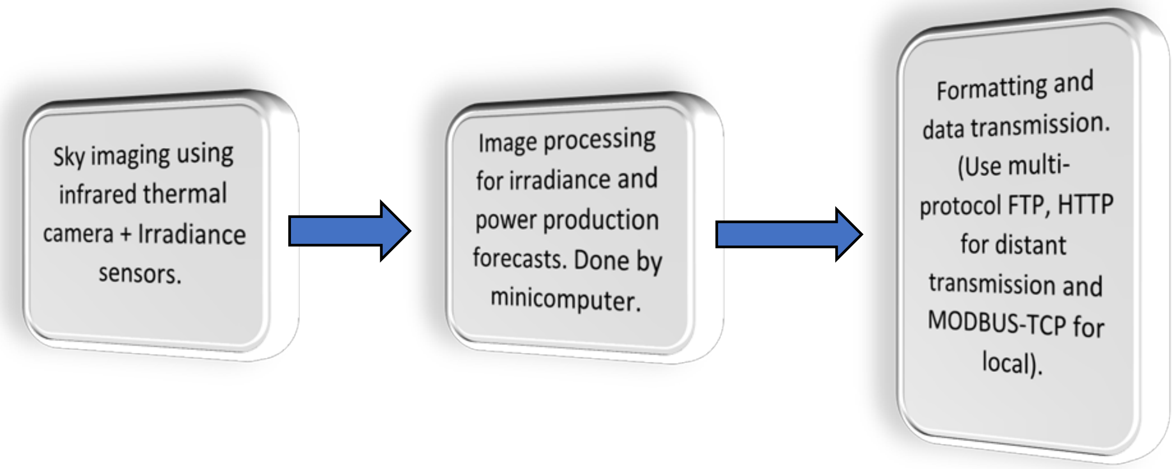

Fig 2.12 Instacast operational block diagram

A summary table of the tool capabilities is as shown in table 2.4 below.

Description	**Capability**
Forecast area	12.5 km^2
Temporal resolution	60s
Spatial resolution	10 m^2
Forecast Horizon	30 minutes
Components	Infrared camera, temperature, humidity and irradiance sensors. Mini PC and relay card.

Table 2.4 Instacast sky imaging tool capabilities.

iv. CloudCAM

Fulcrum3D developed CloudCAM as a STSF product for island grid applications and grid stability by forecasting solar ramps. It uses a site based 180° sky facing camera to capture high resolution sky images at regular intervals. The images are then processed by FDL2 logger algorithm and clouds are detected and tracked. The stages involved are cloud detection, cloud cover measurement, shadow maps generated, and irradiance measurements used to estimate real time power production through application of scaling factor against clear sky production estimates. Other components in use are pyranometer, silicon reference cells, temperature and humidity sensors. The product does nowcasting to 15-minute time horizon forecasts with 1s solar data and 3s other data updates. Real time information is accessible through Modbus TCP/IP to the SCADA or to the Fulcrum3D server, which is accessible via their flight DECK web portal.

Apart from irradiance forecasting this product can also provide current power output estimate and ramp rate control as per customer requirements. The current power output estimate is obtained by use of site equipment parameters such as type of modules, mounting and tracking arrangements in combination with plant feedback information on the status of the equipment such as module temperatures and inverter status to estimate power output. The ramp rate control option can ramp up or down the inverter power output to the customer set ramp rate limits. Cloud detection activates a ramp down signal to a set acceptable level once the cloud clears a ramp up signal is again activated. This product has been deployed in Australia at the Karratha Airport 1MW Solar Project funded by ARENA (Harris 2018b).

A block diagram for the forecast generation is as shown in fig 2.13 below:

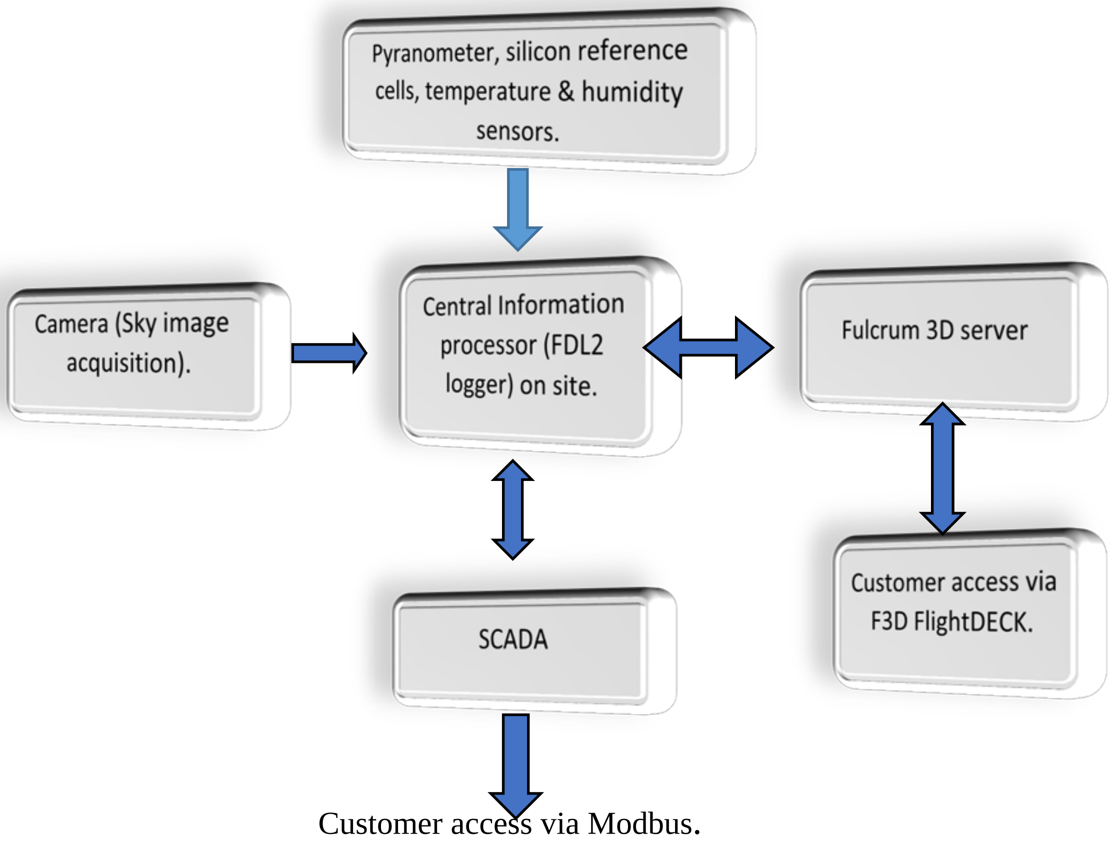

Fig 2.13 CloudCAM operational block diagram

Description	**Capability**
Forecast area	0.2km^2
Temporal resolution	Not provided
Spatial resolution	Not provided
Forecast Horizon	15 minutes
Components	Pyranometer, camera, FDL2 internal processing unit, silicon reference cell. Temperature and humidity sensors.

Table 2.5 Fulcrum3D cloudCAM sky imaging tool capabilities.

Through the analysis of the four short term solar forecasting tools, a summary table based on the capabilities of the individual tools was developed. This chart is as shown in table 2.6 below.

No.	Product	Area of forecast	Spatial Resolution	Temporal resolution	Forecast Horizon	Components	Data Telemetry	Commercial application.	References
1	**SteadyEye**	4 km².	Not available	60s	60 minutes.	Super Wide (SW) lens camera, pyranometer, silicon reference cell,steady sun data processor.	WAN connection data transmitted through steadysun server to customer. Stand alone condtion with no internet data shared by IPC.	Commercially available and used in Power drop detection: Example of a PV plant in Switzerland May 2016.	http://steady-sun.com/technology/steadyeye/
2	**InstaCast**	12.5 km2	10m2	60s	30 minutes	Infrared camera, temperature, humidity and irradiance sensors. Mini PC and relay card.	Use multi- protocal FTP, HTTP for distant transmission and MODBUS-TCP for local.	Available commercially and recently applied for a microgrid in Oiapoque, Brazil.http://reuniwatt.com/en/2018/02/28/voltalia-partners-reuniwatt-first-solar-plant-	http://reuniwatt.com/en/sky-insight-sky-camera-for-intra-hour-solar-forecasts/
3	**WobaS**	Up to 8x8 km².	25 m2	30s	15 minutes.	4 sky cameras- Mobotix Q24-3 MP and Q25-6 MP image resolution. Pyranometers and pyrheliometer with LIDARs.	Synchronised by NTP server for internet data transmission.	Operational at a commercial solar power plant La Africana in Spain.https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10436/12676_read-48274/	http://www.cspservices.de/media/csps/CSPS_DLR_Forecasting_1705.pdf
4	**CloudCAM**	0.2 km2	Not available	Not available	15 minutes.	Pyranometer, camera, FDL2 internal processing unit, silicon reference cell. Temperature and humidity sensors.	Modbus via SCADA to flightdeck .	Used for the Karratha Airport 1MW Solar Project.https://arena.gov.au/assets/2017/02/karratha-solar-farm-public-impact-report.pdf	http://www.fulcrum3d.com/wp-content/uploads/2018/01/CloudCAM_brochure.pdf

Table 2.6 STSF tool capability summary, whole table in appendix 4.

Chapter 3 – Case Studies

3.1 Project Selection

The utility grid in use today was designed to transmit power from centrally positioned generators through the transmission lines to the distribution lines and finally to the customers as stated earlier in this study. Distributed renewable energy generation especially solar PV is changing this scenario by injecting power from the load point causing bidirectional power flow (Katiraei, Mauch, and Dignard-Bailey 2007).This brings about a number of technical concerns that include grid stability, power quality(voltage and frequency fluctuations), system protection and management. These issues become a concern to a utility company when distributed generation (DG) penetration levels are high in a given network. This thesis applies the case study approach in the analysis of several new projects and existing microgrid networks faced with the above challenges.

The focus of this study being to highlight the need for STSF and the tools available in the market to perform this activity, three projects have been chosen for the analysis. The projects that have been implemented recently with considerable amount data available were considered for analysis. These projects are eye catching and are worth the consideration given the relatively limited scope of research available in this new frontier. The main challenge on the project selection was the lack of enough information on this area of research thus limiting the number of projects analysed. While presenting these case studies we shall focus on the local conditions, status and development of the project, tools applied and results with both benefits and shortcomings where possible for the projects. Further to this, the case studies selected depict three case scenarios in line with the thesis research questions as shown below:

- **Case 1**: Uncontrollable distributed energy resource for this case solar PV, together with centrally located fossil fuel powered power plant with no STSF tool in use.
- **Case 2**: Centrally located and controllable solar PV plant, a central fossil fuel power plant and energy storage using an STSF tool.
- **Case 3**: Virtual power plant using an STSF tool.

3.2 Case Study 1: Carnarvon Western Australia

3.2.1 System Summary (as of 2012)

Utility and system owner: Horizon Power (HP)

Size: 11600kW as of 2012

Energy source: Gas/diesel and solar PV generation

Solar resource: 6.2kWh/m^2

Network type: Radial microgrid with 13% PV penetration.

Interconnection Requirements: PV hosting capacity limit of 1.15MWp.

3.2.2 Project importance

This case study highlights the technical issues resulting from high penetration of solar PV generation in a microgrid as shared by stakeholders and study coordinated by Australian PV Association (APVA). It attempts to show the impacts of high penetration of solar PV in electricity grid particularly microgrids which is relevant to this study. Carnarvon is a Western Australian town situated 906 km NW of Perth with a population of 5300 people. Its electricity network was selected for the study for several reasons:

- It is an isolated microgrid with high solar PV penetration of 13% of the system load.
- PV hosting capacity limit was set by Horizon Power, the Carnarvon power station owner and network operator, - due to concerns over impacts of high solar PV penetration in the electricity network.
- There is considerable community interest in adopting solar PV energy generation.
- Horizons Power's desire to increase hosting capacity for the PV generation.

The above issues as per the following case study analysis and observations will demonstrate the need for adoption of STSF tools in such a microgrid situation. The problems are varied in nature and some seem to most likely be solved by use of STSF.

3.2.3 Project Scrutiny

State and federal government policies were the major drivers for PV uptake in Carnarvon including Horizon Power's Renewable Energy Buyback Scheme (REBS). The growth slowed in 2011 when Horizon power decided to limit solar PV in the network as shown below due to concerns on its impact on the electricity network. This means fossil fuel-powered generators would be used more to cover the growing energy demand and that comes with associated costs.

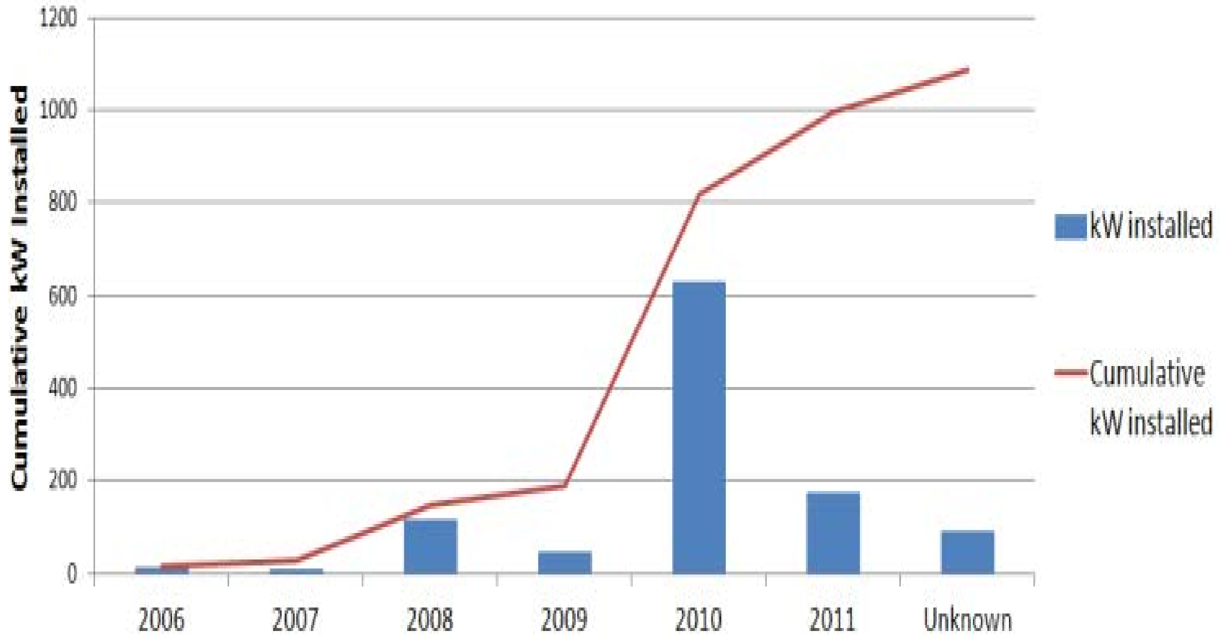

Fig 3.1 Installed PV in Carnarvon. Source (Simon Lewis 2012)

Data available on the load profiles for both summer and winter periods in this area indicates that peak loads occur during the day especially during summer as shown in fig 3.2 below.

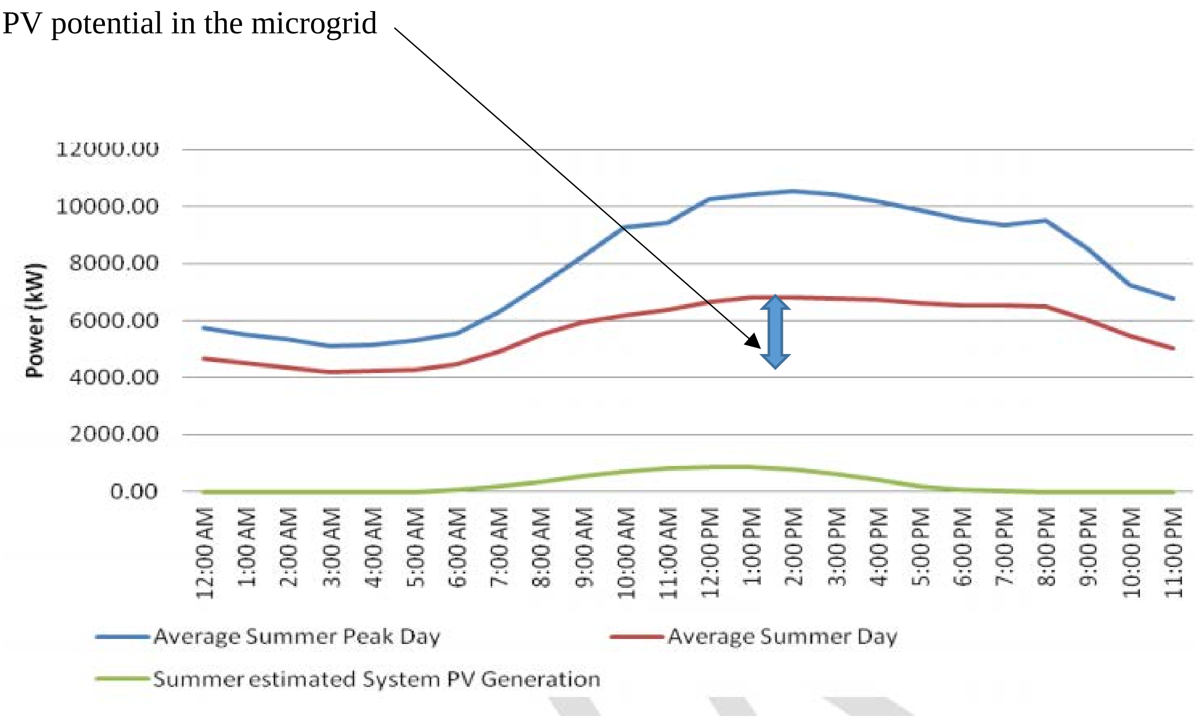

Fig 3.2 Carnarvon summer day load profiles. Source (Simon Lewis 2012)

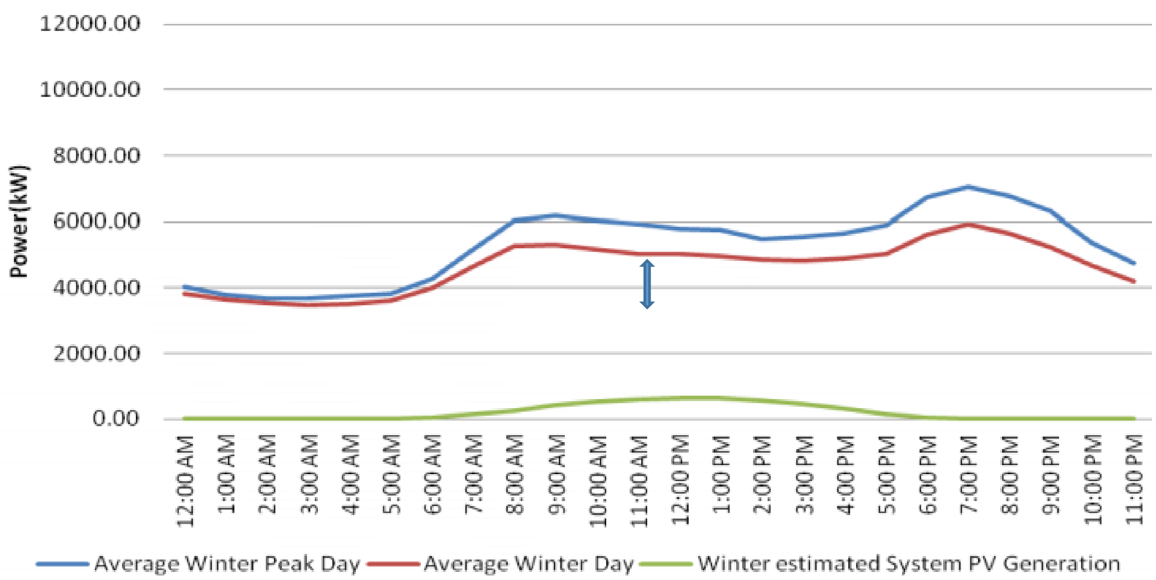

Fig 3.3 Carnarvon winter day load profiles. Source (Simon Lewis 2012).

It is important to note that the two load profiles indicate the high potential of integrating PV into the electricity grid unfortunately this cannot be implemented as it is.

According to the APVA report, there are several technical experiences associated with increasing PV penetration levels in the electricity network. By the time of the study, Horizon Power was experiencing power quality and security problems with existing PV penetration. These concerns resulted in HP implementing a 1.15MW limit on the PV allowed to be connected to the network unless a generation management system was implemented that allows HP to monitor and control system operation. These requirements slowed PV deployment denying the community the benefits. For purposes of this case study, we shall consider whole network level PV system impacts that is generation and system stability and not the distribution network impacts. Two major items will be of concern in line with the interest of the thesis:

- PV system influences on the network due to cloud movement.
- PV system challenges on power planning.

PV system influences due to cloud movement

Changes in solar irradiation levels generally results in PV output variability. Carnarvon PV systems are not an exception and since they are positioned close together within an area of 24km^2, a passing cloud can cause a swift variation in the PV output and to the central generator this appears as a sudden load change. The system stability gets tested depending on the generator ramp rates and spinning reserve. During the system analysis by APVA, an incident on the effects of a passing cloud was recorded at Carnarvon airport, the PV output deviated 80% in 15 minutes, the daily power output with fluctuations is as shown in fig 3.4 below:

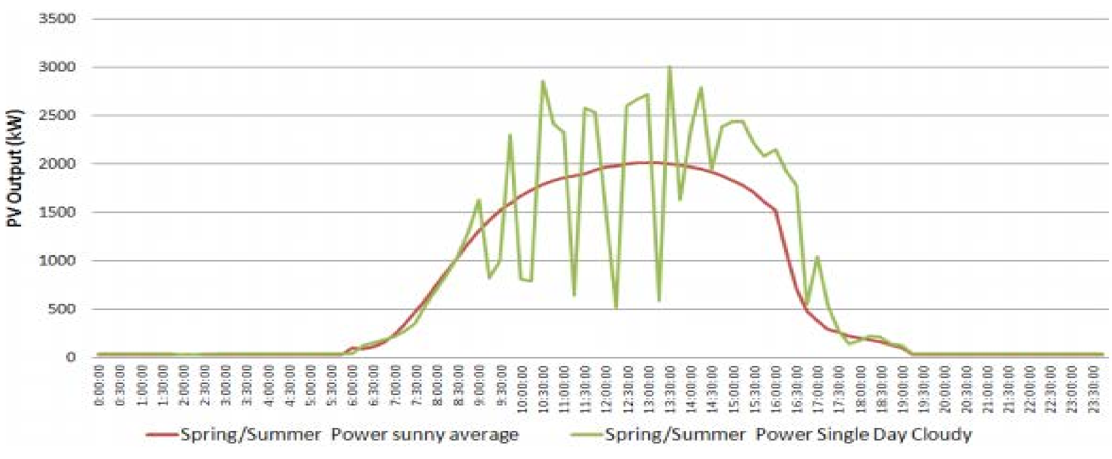

Fig 3.4 Inverter output variation due to passing cloud at Carnarvon airport. Source (Simon Lewis 2012)

This situation can be made worse if the drop in PV output coincides with other load fluctuations from big industries such as the salt plant in Carnarvon. The electricity network in Carnarvon has experienced similar events but there was no documented evidence associated with passing cloud. Horizon Power strategy to counter this problem is by providing enough spinning reserve from generators to counter sudden load changes and maintain system stability which is costly. The use of battery energy storage is another option available, but the utility has chosen to undertake trials on use of solar irradiation sensors and sky cameras for solar forecasting.

The data from the tools could help to predict changes in PV output in the network and thus adjust generator-spinning reserve accordingly. This will result in efficient use of the generators since PV will be optimally used as opposed to running the generators in full spinning reserve. This is a cost reduction measure and may end up with a reduction of electricity prices to the customers apart from other associated benefits. This occurrence together with the proposed solutions clearly demonstrates why STSF tools are required in a microgrid with high PV penetration.

PV system challenges on power planning.

Unknown variability in PV output makes it quite difficult for power planners to predict/tell peak system loads for proper network design. Forecasting techniques can be used to provide information on system load level with and without PV, this in combination with mathematical probabilities could be used to predict the load in future. The data if reliable can help to avoid expenditure on new generation and fully utilise PV generation depending on the risks involved. This in a way is attempting to make PV a dispatchable generation source. The case can be better for large centrally controlled PV systems as is the case for 300kWp system in Carnarvon. HP has proposed a feed in management system where it can ramp up and down the PV output accordingly to maintain system stability during events of passing clouds to avoid sudden power drops. STSF tools can come in handy in such situations and can promote community owned solar farms where customers can buy shares from them and avoid installing rooftop solar. The utility can be in control of the PV system to maintain grid stability.

3.2.4 PV Integration Benefits

Since fossil fuel powered generators are in use for this case study, there are costs involved from the purchase of diesel and gas, generator maintenance and undesirable emission of greenhouse gases mainly CO_2. The use of solar PV systems provides an abatement in GHG emissions and cost reduction occasioned by less generator fuel use. An approximation of the fuel saving with associated CO_2 emissions abatement is shown in a table in appendix 1 section under below assumptions.

- The data is based on annual fuel consumption, assuming solar PV serves a portion of load translating to savings.
- Fossil powered generators produce 49GWh while the solar PV systems produce 1.4GWh per annum.
- Diesel generators operate at 0.26l/kWh and produce 1.22kg/kWh of CO_2 while the gas generators consume $0.24m^3$ /kWh and produce 0.46kg/kWh of CO_2.

The outcome was 833 tonnes of CO_2 abatement which demonstrates that PV use provides for cost savings on fuel and reduction in GHG emissions. Cost of maintenance is not included though there is a high likelihood of reduction on that cost element as the generator run hours may be reduced which lead to reduction in number of scheduled maintenance. With an increase in PV penetration, these costs will be reduced further as generator spinning reserve is expected to fall. Application of STSF tools provide an opportunity for high solar PV penetration (Simon Lewis 2012).

3.3 Case Study 2: Karratha Airport 1 MWp Solar Project

3.3.1 System Summary as of 2018

Utility and system owner: Horizon Power (HP) under NWIS

Size: 1 MWp

Energy source: Gas turbines, solar PV generation and battery storage

PV output curtailment: 778kW

Supply Capacity: One third of the airport energy.

Short term solar
Forecasting tool: Fulcrum3D CloudCAM

3.3.2 Project importance

Karratha Airport 1 MW solar project is important for this thesis study in that through the project we shall be able to demonstrate scenario 2 of our case study where we have a PV system, which is centrally located, controllable with a central power plant and energy storage using STSF tool. This case study is not an ideal microgrid case but is an isolated grid under the North-West Interconnected System (NWIS). Karratha is located roughly 1400 km North of Perth and the area experiences very hot dusty summers with regular cyclones and the solar resource is ideal for solar PV energy generation. As stated earlier the airport is supplied by NWIS, which has Horizon Power’s system serving Karratha and Port Hedland and other privately-owned networks supplying the mines as shown in the appendix 2 section.

Large isolated loads and long transmission lines, which often bring about energy losses thus pushing energy costs high, characterize the NWIS. This project was necessitated by the airport’s upgrade, which meant additional energy requirements together with ARENA's Regional Australia Renewables Program interests. ARENA’S objectives in support of the project were to:

- Demonstrate the role and efficiency of renewable energy systems when combined with solar forecasting techniques and their contribution to isolated grids such as NWIS.
- Provide information to the industry on the economics and technical practicality of using distributed renewable energy generation on isolated grids.

- Provide operational data to Horizon Power showing that the NWIS grid management system requirements can be met with lower levels of energy storage for renewables against current set technical specifications.
- Provide a remote area renewable energy reference site for business case purposes.

3.3.3 Project Operation

This project operates in similar way to other solar PV plants and the power output is connected to the Karratha Airport high voltage electricity network. An aerial view of the system is as shown in fig 3.5.

Fig 3.5 Aerial view of Karratha Airport PV plant (Harris 2018a).

The technical layout below shows the interaction of the various components in operation on the site.

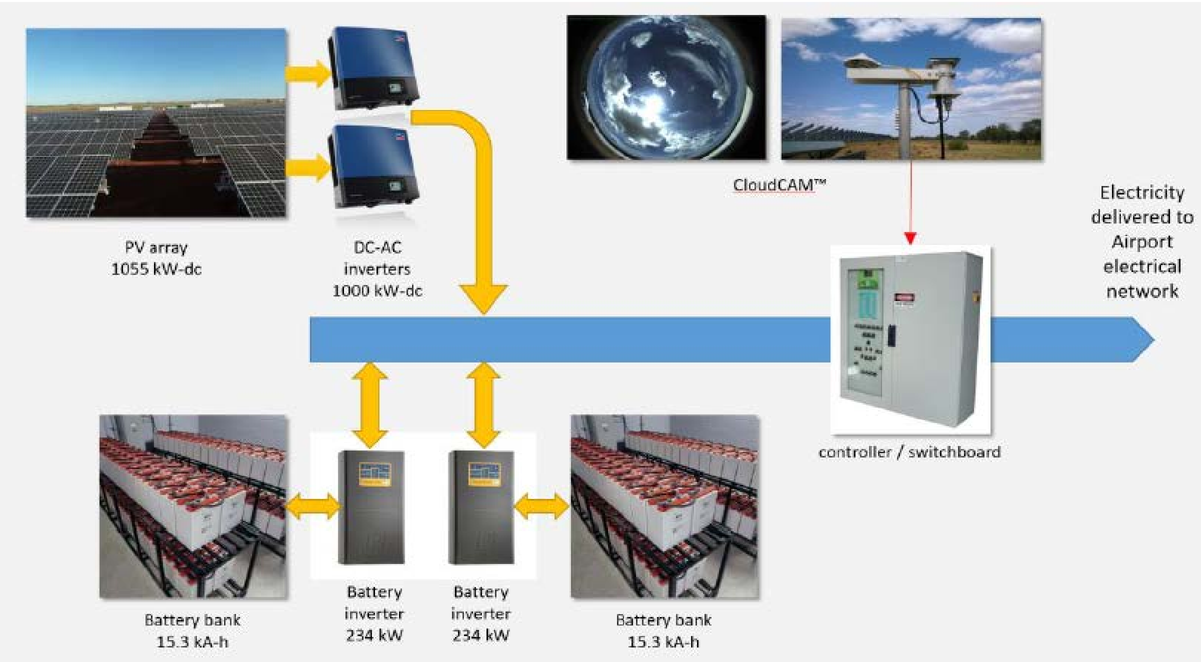

Fig 3.6 Technical layout (Harris 2018a)

The power from the solar PV array is converted from DC- AC and fed to the bus bar serving the Airport's electrical load. The batteries on the other hand supply and tap power from the same bus depending on their charge levels as per set parameters on the controller. Solar forecasting tool, cloudCAM for this case communicates with the controller on the predicted solar energy to be made available from the PV system in the coming seconds and minutes and the controller acts by either ramping power up or down depending on the prediction. At Karratha Airport sunny days provide stable and predictable energy supply, the situation changes when there are passing clouds as the power output can fall by 20% in a period of less than 30 seconds (Harris 2018a). Large stable electricity networks can withstand this rapid change in power output but the generators on the Karratha electricity network cannot counter these rapid changes. Horizon Power has put in place technical requirements on the rate of change of power output from the electricity generators interested in connecting to their grid and this is the reason as to why the Karratha Airport solar project developers deployed cloudCAM's solar forecasting tool for this project.

The CloudCAM solar forecasting tool monitors the sky conditions and by use of the inbuilt image recognition and processing algorithms determines a cloud impact on the solar PV power output from the plant. In case of an oncoming cloud, the tool generates a signal to the controller to reduce the power output of the solar PV to the bus bar. Depending on the rate of fall of the solar PV power output, the batteries are available to tackle very rapid changes for smooth ramp-down to set levels as the conventional generators are allowed enough time to cover for the power deficit if any. The same applies for ramp-up cases with the main aim of achieving a smooth and predictable power pattern. On the 13 of March 2017, a ramp-down event record is as shown in fig 3.7 below.

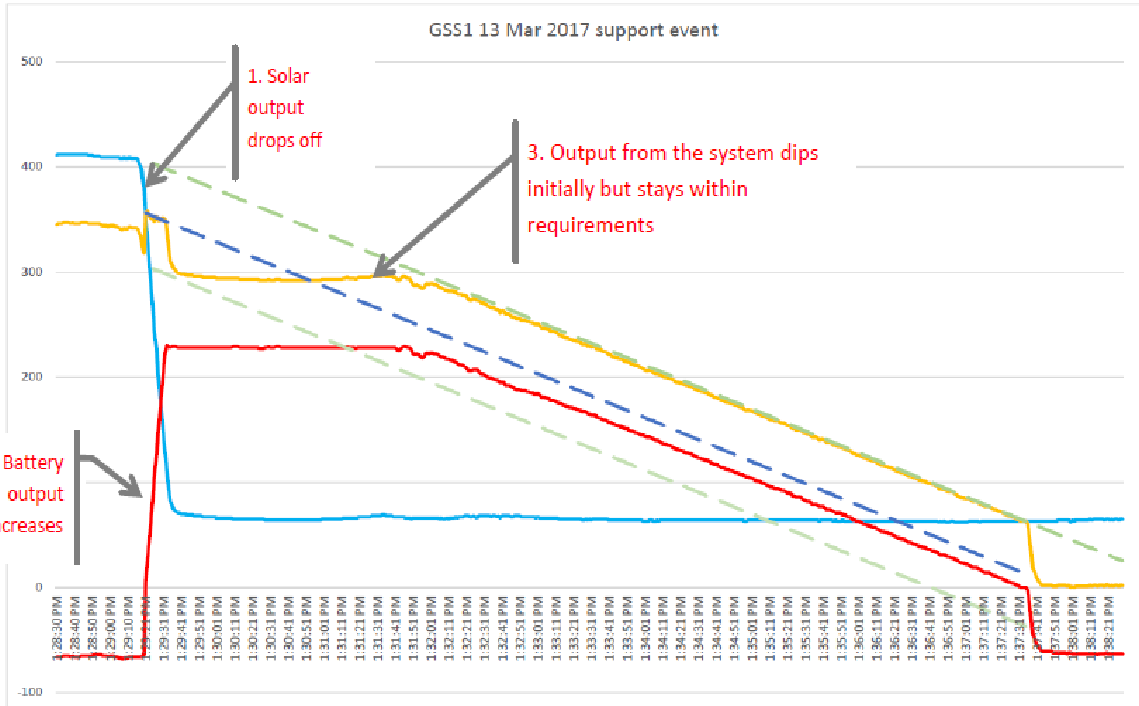

Fig 3.7 Ramp-down event. Source (Harris 2018a).

From the chart above the solar PV power output dropped by nearly 300kW within a period of 20 seconds (blue line). With the help of the cloud information from cloudCAM the battery (red line) chipped in quickly and maintained system power (yellow line) within set operating limits (green line). This information is communicated to the controller by the STSFT prior to the cloud event and the magnitude of the PV power drop is forecasted early enough so that the amount of battery power required is calculated in time. A few minutes before the cloud event, the solar PV ramp down begins, and the battery ramp up starts with the aim of having energy supply fall within acceptable levels.

3.3.4 Project Performance

CloudCAM short-term forecasting tool

According to the report, the cloud detection system has performed at levels above expectation in providing smooth power generation. This by itself demonstrates the success of this project by putting to the test the ability of STSFT to provide smooth power ramp-down or up for a solar PV microgrid system. This is evident as per the solar PV generation plots shown below for a clear morning and cloudy afternoon.

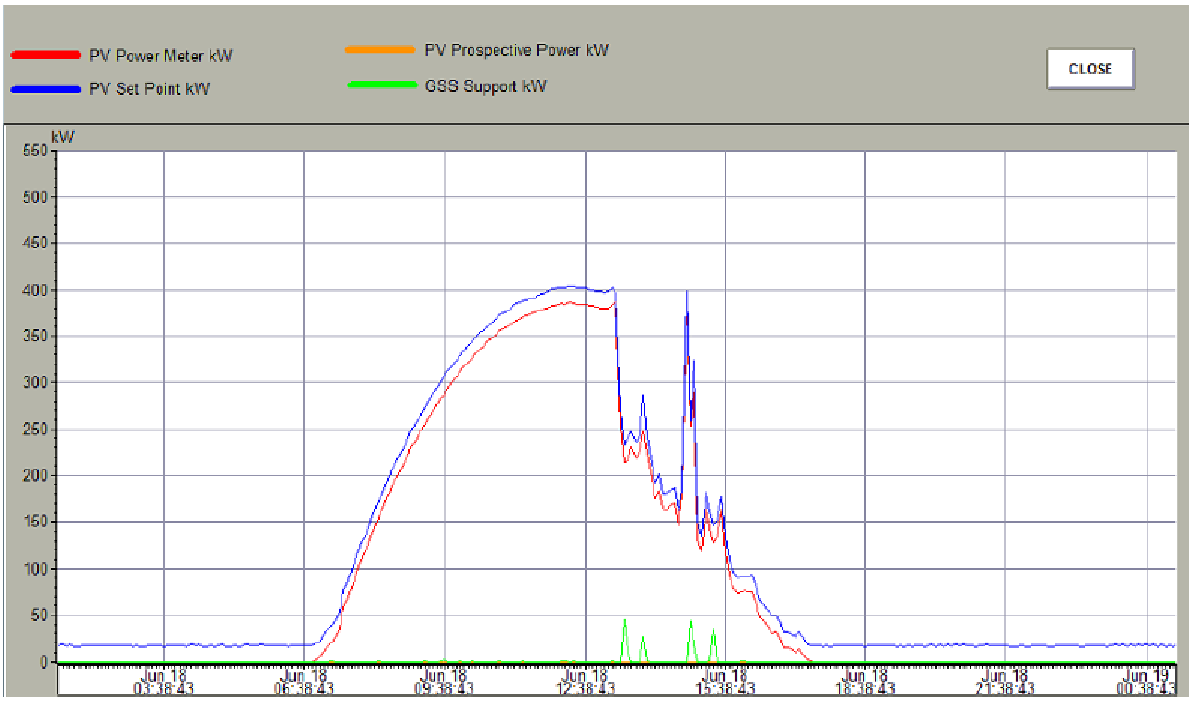

Fig.3.8 June 2018, clear morning and cloudy afternoon (Harris 2018a).

The plot shows the input from the cloud monitoring and battery system in the afternoon.

Battery System

The battery system did perform as expected as the analysis on its ability to provide power to the system under worst-case scenarios and at the same time maintain HP set specifications are as per the following summary. For the year 2017, there were 92 events recorded which required battery support covering a total of 42 minutes and 17 seconds. The battery system met all these requirements. The report also noted a very important aspect that most of the cloud events needing maximum battery input were very short, half of them at 20 seconds and below while 88 % were under a minute. This shows the importance of STSF tools for such solar PV projects when combined with well-sized battery systems. It was also noted that, the highest number of battery requests to inject power into the system was nine in one day, this number could have been higher if the STSF tool was not in use (Harris 2018a).

3.3.5 Project Analysis and Conclusions

The analysis of available data from this project indicates the success of cloudCAM STSF tool in combination with battery storage. The two systems have reliably managed the power ramp-up and down events within the levels set by Horizon Power while keeping the power draw from the batteries very low. This provides an opportunity for downsizing the battery requirements for similar projects in the future thus reducing capital costs.

The STSF tool has considerably limited the amount of time the battery is required to kick in and supply, as per the report without this tool the battery requirement would have doubled, which is a big cost addition to the project. With the depth of battery discharge also reduced by application of the STSF tool, this gives the battery a longer life that provide a saving to the project.

The data results of the battery performance on this project has not identified any situation where battery power output has been curtailed due to low or insufficient battery charge. This is an indication that the battery design was oversized and provides an opportunity for smaller battery system requirements for similar projects.

Overall, this project has been successful in maintaining HP electricity system reliability and stability and at the same time reducing GHG emissions and thus can be replicated for similar projects across the world.

3.4 Case Study 3: ARENA Virtual Power Station 2.0

3.4.1 System Summary as of 2018

Project owner: Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Energy source: Solar PV generation, battery storage and grid power.

PV output curtailment: Using air conditioners and inverters.

Participating households: 67.

Short term solar
Forecasting tool: CSIRO Solar Forecasting System.

Location: Lend Lease development at Yarrabilba, SE Queensland Australia (Knight, 2018).

3.4.2 Project importance

The rapid growth of solar PV and battery storage systems is becoming a concern on the hosting capacity of the grid on the amount of energy generated by this technology. The variability issues associated with it brings power quality problems with it and utilities have placed technical restrictions on new installations. Several solutions exist in the market, but they address either the customer or utility needs but not both. The Virtual Power Station 2.0 (VPS2) project was developed with an intention of delivering technical and economic benefits to both the customers and utilities especially at the distribution level. This product mainly focuses on controllable solar PV, storage (batteries) and large loads like air-conditioners at the customer end. It aims at balancing demand and supply at the customer level and spread the benefits to the entire electricity network. The relevance of this demonstration project case study to our work is to demonstrate scenario 3, whereby we have a distributed PV energy resource in a virtual power plant with limited control using STSF tool in its operation. A summary of problems associated with uncontrolled growth of solar PV generation and possible solutions by using VPS2 is demonstrated in the following description of the project.

The project objectives were to:

- Develop a combined control system for harmonization of supply and demand at the customer level by checking on the appliances loading, PV generation, storage and reactive power components.
- Development of an algorithm to run several households together and provide network services which match the energy needs of that location or group of homes

- Together with other stakeholders, pilot this solution at a new residential set up for this case Lend Lease development at Yarrabilba, SE Queensland.
- Knowledge transfer to distribution network service providers (DNSP) by trials on feeder models developed through the CSIRO National Feeder Taxonomy Study (NFTS). The data outcome of the trial to be made publicly available and can be combined with existing control mechanisms to resolve issues regarding solar PV hosting capacity in Australia https://arena.gov.au/assets/2017/02/csiro-virtual-power-station-2.pdf.

3.4.3 Project Operation

Since the project was the first of its kind, manufacturers of the various test hardware components used in the project were provided with the specifications. The hardware items included inverters, data acquisition components and controllers. Yarrabilba land development site was selected as a test site because it was a new housing development with current energy rating standards.

Residents of the housing development were offered a chance to participate in the trial and it was quite easy to get the participants since they saw an opportunity of taking control of rising energy costs, which has been a concern to many Australians. Five houses were installed with a 10kWh battery system and 29 households with solar PV systems were supplied with controllable SMA inverters.

On the side of controllable loads, Energex the local utility provider supplied single channel Demand Response Enabled Devices (DREDs) on air-conditioners. This enabled remote control of the air conditioners in that the DNSP for this case Energex could send a demand response signal to the DREDs thus remotely control them. 53 air conditioners were allocated a single communication channel thus providing the ability to take control of a large amount of energy and disabling control of individual air conditioning loads. Energy monitors were installed with access to each of the sub-circuits of the households and data was collected every minute and streamed live.

A very critical hardware installed which is important for this case study was the CSIRO Solar Forecasting System for short-term cloud monitoring and a local weather station in Yarrabilba for data gathering.

3.4.4 Project performance test results

Tests were done for the following items:

- Control of air conditioning loads.
- PV output control using inverters.
- Air conditioning load control based on sky camera predictions.
- Simultaneous control of PV output, energy storage and air conditioning load.

We shall focus on the air conditioning load control based on sky camera predictions test and simultaneous control of PV output, energy storage and air conditioning load as of interest to the study.

Air conditioning load control based on sky camera predictions

This test is of high relevance to the thesis and involved matching of the DRM control of the air conditioning load with the variation in solar PV output caused by passing clouds. CSIRO STSF tool installed on site provided 5-minute solar irradiance predictions. These irradiance predictions were monitored in real time and request for activation of the DRMs done on phone to Energex control centre based on predicted drops in solar PV irradiance. The DRM commands were then transmitted via the network as Audio Frequency load Control (AFLC) signal. The air-conditioning load was reduced based on the PV predictions fig.3.9. From the diagram it is notable that there is a delay in air conditioning load drop due to verbal requests made to the control centre, there is also a delay in transmission of AFLC signal. This can be improved through automatic data transmission by integrating the STSF processed output data with the control centre and DRM activation.

Fig 3.9 Air conditioning load control using STSFT predictions (Knight 2018).

Simultaneous control of PV output, energy storage and air conditioning load

A combination of the previous tests done were all put under one test, energy storage included for this case. The same inverters were used to control energy storage and PV generation using DRMs over TCP/IP communications.

Two CSIRO STSF tools were deployed providing 5-minute ahead irradiance forecasts. The forecast data was used to activate DRM commands on the inverters and air conditioners to lower air conditioning load, gently ramp down PV output and increase the power output from the batteries according to the 5-minute ahead irradiance predictions provided by the CSIRO STSF tool. Execution of the DRMs were automated and required little human input and the default rates for the inverters were adjusted to match the fast responses needed to counter sudden changes in PV output variation due to passing clouds.

The results from the tests not provided in this report indicated that these systems could be effectively operated and controlled centrally and eventually provide a solution to challenges caused by variable solar PV energy generation. By so doing, grid stability is maintained, and PV curtailment and hosting capacity issues will not be of much concern.

3.4.5 Project Analysis and Conclusions

The findings of this report indicate that this pilot project successfully demonstrated STSF tools can be combined with energy storage, inverter and load control to ease the challenges faced by the utilities due to variable solar PV energy generation. This in turn leads higher penetration of PV, which comes with associated benefits to customers. VPS2 thinking is in the use of distributed energy resource to solve grid problems and at the same time provide some benefit to the customer. Around the world, there are similar projects, with similar intentions but are mainly focused on demand response for capacity provision aimed at the wholesale market. VPS2 on the other hand is different approach:

- Avoids turning off devices by slowly varying power supply or demand from devices using variable controls.
- Focused on providing grid services at the distribution level rather than electricity wholesale market.
- Combines load, generation and storage management in a network.

None of the other available technologies provide all the three benefits at once, most have one or two not all(Knight 2018). Similar project to this is the 250 kW solar city project done by Tesla and Southern California Edison which involves storage, PV and controllable loads to demonstrate capacity, reactive power support, frequency regulation and reserves (TESLA 2017).

In a microgrid situation, this technology can be handy due to the small size of the grid like this pilot project and the power variability challenges the same grid faces. The VPS2 project can be refined further to offer solutions to microgrid solar PV variability challenges by developing centrally managed controllers. These controllers can be deployed to run and provide a balance between solar PV generation and energy demand for controllable loads thus providing support and stability to the grid by cancelling the power generation fluctuations at the customer level in a network (Knight 2018). This eventually may lead to development of smart grid model based on predictive control whereby demand response signals are generated to manipulate controllable loads so as to maximise on the available solar PV resource and energy storage while at the same time maintaining grid stability partly explained in (Mahdavi et al. 2017). This case study presents a scenario whereby VPS2 technology capabilities can be used in a microgrid with a few modifications depending on the desired results.

3.5 Lessons learnt, and conclusion drawn from the experience on the case studies

The case studies analysed in this study are all different and complex. Every project selected had its own unique features thus making it difficult to compare and evaluate the success of all of them at one go. This was partly due to the lack of a wide field of projects to select from making it challenging to identify similar projects for performance comparison. A more detailed approach may be required to do such analysis. This however was not the aim of this thesis our interest was to focus on the application of STSFT on microgrids based on the set objectives. This was not fully achieved since we could not identify a microgrid using STSF tool with reasonable data available to demonstrate the performance of the tool. This challenge was addressed by selecting projects with similar characteristics as those of microgrids and use the results obtained to demonstrate that the same behaviour was most likely to be replicated in a microgrid. It was therefore justified to some extend to explain the performance of STSF tool case by case rather than as whole but going forward this may change as the technology becomes common. The case studies selected were successful in demonstrating the applications of STSF tools based on set objectives and this appeared an effective method to display the performance of the tools.

Chapter 4 – Conclusion, Limitation & Future work

In this thesis, the challenges associated with high penetration of solar PV generation in the electricity grid and available solutions have been discussed. Among the many solutions currently in use, sky imaging was considered due to its low cost and the ability to match its capabilities in solving PV generation fluctuations in a microgrid grid caused by passing clouds. The working principle of sky imaging tools was discussed and the capabilities of four tools/products currently available in the market summarised in a table. The application of the sky imaging tool in solar forecasting was demonstrated in the case studies where the need and benefits associated with the use of this technology came out clearly in real life scenarios.

The study through literature review showed that solar PV fluctuations may cause electricity system stability problems in microgrids which calls for provision of higher spinning reserve from conventional generation leading to an increase in plant as well as O&M costs if more generators or storage is required. Hosting capacities and curtailment have been identified as methods used to solve the problem. These methods limit growth of PV as demonstrated by the Carnarvon case study. The need for solar forecasting as one of the methods of increasing solar PV penetration due to its ability to tackle the solar PV variability problem is identified in the case study and the literature review. This answers part of the research question: can short-term solar forecasting contribute to power system management and allow for an increase in PV generation?

Having demonstrated the advantage for STSF in microgrids, the application and benefits of STSF was discussed in the Karratha Airport 1 MWp Solar Project case study. From this project the operation of CloudCAM forecasting tool was described in detail. This tool was able to keep the ramp up and down of solar PV within Horizon Power's set limits and reduce curtailment losses. The tool in combination with the battery system provided a win-win situation in that the energy draw from the battery was low and the ramps were smooth and long enough to enable other generators to come on line. This performance provides some positives of STSF tool applications in that for a well-designed system, power ramps experienced are smooth and long which is desirable, the draw on batteries is low thus reducing capital cost as smaller batteries are needed. The ramp time is the key benefit for microgrid control and the forecasting enables the battery size to be smaller with same functionality. This is a clear demonstration that STSF tools are beneficial and needed for microgrids with high solar PV penetration and answers the research question on the contribution of short-term solar forecasting to power system management in a microgrid.

The STSF tools/products analysed in this thesis portrayed a range of capabilities, some common among the four tools while others were unique to specific tools. One common feature was the temporal and spatial resolution of a tool. To obtain better forecast results and fill the gap for microgrid requirements, local high-resolution and (0-30) minutes forecasts are important. Manufacture's data sheets available were not very specific on the lowest values their tools could achieve based on the two parameters. The CSIRO STSF tool used in the virtual power plant case study for load control highlighted the importance of time and area of coverage in execution of the commands. It was noted that a phone call command negatively impacted on the switching of air conditioners by causing delay. A tool with high spatial and temporal resolution working in a smart grid may certainly provide better outcomes and mostly likely preferred by microgrids.

This thesis has demonstrated the applicability of STSF in the management of solar PV variability in microgrids thus maintaining system stability and maximising the utilization of available PV leading to reduction in O&M and capital costs on generators and batteries respectively. In the transformation to smart grid this technology will most likely be a requirement as the grid transitions from fossil fuel generation to renewable energy generation.

During this study limited literature and information on STSF was one of the major challenges. This was replicated in the small number of sky imaging tools available in the market and the very few documented case studies using STSF tools. This in a way narrowed the scope and depth of the research as there were not a variety of options to choose from.

STSF product manufacturers' unwillingness to provide more information regarding capabilities of the tools was another limitation. The ones contacted were sceptical on learning that the information requested was for research purposes, one of the reasons may be the details of their technology is a secret which keeps them an edge in the market. The time frame allocated to this thesis was not enough to get into the full details of solar forecasting and collect data for analysis from utility companies as there were other units to study at the same time.

There are opportunities for future research in this field, development of a software which can help in selection of a specific STSF tool to deploy for a given microgrid system requirements is needed. This is because microgrids have different operation mechanisms and characteristics, a software which can match and rank available tools to a microgrid as per their capabilities would be beneficial to microgrid management. Finally, a combination of sky imaging and other forecasting techniques may also be an attractive option for STSF (Williamson 2017).

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Appendix

Fuel Type	Volume used per annum for load (kUnits)	Volume offset by PV systems (kUnits)	Carbon Dioxide produced by load requirements (tonnes)	Carbon dioxide offset by PV systems (tonnes)
Diesel	1,561	51	7,369	242
Gas	10,146	308	19,506	591

Appendix 1 Fossil fuel savings and CO2 abatement in the Carnarvon network due to PV systems. Source (Simon Lewis 2012)

Appendix 2 NWIS network (Harris 2018a).

Mode	AS/NZS 4755.3 (2012)	AS/NZS 4755.3 (2014)	Compliance
DRM1	Compressor off	Compressor off	Mandatory
DRM2	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 50% of the total electrical energy that would be consumed **if operating at the rated capacity in a half hour period.**	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 50% of the total electrical energy that would be consumed **in a half hour period during normal operation under the same temperature and humidity conditions, and the same user settings.**	Not Mandatory
DRM3	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 75% of the total electrical energy that would be consumed **if operating at the rated capacity in a half hour period.**	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 75% of the total electrical energy that would be consumed **in a half hour period during normal operation under the same temperature and humidity conditions, and the same user settings.**	Not Mandatory

Appendix 3 A sample of AS/NZS 4755 DRM modes standards (Knight 2018).

No.	Product	Area of forecast	Spatial Resolution	Temporal resolution	Components	Irradiance Forecast Parameters	Camera type and image resolution	Forecast Horizon	Data Telemetry/Communi	Commercial availability and demonstrated application.	References
1	SteadyEye by Steadysun.	4 km^2.	Not available	60s	Super Wide (SW) lens camera, pyranometer, silicon reference cell,steady sun data processor.	GHI, DNI and GTI .	180° sky facing high resolution camera .	60 minutes.	WAN connection data transmitted through steadysun server to customer. Stand alone condtion with no internet data shared by IPC.	Commercially available and used in Power drop detection: Example of a PV plant in Switzerland May 2016.	http://steady-sun.com/technology/steadyeye/
2	InstaCast by Reuniwatt.	12.5 km2	10m2	60s	Infrared camera, temperature, humidity and irradiance sensors. Mini PC and relay card.	DNI,GHI and GTI.	180 degree angle using Infrared thermal camera with hemispherical mirror.	30 minutes	Use multi- protocal FTP, HTTP for distant transmission and MODBUS-TCP for local.	Available commercially and recently applied for a microgrid in Oiapoque, Brazil.http://reuniwatt.com/en/2018/02/28/voltalia-partners-reuniwatt-first-solar-plant-brazil/	http://reuniwatt.com/en/sky-insight-sky-camera-for-intra-hour-solar-forecasts/
3	WobaS	Up to 8x8 km^2.	25 m2	30s	4 sky cameras- Mobotix Q24-3 MP and Q25-6 MP image resolution. Pyranometers and pyrheliometer with LIDARs.	DNI,GHI and GTI.	180 degree angle 6 MP sky camera.	15 minutes.	Synchronised by NTP server for internet data transmission.	Operational at a commercial solar power plant La Africana in Spain.https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10436/12676_read-48274/	http://www.cspservices.de/media/csps/CSPS_DLR_Forecasting_1705.pdf
4	Fulcrum3D-CloudCAM.	0.2 km2	Not available	Not available	Pyranometer, camera, FDL2 internal processing unit, silicon reference cell. Temperature and humidity sensors.	GHI	Cloudcam 180° sky facing camera .	15 minutes.	Modbus via SCADA to flightdeck .	Used for the Karratha Airport 1MW Solar Project.https://arena.gov.au/assets/2017/02/karratha-solar-farm-public-impact-report.pdf	http://www.fulcrum3d.com/wp-content/uploads/2018/01/CloudCAM_brochure.pdf

Appendix.4 Table .6 STSF tool capability summary