UNIVERSITY OF THE WESTERN CAPE

Smart Renewable Energy: Architectures, Dimensioning and Monitoring

by

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A thesis submitted in partial fulfillment for the degree of Master of Science

in the
Faculty of Science
Department of Computer Science

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Declaration of Authorship

I declare that *Smart Renewable Energy: Architectures, Dimensioning and Monitoring* is my own work, that it has not been submitted for any degree or examination in any other university and that all sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Zenville Erasmus

Date:

Signed:

"Knowledge is power. Information is liberating. Education is the premise of progress, in every society, in every family."

Kofi Annan

UNIVERSITY OF THE WESTERN CAPE

Abstract

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The Smart Renewable Energy project at the University of The Western Cape, under the guidance of the Intelligent Systems and Advanced Telecommunication (ISAT) group, aims at developing a dynamic system that enables users to (1) design smart architectures for next generation wind and solar systems to meet African power challenges (2) use these architectures to dimension the underlying solar and wind power systems and (3) simulate, implement and evaluate the performance of such power systems.

The project's existing web and mobile monitoring system will undergo a much needed upgrade to cater for monitoring of the existing system's environmental and battery bank parameters. This will be implemented by allowing users to monitor input, storage and output trends over various time frames. These time frames would include hourly, daily, weekly and monthly readings. The visual evaluation of the system will be generated by mathematical, statistical and machine learning techniques. Trends will be discovered that will allow users to optimize the system's efficiency and their usage patterns.

The accompanied dimensioning system will allow users to cater for their needs in a two-way fashion. Users will be able to specify the number of devices that they want to run from a solar or wind based system and their power needs will be generated. They will also be able to determine what a given system is capable of producing and the number of devices that can be used simultaneously, as a result.

Acknowledgements

Acknowledgement is generously due to my project supervisor, Professor Antoine Bagula and to the continuous support of my family, friends, colleagues and the Computer Science department. I would also like to thank the Namibia Students Financial Assistance Fund (NSFAF) and the National Research Fund (NRF) for their financial support....

Publications

Zenville Erasmus and Antoine Bagula. Remote Sensor Network for Off-grid Renewable Energy Monitoring - WIP. Southern Africa Telecommunication Networks and Applications Conference (SATNAC) 2015, 2015.

Zenville Erasmus and Antoine Bagula. Remote Sensor Network for Off-Grid Renewable Energy Monitoring. IST-Africa Week Conference, May 2016.

MNS Miazi, Zenville Erasmus, Md. Abdur Razzaque, Marco Zennaro, and Antoine Bagula. Enabling the Internet of Things in Developing Countries: Opportunities and Challenges. International conference on Informatics, Electronics and Vision (ICIEV), Dhaka, Bangladesh, May 2016.

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Abbreviations

RSS	**R**emote **S**ensor **S**ystem
RSN	**R**emote **S**ensor **N**etwork
PV	**P**hotovoltaic
SMS	**S**hort **M**essage **S**ervice
GSM	**G**lobal **S**ystem for **M**obile communication
SHS	**S**olar **H**ome **S**ystem
RES	**R**enewable **E**nergy **S**ource
PC	**P**ersonal **C**omputer
$\mathbf{kW_p}$	**K**ilo **W**att **P**eak
EU	**E**uropean **U**nion
PVSAT-2	**P**hoto **V**oltaic satellite 2
I\O	**I**nput**O**utput
FP	**F**ield **P**oint
I-V	**C**urrent-**V**oltage
DC	**D**irect **C**urrent
$\mathbf{L_{ct}}$	thermal capture losses
$\mathbf{L_{cm}}$	miscellaneous capture losses
$\mathbf{R_C}$	current ratio
$\mathbf{R_V}$	voltage ratio
TRNSYS	Transient System Simulation Tool
MPPT	**M**aximum **P**ower **P**oint **T**racking
MICS	**M**odule **I**ntergrated **C**onverters
SOC-MPPT	**S**eries **O**utput **C**onnection-**M**aximum **P**ower **P**oint **T**racking
FoI	**F**actor **of** **I**ncrease

Dedicated to my beloved mother, whose encouragement, sacrifices and prayers have been beyond borders. . .

Chapter 1

Introduction

1.0.1 Research problem

To date, the harvesting of solar energy remains a resource that is inadequately harnessed. It represents a tiny proportion of the planets capacity to generate electricity. The World could have an avenue to sixfold the amount of energy that we utilize in numerous forms to the present day, if we could collect 0.001 percent of the energy from the Sun reaching planet Earth.

By adopting solar technologies and by further investing in the installment of solar systems, an alternative and low polluting energy source can be utilized to ease the threat of the emissions of greenhouse gasses. These emissions ultimately contribute to climate change. The adoption would also raise universal electricity access that will empower the ability to meet the distribution gap between the increasing requirement for electricity and the primary electric power reserve. In this modernized day and age, the generation of electricity plays a critical part in the economy of every nation.

South Africa represents the case of an African country that has the second largest economy in Africa. Even though it boasts this status, its nationalized electricity supplier, Eskom, started experiencing a shortage in capacity during 2007. This deficiency was with regards to electric generation and reticulation infrastructure. It came as a consequence of improper planning and the lack of ability to cater for the construction of ample generated electric proportions that would meet increasing requirements.

This inability affected the demands of industry and consumers. Eskom thus decided to implement planned rolling blackouts countrywide. The solar map illustrated by Figure 1.1, reveals that South Africa is an African country that experiences exceptional levels of solar radiance. These levels would allow the use of the Sun's power to top up a portion of the present energy shortfall.

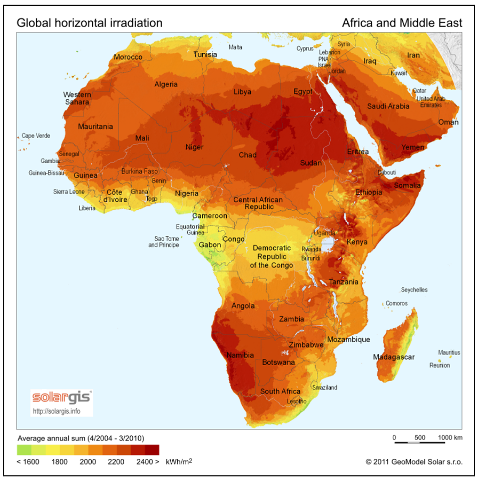


Figure 1.1: Africa Solar Radiance

Monitoring systems that are able to efficiently manage renewable energy systems are required. They should be able to (1) enable owners of homes, businesses and properties to receive live readings of their systems with the accompanied monetary perk of making the most preferred adjustment in terms of interchanging among on-grid (electrical) and off-grid (solar/wind/generator supply) (2) allow the swift diagnosis of problems and the preventative capacity to recover from malfunctions, enabling service technicians with proper qualifications to promptly correct the complication (3) deploy self-repairing of the renewable system, when possible, by means of automated software.

Furthermore, good dimensioning of solar systems is an important requirement which, if performed inefficiently, can outweigh the benefits of an efficient monitoring system.

1.0.2 Objectives

The goals of this project are as follows: (1) design smart architectures for next generation wind and solar systems to meet African power challenges (2) use these architectures to dimension the underlying solar and wind power systems (3) develop a low cost remote monitoring system that is capable of obtaining quantities of harvested energy and variables pertaining to the operations of networks of solar energy systems and (4) simulate, implement and evaluate the performance of said power systems.

1.0.3 Hypothesis

All the stages of selection, sizing and architectures of solar/wind systems are key factors that can impact performance. Changing panel configurations will allow for variations of power produced. The same hypothesis is applied to the wiring of batteries amongst each other. This will be made evident by the software to be developed, keeping in mind the physics behind the underlying technology. See Figure 1.2 for an example of solar panels in a series configuration, batteries in a combination configuration and various other system units that effect performance.

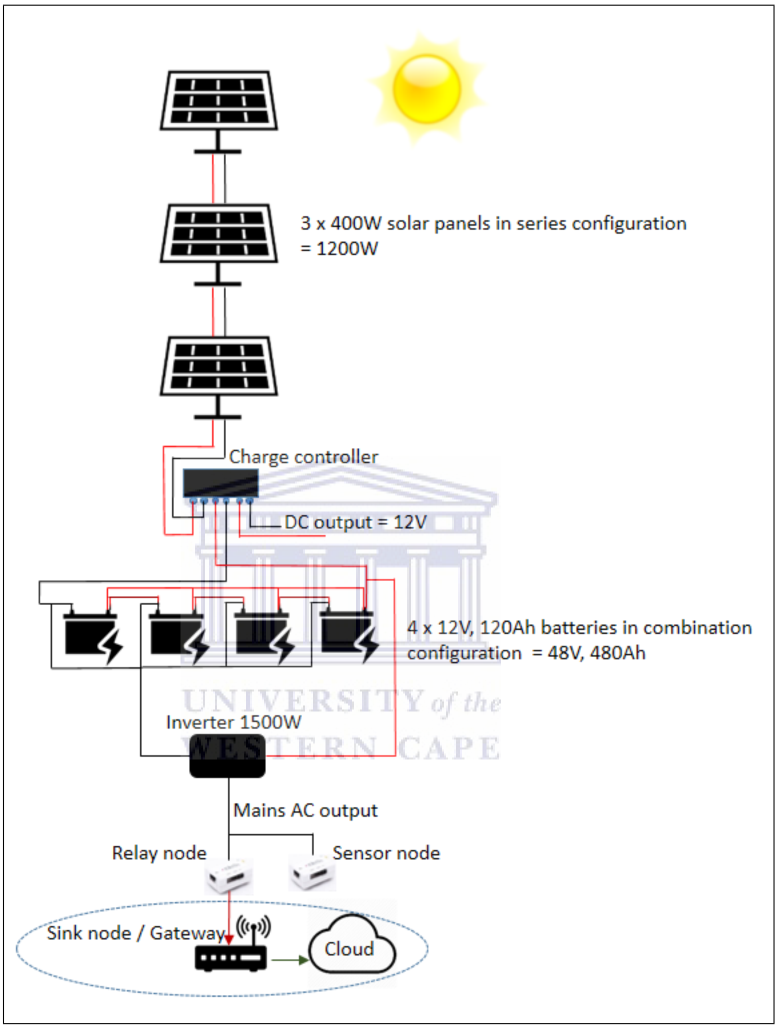


FIGURE 1.2: An example of possible configurations selected for a solar system

1.0.4 Structure and methodology

It is assumed that a renewable power system is capable of being dimensioned to cater for the needs of a household, business or larger structures. The project will employ two-fold dimensioning as an experimental approach to determine and cater for the needs of a user based on the number of devices that they want to run simultaneously. It will also show a user the number of devices that can be run simultaneously from what is currently available in battery storage. This will be tested to rule out devices that are not recommended as per availability and power drain.

The project will take on an iterative development life cycle. This methodology will allow for continuous integration of parts towards the system being constructed.

1.0.5 Contribution

The main contribution of the thesis is to propose a framework and design the three main components of it:

- System sizing
  - Takes into account the required capacity of solar panels, wind turbines and batteries. Based on the energy requirement per day, the "size" of the system can be calculated[1].
- System engineering
  - Upon knowing the system/energy requirements per day, such as solar panel and battery capacity, the actual system can be designed. This will involve deciding upon the size and quantity of solar panels, wind turbines and batteries.
- System monitoring
  - Involves access to information pertaining to a system's performance.

The framework is presented by Figure 1.3, where sensor devices are used in a wireless rechargeable sensor network (WRSN) to collect energy yields as well as external parameters that are potentially affecting the frameworks performance. The information collected by these sensors is disseminated to a middleware platform where it is stored and processed to provide different services to different users, such as insurance companies, researchers, engineers, community leaders, solar home owners, green house management and even public energy providers such as Eskom.

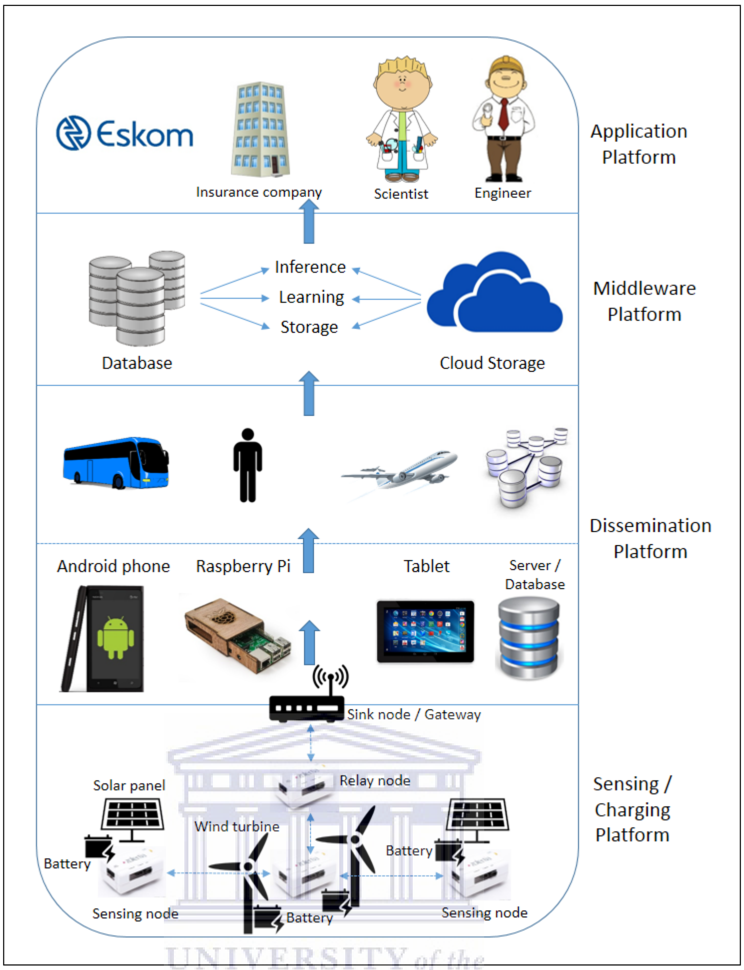


FIGURE 1.3: Framework / Multilayer architecture

The framework is based on a multilayer architecture where:

- A sensing/charging platform at the bottom of the architecture is used to collect battery, solar panel and wind turbine parameters. The environmental conditions where the solar/wind system is operating will also be accounted for by including environmental parameters such as ambient temperature, relative humidity, luminosity and even air pressure.
- A dissemination platform layered on top of the sensing platform to enable secure communication of the sensor yields to places where these readings are processed and further decisions are taken about the smart energy system. Such a platform may be implemented by combining different IP-based technologies and protocols. This will depend on availability and the smart energy system's requirements.
- A middleware platform that serves as cement between the lower and higher layers of the architecture and hides the complexity of the lower layers to the application

layer. In that platform, situation recognition operations and any form of energy harvesting prediction based on intelligent algorithms is performed.

- The application platform is where different energy applications are integrated into the smart energy system. These include insurance company controls, research and engineering management. This also includes other systems that are not necessarily connected to sensor networks, but use the data storage collected through system monitoring.

The sensing/charging platform can be further dissected into three layers that have various architectures/configurations pertaining to battery storage, sensors/sensor nodes and solar panels/wind turbines. Figure 1.4 gives an indication of the layers.

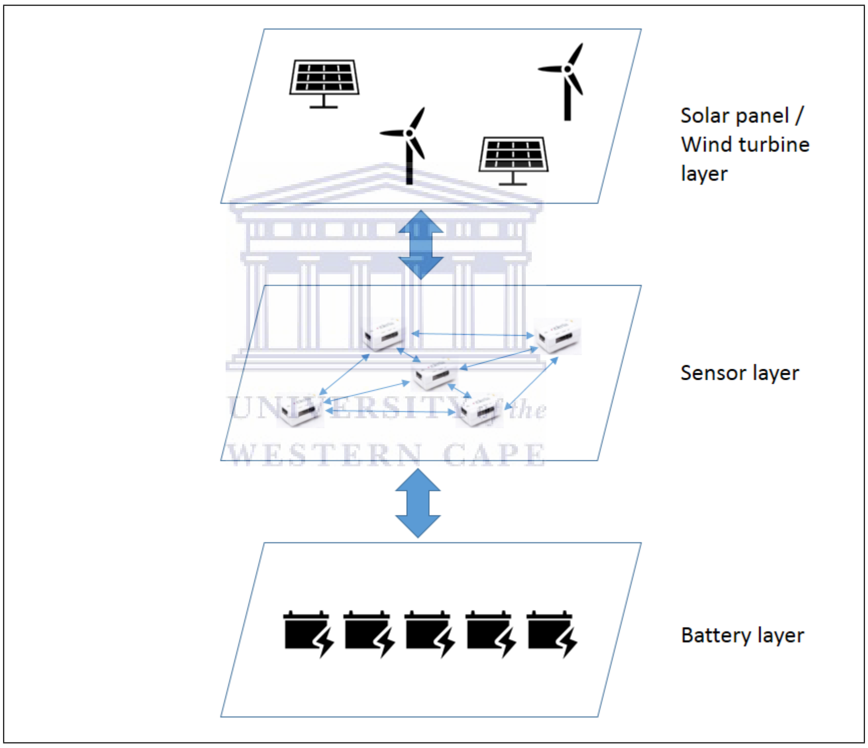


FIGURE 1.4: Further architectural layers of the sensing/charging platform

In the solar panel/wind turbine layer, series, parallel and combination configurations exist. The same is true for the battery layer. The sensor layer allows for bus, star and mesh configurations.

1.0.6 The Internet of Things (IoT)

From the work published at ICIEV16[2], it is worth mentioning the role of IoT towards this research. IoT is a concept that is rapidly gaining ground in the era of modern pervasive computing. Based on the idea that numerous things or objects are connected with the Internet, each object will have a unique address and it is able to interact with other objects, as demonstrated by Figure 1.5.

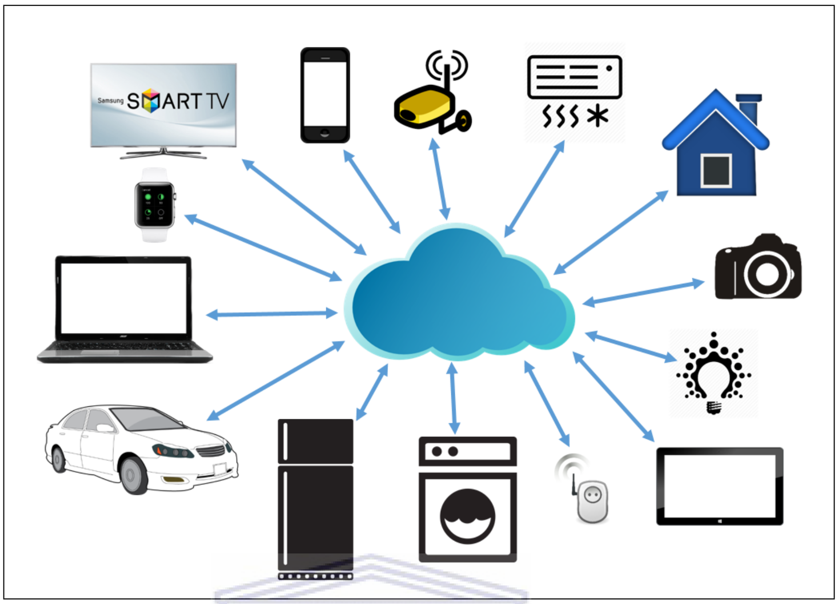


FIGURE 1.5: The Internet of Things

These objects can be connected to sensors involved in remote monitoring that can essentially be responsible for collecting the parameters of smart energy systems. These parameters can be relayed across the Internet to remote locations, where they are stored, analysed and displayed to users in an informative way.

1.0.7 The Internet of Things for Development (IoT4D)

With the help that IoT can present, it is also important to keep in the mind that there exists challenges or limitations with its deployment in the developing world. In developing countries, the administrative and financial systems run by mostly without any integrated and automated system. The level of technology usage is low and there is minor investment on research and development. I will briefly list and elaborate on some of these challenges with respect to smart energy systems.

- Internet connectivity
  - This is a major issue towards the enablement of IoT as there exists a demand for flawless and adequate connectivity amongst objects. In order to sustain flawless connectivity, there exists a need for fast internet speed, a continuous power supply, robust backup systems, reliable and scalable infrastructure.

- Data centers
  - With the rise of IoT, vast amounts of data is created. As the Internet consumes up to 5%[3] of the total energy generated today and with IoT demands on the rise, energy consumption is guaranteed to escalate as a consequence. Data centers in developing countries that are powered by harvested energy and are centralized will cater for energy efficiency and reliability. This introduces a need to store data intelligently so that smart monitoring and actuation can take place.
- Power resources
  - In comparison with developed countries, the planning of electricity for developing countries presents itself as a complicated dilemma. The challenge exceeds the mere acquisition of finances for energy related investments. Energy development is challenging as electric power industries are among the most intensive in an economy. This leads to the severe draining of financial resources.
- Human resources
  - Technically knowledgeable personnel is greatly lacking. They include engineers, scientists and technicians. IoT is a state-of-the-art term and implementing the technologies to build up IoT platforms requires learned personnel. The number of research centers are also very low in developing countries. Funding and investment to innovations follows the same trend currently.

IoT for developing countries will aid in providing power solutions by enabling clean energy technologies, creating smarter energy markets and by optimizing the implementation of existing products. For example, to improve the use of energy in homes, the IoT will automate and promote energy efficient practices such as the running of appliances at off-peak times.

In terms of a solution presented by IoT, customers can be serviced with information regarding energy utilities. These devices, known as smart meters, can provide real-time, two-way communication with customers. Granular detail about electrical usage can be provided. These meters can also aid customers in modifying their energy consumption in relation to current prices. Data collection occurs automatically with these devices and resolves the issue of a company needing to send out personnel for data collection purposes. Outages can be detected and even the need for repairs[4].

1.0.8 Limitations observed in the literature

From the literature to be presented, limitations arise that need to be catered for in order to improve system architectures, the important role that dimensioning can play if used efficiently and how monitoring efforts can be extended from legacy systems to make use of modern platforms such as web, mobile and desktop.

- Architectures
  - Multilayer frameworks/architectures have benefits over traditional communication architectures. It will be shown how IoT can play a role in enhancing the automation process and its effectiveness in solving communication and scheduling issues. Solutions will be presented for mitigating environmental impacts of solar technologies.
- Dimensioning
  - The provision of tools that allow laymen of renewable energy systems to analyse and determine their solar/wind power needs are lacking.
- Monitoring
  - Real-time, remote monitoring tools are needed to aid users with respect to the performance of their systems. These systems should also run on modern platforms and should be user friendly.

1.0.9 Thesis organisation

The chapters to follow will address existing products and their features (literature review/theoretical framework - chapter 2), the research design and methodology (chapter 3), a presentation of the systems and discussion of the results (chapter 4) and the conclusions and recommendations (chapter 5) that can be taken from the research.

Chapter 2 will present reviews for architectures, dimensioning and then remote monitoring. There does exist an overlap between the architectures and dimensioning sections, as the two go hand in hand and effect each other. Chapter 3 will address the various components of the dimensioning tool set, namely, the computations involved and how this relates to the ease of user adoption and use. The tool set intends to educate users in a practical and meaningful way. The results presented in Chapter 4 offer an idea of the benefits of the proposed tool set and further highlight use cases to illustrate the benefits of simulation.

Chapter 2

Literature Review

2.1 Introduction

This review will touch on three aspects related to the project. Architectures will be discussed first, followed by dimensioning and thereafter remote monitoring.

2.1.1 Architectures

The science and art of designing objects and other physical structures is known as architecture. In relation to this research, findings will be given towards describing solar and storage architectures and how best to integrate them efficiently in a user's operation.

2.1.1.1 MPPT Control and Architecture for PV Solar Panel with Sub-Module Integrated Converters

Photovoltaic solar systems with series-connected module integrated converters (MICs) are receiving growing attention because of their ability to create high output voltage while performing local maximum power point tracking (MPPT) control for individual solar panels. This is a solution for the effects of partial shading in PV systems at solar panel level. In order to eliminate the effects of partial shading in PV systems effectively, sub-MICs are utilized at the cell level or grouped cell level within a solar panel. The results of a series-output-connection MPPT (SOC-MPPT) controller for sub-MIC architectures using a single sensor at the output and a single digital MPPT controller are presented based upon boost type sub-MICs. The controller and architecture is represented by Figure 2.1. Experimental results under steady-state and transient conditions are presented to verify the performance of the controller and the effectiveness of the architecture[5].

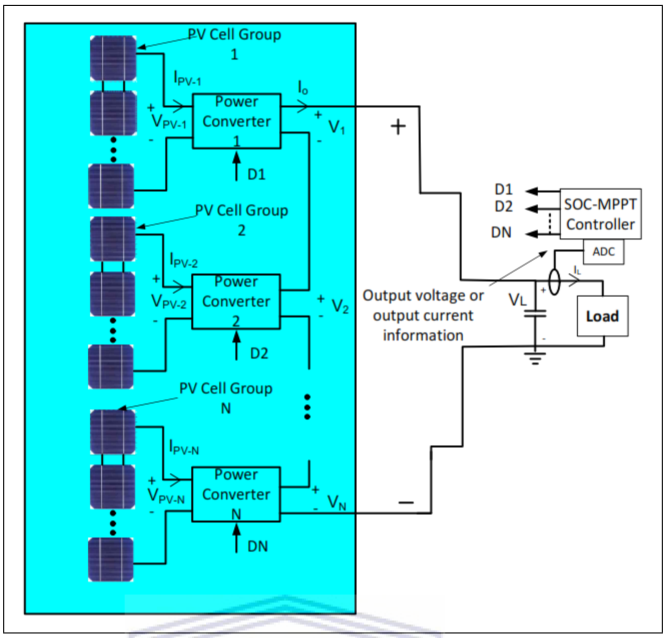


FIGURE 2.1: Sub-MIC SOC-MPPT controller and architecture with voltage type load or current type load (Source: Image by Qahouq)

Features listing the advantages of the mentioned controller and architecture, include:

- MPPT is performed at the cell level or at the grouped cells level through sub-MICs. The system can extract more power under partial shading and mismatch conditions. The energy harvesting efficiency is higher than when MPPT is performed at the panel level.

- Controller cost and power consumption are reduced as a result of using only a single output parameter sensor instead of N sensors, one ADC instead of $2N$ ADCs, one digital controller and fewer conditioning circuitries which are needed for sensors, ADCs and controllers for a PV system.

- Reduced noise. Low-pass filter circuits are often used to guarantee clean and error-free signals. By utilizing the load signal at the output of the DC stage ensures a cleaner sensed signal.

- Reduced errors and improved accuracy.

2.1.1.2 A survey on the communication architectures in smart grid

Intensive study has been made of next-generation electric power systems, or a smart grid, as a promising answer for energy crisis'. A significant aspect of a smart grid is the integration of fast, secure and reliable data communication networks to oversee intricate power systems intelligently and effectively. A comprehensive survey on the communication architectures is carried out to reveal communication network compositions, technologies used, functions, requirements and research challenges. Figure 2.2 illustrates the communications between automated meters and a facility company.

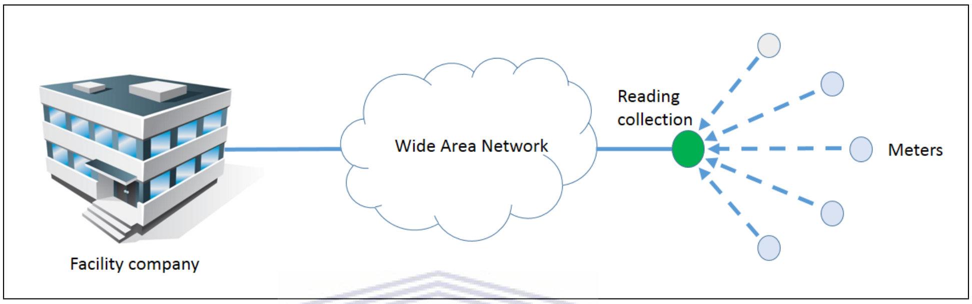


FIGURE 2.2: Communications for automatic meter reading

Since these communication networks are responsible for delivering power system related messages, great significance is placed on network implementation considerations and challenges in power system settings[6].

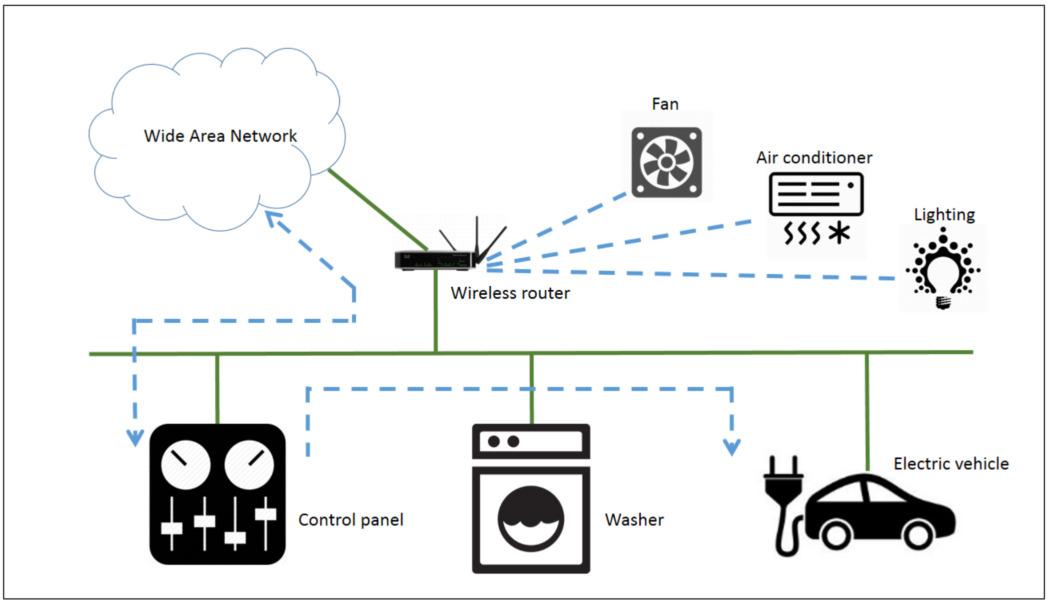


FIGURE 2.3: Scheduling of electricity usage by means of a home communications network

Figure 2.3 represents an example of a home network in which scheduling takes place. A washer could be used at night alongside a dryer and an electric vehicle can be charged during the night-time hours when it is not in use. With the use of home area networks, household electrical appliances can be connected to a scheduler that activates each appliance at an appropriate time in order to minimize electrical costs. The scheduling controller frequently requests electricity prices from the energy market. With this information, the controller decides on an economic schedule to activate each appliance at a suitable operation time.

2.1.1.3 Environmental impacts from the solar energy technologies

Solar thermal and photovoltaics are examples of solar energy systems that provide remarkable amounts of benefits in comparison to conventional energy sources. These benefits contribute to the sustainable development of human activities. Their wide scale deployment does however produce potential negative environmental implications. These potential implications appear to be a tough barrier for further circulation of these systems amongst customers. This research evaluates the potential environmental incursions in order to replace them with new technological innovations and practices for power systems of the future. The potential environmental burdens taken under analysis are during construction, installation and demolition phases and in the case of central solar technologies - energy consumption, greenhouse gas emissions, impacts on archaeological sites or on sensitive ecosystems, labour incidents, noise and visual intrusion, soil and water pollution. Negative and positive socio-economic effects are also placed under a microscope[7].

Glare is a common occurrence with solar arrays as depicted by Figure 2.4. This can be a visual burden to neighbours in the vicinity as well as a nuisance for air planes.

FIGURE 2.4: Glare viewed from Air Traffic Control Tower at Manchester/Boston Regional Airport (8:15 AM EDT, 4/25/12, Source: Image by Free Republic)

Reflection of the Sun's rays can distract or annoy an observer. These impacts are generally categorised as:

- Glint - a momentary flash of light; or
- Glare - a continuous source of excessive brightness.

With these potential issues in mind, steps can be taken to reduce both. Modern solar panels are produced with an anti-reflective coating that reduces the amount of light that is reflected. This is a great measure for reducing glint and glare[8].

Observers that have a visual line of sight to solar panels experience either glint or glare. Screening as depicted by Figure 2.5 can mitigate the effects between observers and the reflecting panels. Based on the height of the observer and the reflecting panel, as well as the terrain elevation at the screening location, a detailed analysis can be determined of the level of screening required.

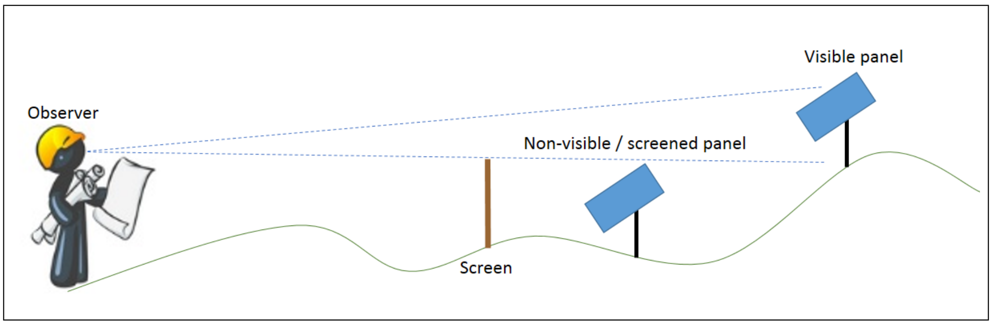


FIGURE 2.5: Screening as a form of mitigation

With the knowledge that for a reflection on a flat surface, the angle of incidence is equal to the angle of reflection, glint and glare can be mitigated. Said differently, changing the vertical angle of the reflector (panel) can affect the path of the reflected rays that are responsible for glint and glare. This is depicted by Figure 2.6.

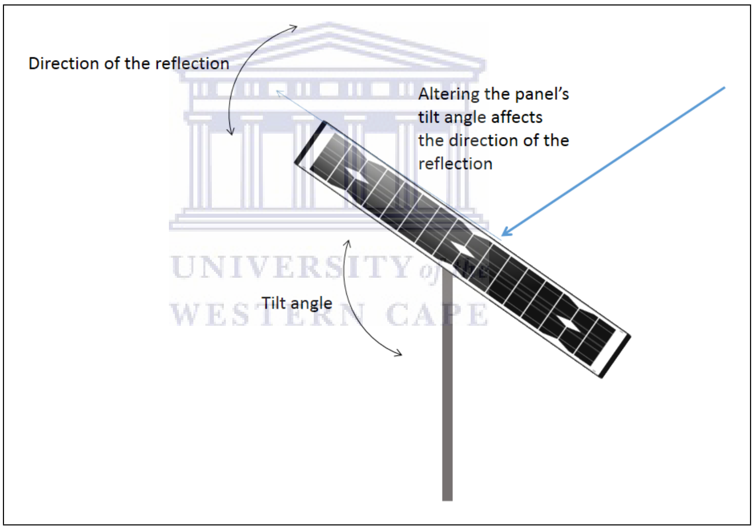


FIGURE 2.6: Altering the vertical tilt as a form of mitigation

By changing the vertical tilt of a solar panel within an economically viable range is unlikely to remove the potential impact altogether. However, in marginal cases, this could contribute to a mitigation strategy.

Further changing the direction that the panels are 'facing' is known as the azimuth angle and lends itself as a mitigation strategy with minimal effects within an economically viable range. This angle is illustrated by Figure 2.7. Altering the azimuth angle of the panels affects the path of the reflected light. Therefore, the effects at a specific receptor site can be reduced or removed by adjusting the panel alignment.

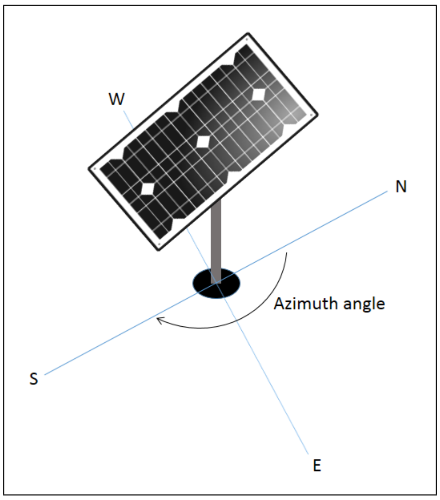


FIGURE 2.7: Altering the azimuth angle as a form of mitigation

It is to be noted that reflections may well be possible from a particular portion of a solar installation and as a result the required adjustments can be relatively minimal.

2.1.2 Dimensioning

The ability to cut or shape an object to particular measurements is known as dimensioning. It also is the process of measuring either the area or volume that an object occupies. This allows for capacity calculations which in context of the project would enable the sizing of solar systems that will enable a user to know what energy will be available. The following research will give an idea of the usage of dimensioning and the benefits it can deliver.

2.1.2.1 Development of a solar district heating online calculation tool

Solites developed an online calculation tool to facilitate an approach to the integration of solar thermal energy into district heating systems. From the TRNSYS (Transient System Simulation Tool) results of more than 100 000 simulations, the tool allows its user to perform a first calculation of the dimensioning and economics of a solar district heating plant for different climates in Europe. Two configurations are available: a central solar heating plant with heat storage, shown by Figure 2.8 and a distributed solar district heating plant, shown by Figure 2.9. The performance values of the user-defined plant are obtained by multi-linear interpolation between the outputs of the TRNSYS simulations. This allows the inference of economic and energy savings from the calculated performance values. Furthermore, the process of running a high number of simulations allowed a good analysis of the impact of the variation of the parameters on the system's performance[9].

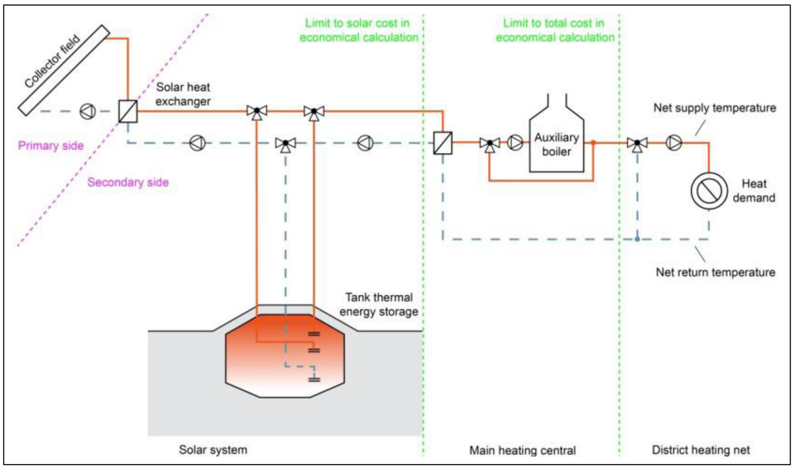


FIGURE 2.8: Central solar district heating system (Source: Image by Laure Deschaintre)

The central solar heating plant consists of a large collector field that feeds into a thermal energy storage tank. This occurs at the central/main heating site of the system. The pumps on the primary and the secondary side of the solar heat exchanger are matched-flow regulated.

When the solar plant produces heat and there is no demand for it, it is fed into the storage tank. Depending on the temperature in the storage tank and the temperature of the heat flowing from the collectors, the heat can be let in from the top of the tank or through the middle. In the periods when the solar plant produces heat and there is a demand for it, 'pre-heating' is possible. This means that the solar heat feeds directly into the main heating station and not through storage. An auxiliary heat source supplements the plant in order to cover the total heat demand. This demand is obtained via TRNSYS simulations of average buildings by a distribution network which takes into account the hot water demand.

The central system took the following parameters into account for the reference simulation:

- Collector area
- Collector azimuth
- Collector slope
- Specific storage volume

- Specific yearly heat demand

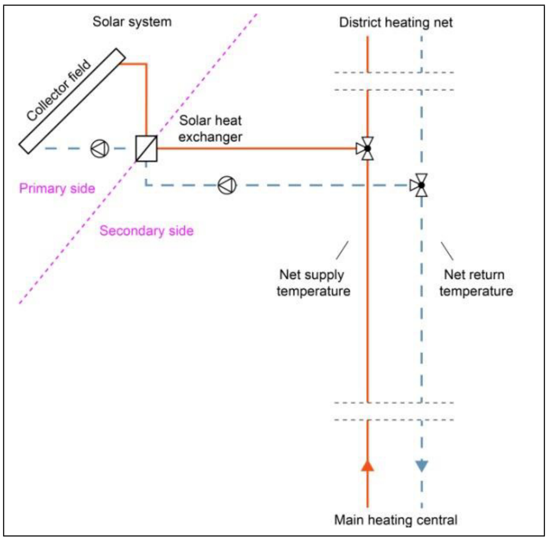


FIGURE 2.9: Distributed solar district heating system (Source: Image by Laure Deschaintre)

In the distributed solar heating plant, no specific heat demand profile is defined. The solar plant feeds into a theoretically infinite net as much heat as it produces at the set temperature. The plant feeds into the supply pipe of the net, implying a minimal set temperature of 70 °C for low-temperature nets and up to 110 °C for high-temperature nets. Pumps on the primary and secondary side of the heat exchanger are matched-flow regulated.

The distributed system took the following parameters into account for the reference simulation:

- Collector area
- Collector azimuth
- Collector slope

2.1.2.2 Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank

Tremendous attempts have been made to sufficiently measure the production of solar thermal collectors and compare it to the production of domestic hot water of the inhabitants of a building. Of note, is the knowledge that the majority of the design rules of solar plants are based on steady state models, where solar irradiance, consumption and thermal accumulation are basically momentary processes. Do to the lack of physical accuracy, designers often select storage tank sizes without detailed guidance to influence their judgement. This can become an issue if solar thermal systems are to be set-up in modern buildings, where space might be limited. Adding on to that, an excessive storage volume could not increase efficiency in diverse industrial applications. Extremities in space utilization would be costly and overweight in some cases[10].

Based on the consumption profile of 215 inhabitants partaking in the study, the authors were able to monitor their hot water consumption and generate the results presented by Figure 2.10.

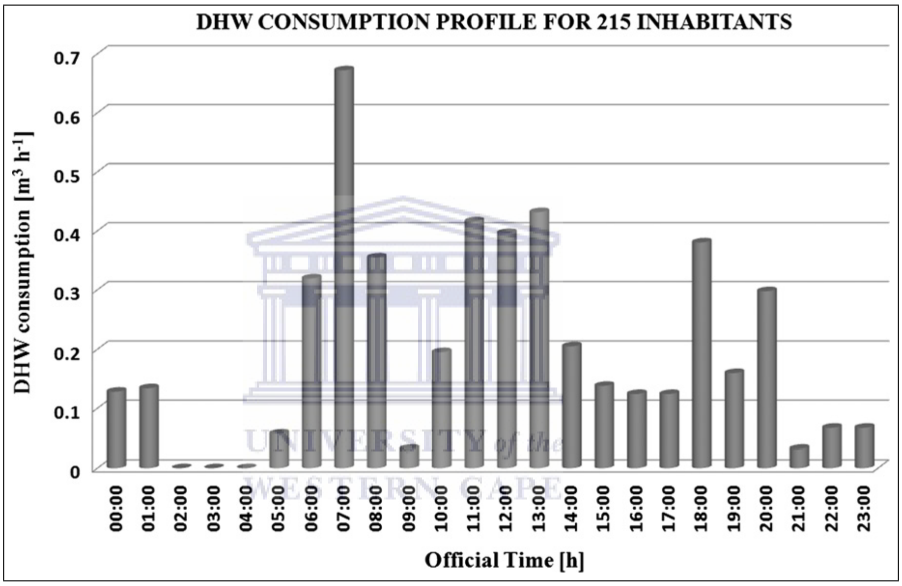


FIGURE 2.10: Domestic hot water consumption profile for 215 inhabitants (Source: Image by Rodríguez-Hidalgo)

The greatest need for hot water was observed at 7 a.m. in the morning, presumably as the inhabitants were readying for work. The 2^{nd} highest need was observed around lunch time. This could indicate usage for food preparations.

2.1.2.3 Photovoltaic Diesel-Generator Hybrid Power System Sizing

This author determines to reduce PV system costs according to the minimization of the area of the PV array and battery bank with his research. A procedure is used to compute the minimum number of storage days and the minimum area of the PV array. The pre-operating time of the diesel-generator is also incorporated in the system's design. A system sizing program using the FORTRAN language has been developed for this purpose. This program is used to size the experimental system which consists of a PV system, a storage subsystem and a diesel generator. The sizing program can be used to size any PV diesel-generator hybrid power system. The author also compares the sizing of a stand-alone and hybrid system in his research[11]. The configuration of the proposed hybrid system is demonstrated by Figure 2.11.

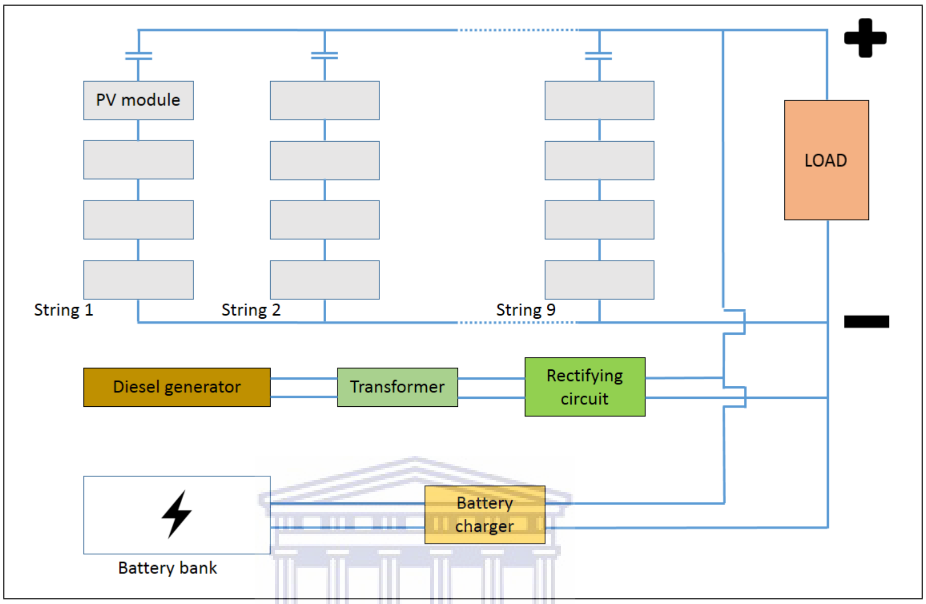


FIGURE 2.11: Configuration of the hybrid system proposed

From the research, he concludes that the hybrid system is economically superior than a stand-alone system, due to the minimization of the size of the array and the required battery capacity.

2.1.2.4 Optimal PV System Dimensioning with Obstructed Solar Radiation

This research describes an analytical methodology for the optimized design of stand-alone photovoltaic systems which are installed at locations where solar radiation is considerably shortened by obstacles, such as at the bottom of a gorge. A procedure for the calculation of real available solar energy incident on a PV panel is proposed, based on simple measurements. The optimum tilt of the PV array, under obstructions, is obtained and a procedure is implemented to dimension the optimal size of the PV array and the related storage system. A verification routine is run on the system as a means of testing[12].

This algorithm was employed in the Samaria gorge, on the island of Crete. At this location, the electricity demand of a small observatory in the middle of the gorge was studied. The utility grid is not available inside the gorge and the walls markedly obstruct solar radiation from reaching the bottom. The results stipulate that a change of the tilt of the PV array twice a year returns almost the same size as if one constant tilt is used. The highest of the two optimal slopes is used. This is because the load has to be mainly supplied during the night times and it is almost constant during the year. The two optimal slopes for the area under consideration is 6.94° and 48.63°.

Obstacles in regards to the type of gorge walls can reduce solar energy considerably. The computation of their impact for optimal dimensioning is thus necessary. The proper slope of the PV array improves the efficiency of the system, especially during the winter months when the system is more vital. The research proposes that the same slope is used for the entire year, with the higher slope from the two optimal slopes calculated by the dimensioning software.

2.1.3 Remote Monitoring

Remote monitoring refers to the monitoring of select parameters outside of conventional settings, such as distant locations. This may increase access to information, maintenance and knowledge of a systems performance. An added benefit is the decrease of travelling costs to take measurements manually and the possibility of introducing a degree of automation into the system being monitored. The following research will give an idea of the usage of remote monitoring and the benefits it can deliver.

2.1.3.1 Automatic fault detection in grid connected PV systems

The project details a method for automated supervision, fault detection and diagnosis of possible failure sources which could lead to total or partial loss of productivity in grid connected PV systems. The diagnostic method is part of the monitoring system. It allows modelling, simulation of the whole system and variable measurements in real time, simultaneously. The project's fault detection algorithm is based on the comparison of simulated and measured yields by analyzing the losses present in the system detailed by Figure 2.12.

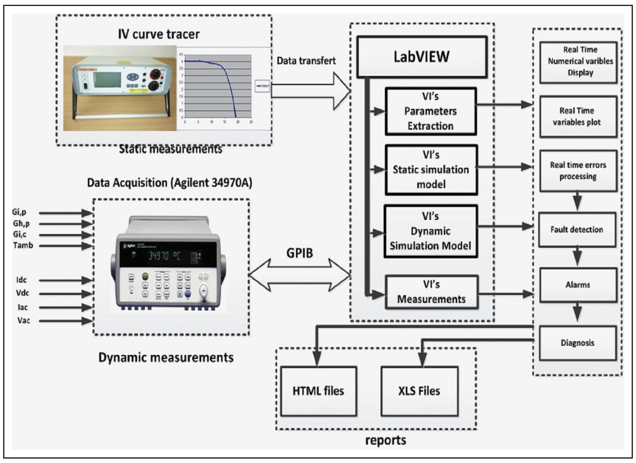


FIGURE 2.12: Schematic diagram of the data acquisition system (Source: Image by Santiago Silvestre)

This is done while the recognition of the fault type is executed by analyzing and comparing the amount of errors deviation in both the DC current and voltage with respect to a set of thresholds evaluated on the basis of a free fault system. The grid connected PV system is located in Centre de Developpement des Energies Renouvelables (CDER) in Algeria[13]. At this location, a grid connected PV system has undergone validation through field tests to determine the accuracy of the procedure. The following faults have been identified: inverter disconnection, partial shading shown by Figure 2.13 and disconnection of a string of the array. Reference thresholds of current and voltage have been established to determine whether the fault is due to current reduction or voltage reduction. Based on this, the most likely fault can be determined.

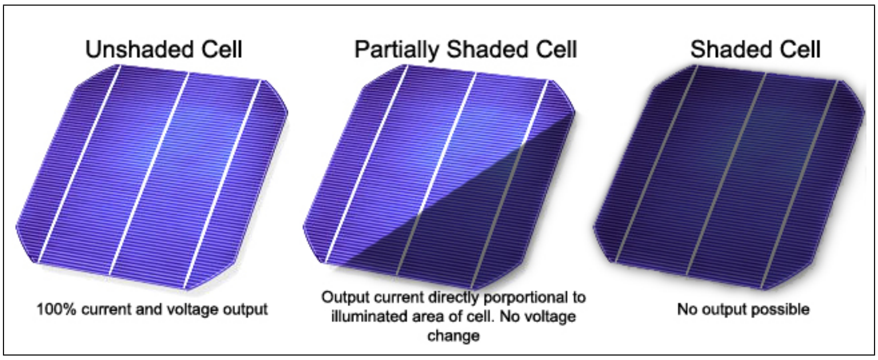


FIGURE 2.13: Effect of shading on solar cells (Source: Image by Sargosis Solar & Electric)

2.1.3.2 An evaluation of the Solar Monitoring System in Malawi

In order to facilitate the access of information regarding electric power that has been generated at a rural site, this project makes use of wireless sensor nodes and the transmission of short message service or SMS messages over mobile phone networks. The receiver of SMSs at the main site incorporates a system making use of FrontlineSMS which is an intelligent management system. This system hosts SMSs and publishes the sensed readings and patterns detected over cyberspace. Figure 2.14, gives an indication of the system implemented in Malawi.

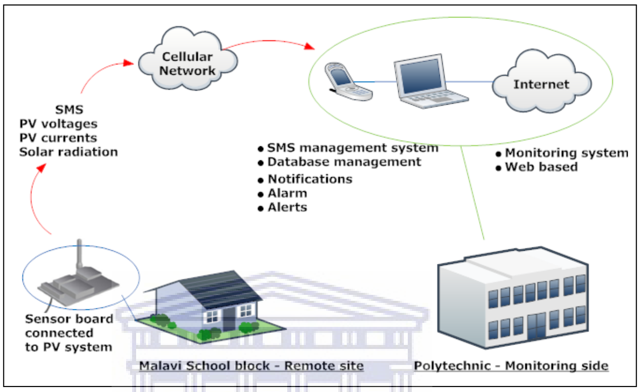


FIGURE 2.14: System Architecture: Solar PV with Wireless Sensor and Central Management Servers (Source: SM^2. Image by Nkoloma)

The SIMbaLink project aims to provide sustainable electric solutions for rural areas. SIMbaLink is based on an extremely low cost, real-time solar monitoring system that reduces maintenance costs and repair times. The system reveals important information about the battery bank's state of charge and daily energy usage. Data is transmitted over GSM cellular networks to a regional technician and this allows the viewing of remote system diagnostics. However, sensor readings are only taken 4 times per day, as depicted by Figure 2.15. This does not enable real-time trends to allow critical performance analysis and timely detection of solar plant problems[14].

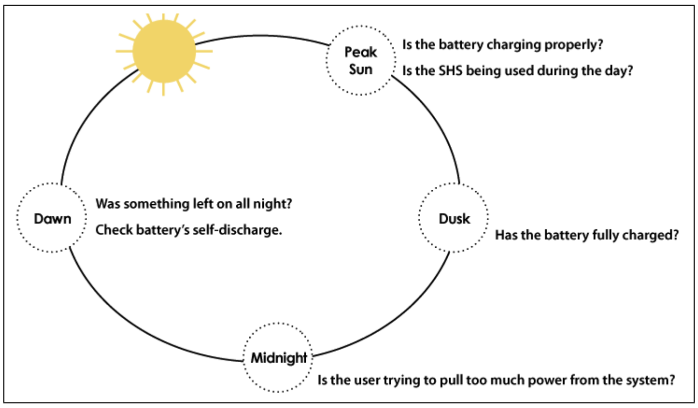


FIGURE 2.15: 4 data readings per day based on the SIMbaLink System (Source: SM[2]. Image by Nkoloma)

2.1.3.3 SIMbaLink: Towards a Sustainable and Feasible Solar Rural Electrification System

A website is made use of by the project to function as a platform that contains detailed information with regards to Solar Home Systems (SHSs) in rural areas. A short message service system is used to accelerate the recurrence of sensor readings or to deploy a rigorous hourly diagnosis of the system. The grouping of SHSs by location is performed by a software suite. This empowers technicians to plan the servicing of equipment in a manner that improves not only time, but also the costs of operations and the procurement of materials. Since the presence of GSM coverage is a core component for users intending to make use of these systems in rural areas, it provides the necessary access for these systems to operate with reduced costs. Making use of GSM networks to send a SMS from rural areas is presently the foremost preference for the gathering of data[15]. Figure 2.16, shows a sketch of the SIMbaLink module used in rural electrification systems together with the charge controller, PV panels, the connected components to the system and the rechargeable battery in use.

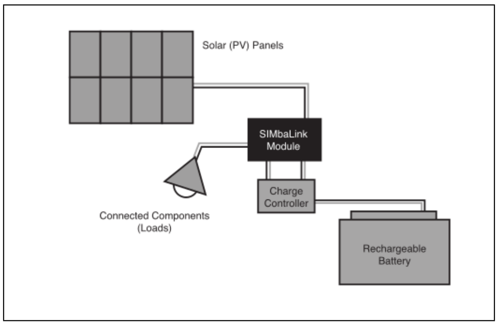


FIGURE 2.16: Integrating SIMbaLink with solar home system components (Source: SIMbaLink. Image by Schelling)

2.1.3.4 Automatic supervision and fault detection of PV systems based on power

This project entails an automatic supervision and fault detection procedure for PV systems based on power losses analysis. This system has been developed with Matlab & Simulink. It includes parameter extraction techniques to compute main PV system parameters from monitoring data in real working conditions, while taking into account the environmental irradiance and module temperature evolution. This allows for real time simulation of the behaviour of the PV system. The system analyzes the output power losses present in the DC side of the PV generator and captures the losses. Two new power loss indicators are defined: thermal capture losses (L_{ct})and miscellaneous capture losses (L_{cm}). The processing of these indicators enables the supervision system to generate a faulty signal as indicator of fault detection in the operaion of the PV system. Two new indicators of the deviation of the DC variables with respect to the simulated ones have been also defined. These indicators are the current and voltage ratios: R_C and R_V. By analysing both, the faulty signal and the current/voltage ratios, the fault type can be identified[16].

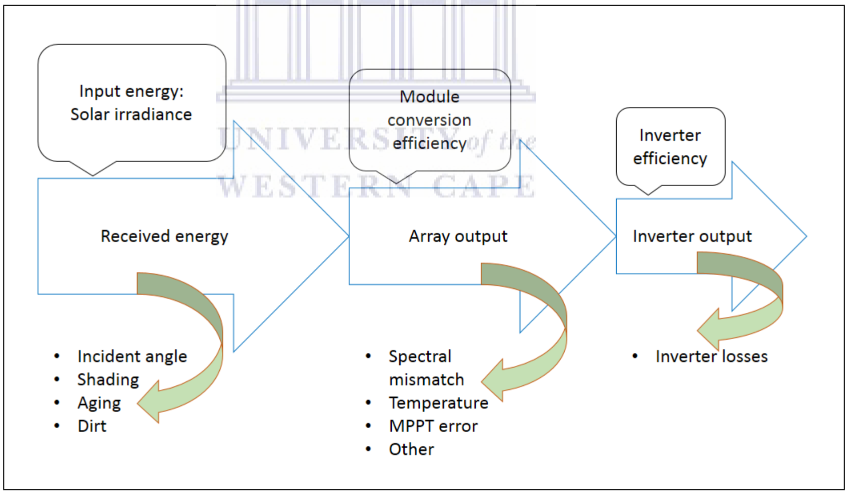


FIGURE 2.17: Factors of power losses in PV systems

Figure 2.17 gives an indication of power loss factors in PV systems. The supervision of the operations of a PV system is important in order to reduce losses of output power and for identifying system and component malfunctions. A supervisory formula for a PV system should discover failures of the system. The initial step would be the detection of losses existing in the entire system. This is critical for determining the limits in which the system is operating normally.

During the first step of energy conversion, the incoming energy will be reduced by shading or shadowing, reflections caused by the angle of incidence as well as dust, dirt and debris on the surface of the PV arrays prior to energy reaching the solar cells.

The next step is the PV energy conversion process in which the efficiency is determined for the standard test conditions so that it will always be different under real weather conditions. Solar cell temperature is defined as $25°C$, where a crystalline silicon solar cell has a negative temperature coefficient. Since the temperature of the module is normally higher than $25°C$, there will be losses in output power due to efficiencies of the conversion process.

Additional power losses can be expected on the DC side from partial shadowing/shading, mismatching of PV modules as a result of the non-uniform distribution of irradiance and temperature, maximum power point tracking and a host of other factors. Prior to the converted energy reaching the utility grid (on-grid), or the load (off-grid), new power losses will appear as a consequence of the efficiency of the power conditioning units, inverters, regulators and so on.

2.1.3.5 A simple model of PV system performance and its use in fault detection

The results of this study are from a sample of the performance of two UK domestic photovoltaic systems. This sample is made up of two sites, hosting twenty-seven PV systems over a time frame of two years. An average, yearly loss of energy due to faults at Site A, during its first year of operation, was 3.6%, 6.6%, during its second year of operation and at Site B, during its first year of operation, was 18.9%.

Analysis techniques have been derived from the study which recognize faults that take place during operations. Energy losses are then determined based on these faults. Four fault categories were distinguished. They include: sustained zero efficiency faults, brief zero efficiency faults, shading faults and non-zero efficiency non-shading faults. Based on these fault categories and the percentages presented annually, it is clearly shown that faults have the likelihood to cause serious electricity generation losses in domestic photovoltaic systems.

The greatest losses were caused by sustained zero efficiency faults. These are when the photovoltaic system halted electricity generation for lengthy time frames. One of the systems experienced a maximum energy loss of 58.0%. This issue affirms the urgency for systems that will notify operators of these malfunctions. Discussions have been made around the need for a monitoring plan for clusters of PV systems that are capable of performing this duty. The research shows that the computation of energy losses due to shading would be absolutely necessary in negotiations with third parties for the possible removal of shading objects [17].

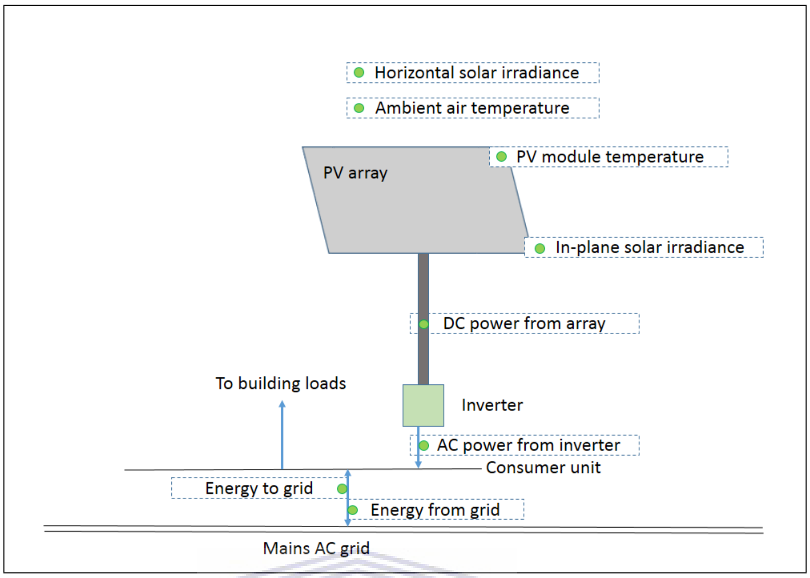


FIGURE 2.18: Monitored parameters for the PV system

The above mentioned monitoring strategy is shown by Figure 2.18. With the monitored parameters in mind, a model was constructed to describe the performance of a well operating PV system at 5 minute intervals. Operational efficiency was evaluated with the system's efficiency. A ratio was taken between the in-plane solar energy reaching the PV array to the AC output energy from the inverter.

2.1.3.6 Monitoring and remote failure detection of grid-connected PV systems based on satellite observations

Solar systems up to 5 kW_p which are grid-connected are seldom monitored due to the high costs of surveillance systems. As a consequence, malfunctions of the system that further result in partial losses of energy remain unrecognized for lengthy periods of time. Failures that result in even greater losses of energy can be hard to identify by amateurs of photovoltaic systems due to the seesawing of energy quantities. PVSAT-2 is an EU project that developed a fully automated operations audit to guarantee the production of maximum energy and to optimize the maintenance of small grid-connected PV systems. The prompt detection of malfunctions in the system and conditions that change during execution in order to prevent energy and financial losses is the main aim for the operator. A method to replace on-the-spot measurements has been developed and it is based on solar irradiance information obtained from satellites. In combination with a simulation model, the expected amounts of energy from a PV system is computed. Should a difference occur between the simulated and the actual energy produced, an automated failure detection program is deployed to search for the most anticipated source of malfunction and the operator is informed[18].

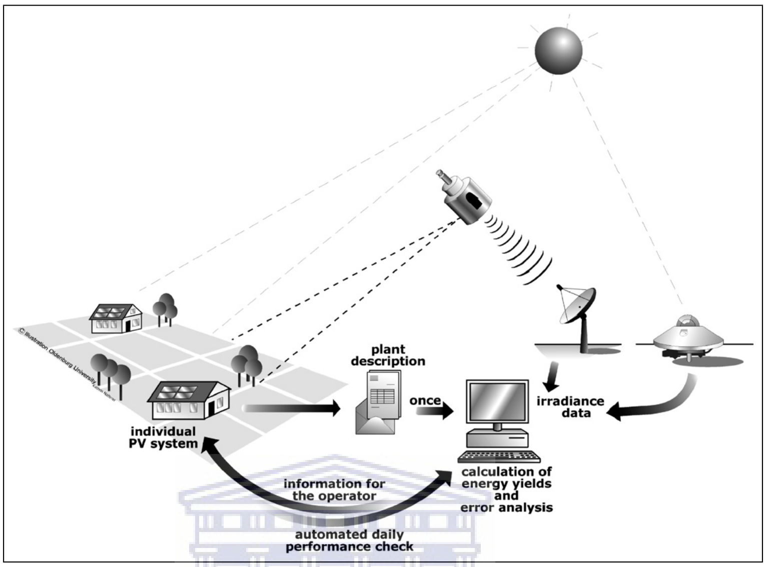


FIGURE 2.19: PVSAT-2 overview scheme (Source: Oldenburg University. Image by A. Drews)

From the overview provided by Figure 2.19, the PVSAT-2 procedure can be seen in its basic structure. Solar irradiance is derived on an hourly basis from the data of a meteorological satellite. Based only on satellite derived irradiance data, the expected yield of a PV system is calculated using a PV simulation model. This model is illustrated by Figure 2.20.

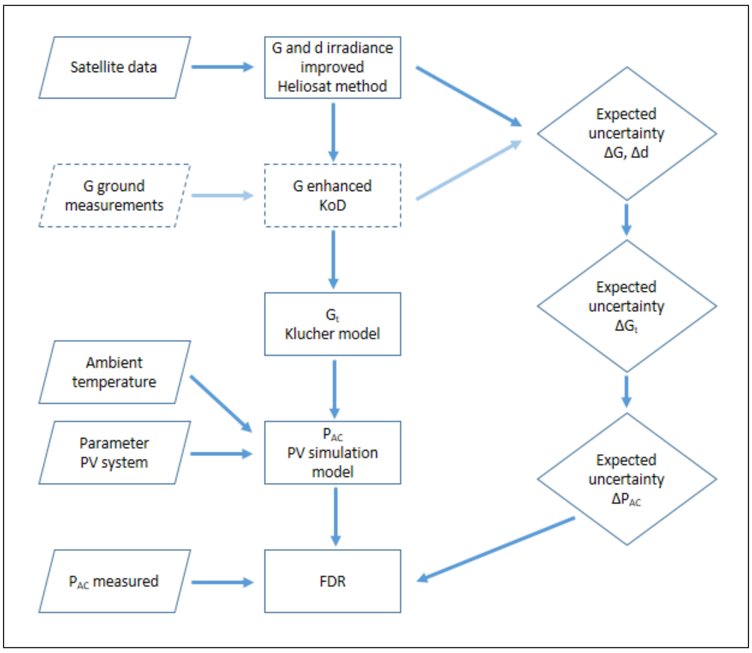


Figure 2.20: PVSAT-2 overview scheme on the applied methodology

The nomenclature for the figure is provided below:

- G - global irradiance on the horizontal plane (W/m^2)
- d - diffuse fraction (W/m^2)
- KoD - "Kriging-of-Differences" method
- G_t - global irradiance on the tilted plane (W/m^2)
- P_{AC} - PV power output (W or kW)
- FDR - Failure Detection Routine
- ΔG, Δd, ΔG_t, ΔP_{AC} - expression of uncertainty for the named quantities (W/m^2, W)

The symbology is as follows:

- Rhombus - input data
- Squares - steps in the method
- diamonds - expected maximum uncertainty of the simulation

The major input data to the routines are given on the left. The dash-lined elements and faded arrows explain how the results of the performed KoD study can be implemented into the processing chain. Moreover, information on the accuracy of the PV simulation results (ΔP_{AC}) is prepared for further utilization in the FDR as displayed with diamonds on the right.

2.1.3.7 Development of a monitoring system for a PV solar plant

To be capable of monitoring PV plants, a system has been developed that utilizes an unconventional method established on virtual instrumentation (VI). Sensing and processing of sensor readings are executed by I/O modular field point (FP) devices with high precision, a data acquisition card and a graphic programming package, named LabVIEW, shown by Figure 2.21. The system is able to save and present gathered data of the environment, as well as the electric variables of the PV plant. This also includes the I-V curve of the plant. The development of a device that automatically measures the I-V curve of the solar plant is a key element. This device will utilize a car battery for its power supply[19].

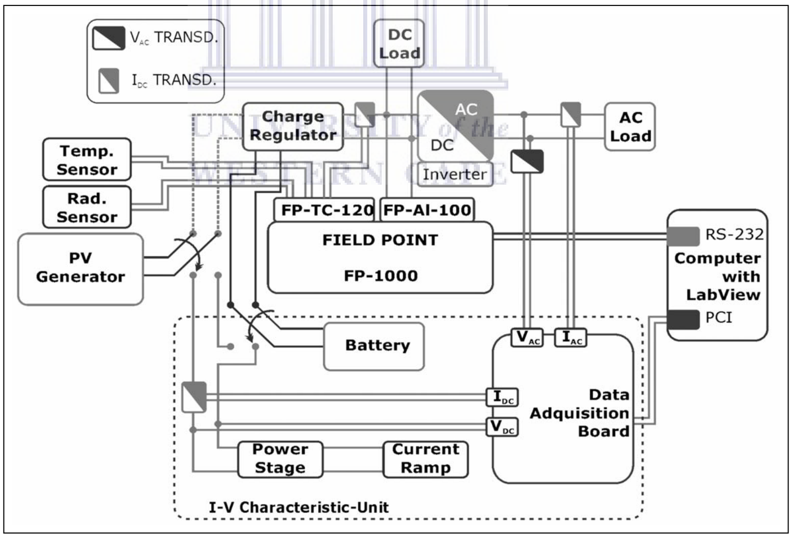


FIGURE 2.21: Block diagram of the system proposed for monitoring the performance of a PV solar plant (Source: Universidad Distrital Bogotá. Image by N. Forero)

The data gathered by the system is stored in a computer hard disk in a universal format, allowing for processing with LabVIEW or any other electronic sheet. The following Virtual Instruments (VIs) were implemented:

- VI for monitoring the solar radiation and ambient temperature as shown by Figure 2.22

- VI for monitoring the system variables
  - The numerical data of current and voltage supplied to both DC and AC loads.
  - Determine the efficiency of the PV system and of the inverter, as well as the DC and AC energy, through calculations performed with LabVIEW.
  - Harmonic analysis of the AC signal generated by the inverter through Fourier analysis performed with the aid of the LabVIEW package.
- VI for measuring the I-V characteristic

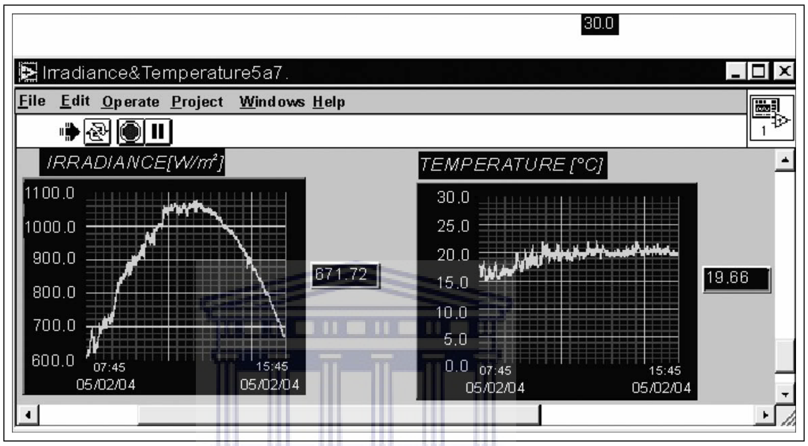


FIGURE 2.22: VI front panel for monitoring the solar radiation and ambient temperature (Source: Universidad Distrital Bogotá. Image by N. Forero)

2.1.3.8 Development of an integrated data-acquisition system for renewable energy source systems

Renewable energy source (RES) applications make wide use of data-acquisition systems. They are deployed to collect data with respect to assessing how a system is operating. The intended system comprises of a computer for system's monitoring of renewable energy. It makes use of sensors for measuring meteorological and electrical parameters of the system/surrounding the system. The readings are prepared using precision electronic circuits. It is thereafter consolidated to a PC by means of a data acquisition card. With a LABVIEW program, the readings are furthered processed, displayed and stored in a PC disk.

The architecture intended to be used, allows for fast development of the system and is agile towards changes. It is flexible if further extensions are sought for governing the operations of the system.[20]. Figure 2.23 is a depiction of the interface of the implemented RES application with the monitored parameters of two PV panels, a battery bank, battery charge controllers and inverters and a wind turbine, making use of a laboratory manufactured data acquisition unit. This unit communicates with a RES-Server with the aid of a RF link.

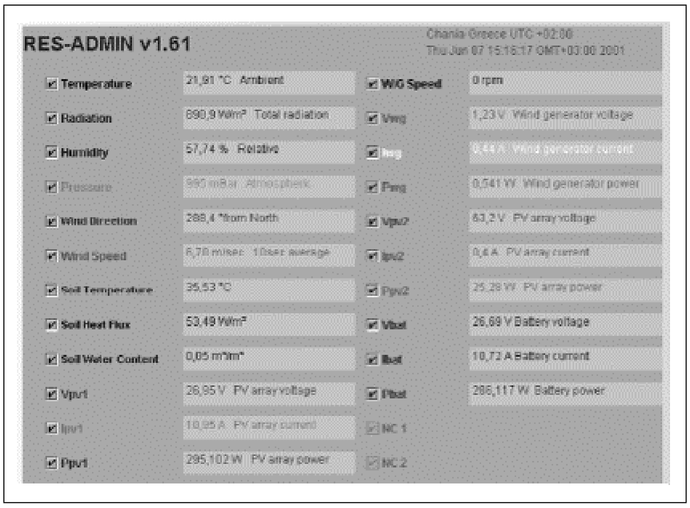


FIGURE 2.23: The RES-Applet interface (Source: Technical University of Crete. Image by K. Kalaitzakis et al.)

2.2 Conclusion

This chapter has addressed related work in the fields of architectures, dimensioning and remote monitoring involving solar, smart grids, thermal, diesel and wind technologies for power generation. Chapter 3 will introduce the research design and methodology that has been selected and the benefits that can be derived from simulation.

Chapter 3

Research Design and Methodology

3.1 Introduction

Following the examples set forth by the literature review, the research is designed according to three aspects: (1) architectures, (2) dimensioning and (3) remote monitoring. The aspects mentioned will introduce systems that can inform users of trends, simulations that will show them what their solar/wind system can achieve and how the architectures in use will affect performance. The architecture and dimensioning sections form part of system's engineering and will be jointly addressed, as dimensioning depends on architectural implementations.

Based on the knowledge provided by Figure 3.1, a solar/wind implementation will progress through the following flow cycle.

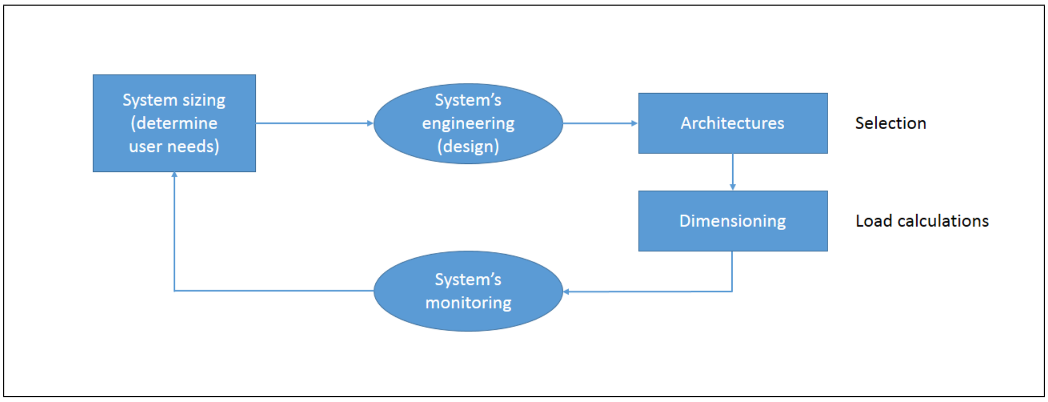


FIGURE 3.1: Flow cycle

Being able to determine user needs is the component that will initiate the actual design of the system intended to be implemented. Based on various architectures pertaining to solar panel, wind turbine and battery configurations, dimensioning can take place with the actual loads in consideration. With the aid of dimensioning, physical components can be installed and its usage monitored to ensure that user needs are met. If user needs are altered at any time, the flow cycle will resume again in order to meet those needs.

3.2 System's Engineering - Architectures and Dimensioning

With first time solar/wind system buyers in mind, who might have very little knowledge with regards to renewable energy systems, the software to be written will have to aid users in determining the size of their solar system, how to set it up and the various configurations that are available to them. These configurations will effect energy production, storage and utilization. It is up to the software to make this process easier for users and to advise them on possible alterations during various times of a given year.

The dimensioning tools that will be made available to users is included with explanations to their usage and relevance in the subsections below. Like the web portal, the dimensioning software is web based and makes use of the latest web technologies.

3.2.1 PWM vs MPPT charge controllers

A charge controller is a crucial component of a solar power system. It is responsible for adjusting charge rates which is dependent on a battery's charge level to allow charging closer to the battery's maximum capacity. It also monitors battery temperature in order to prevent overheating. PWM (Pulse Width Modulation) and MPPT (Maximum Power Point Tracking) are the most commonly used in present solar power system's.

The two charge controllers present their own benefits with the decision depending on the conditions of the site, the array size, the system components, the load on the system and the cost as a final factor for a solar powered system. As an example, the use of a MPPT controller is preferred in colder conditions. As a solar module's operating temperature decreases, the V_{mp} (maximum power voltage) increases. The voltage of solar panels operating at their peak power point at Standard Test Conditions (STC is 25°C) is about 17V, while the battery voltage is about 13.5V. The MPPT controller is able to capture the excess module voltage to charge batteries. As a result, a MPPT controller in cool conditions can produce 20 - 25% more efficiently than a PWM controller.

Comparatively, a PWM controller is unable to capture excess voltage since the pulse width modulation technology charges at the same voltage as a battery. However, when solar panels are deployed in warm or hot climates, their V_{mp} decreases and the peak power point operates at a voltage that is closer to the voltage of a 12V battery. There is no excess voltage to be transferred to the battery, which makes a MPPT controller unnecessary, nullifying the advantage it has over a PWM controller.

As a software defined illustration - Figure 3.2, we will view a case where at low battery (11V) and at high battery (14V), the performance of both controllers.

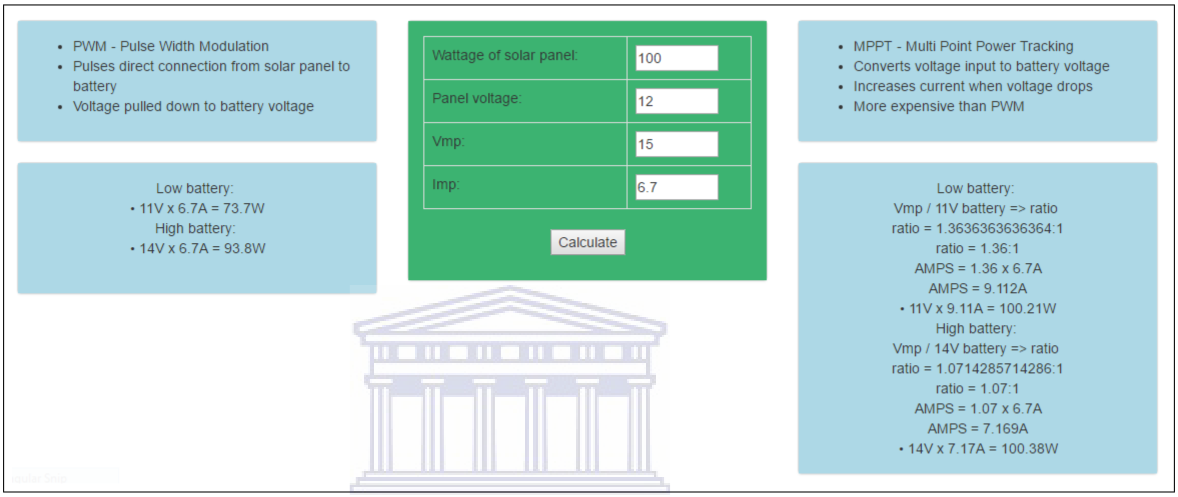


Figure 3.2: PWM vs MPPT charge controllers

From the above figure, it is evident that MPPT charge controllers measured at low and high battery voltages are more efficient in terms of wattage produced than PWM controllers. Please note that V_{mp} - Voltage at maximum output and I_{mp} - Amperage at maximum output can be found on the data sheets of your solar panels as they serve as inputs to the computation.

The computations for PWM and MPPT at low and high battery are described below.

Algorithm 1 Calculate PWM for low and high battery

$lowBattery \leftarrow 11 * I_{mp}$
$highBattery \leftarrow 14 * I_{mp}$

Algorithm 2 Calculate MPPT for low and high battery

$ratioLow \leftarrow V_{\text{mp}}/11$
$ratioLow \leftarrow round(ratioLow, 2)$
$ampsLow \leftarrow ratioLow * I_{\text{mp}}$
$batteryMPPTlow \leftarrow 11 * round(ampsLow, 2)$

$ratioHigh \leftarrow V_{\text{mp}}/14$
$ratioHigh \leftarrow round(ratioHigh, 2)$
$ampsHigh \leftarrow ratioHigh * I_{\text{mp}}$
$batteryMPPThigh \leftarrow 14 * round(ampsHigh, 2)$

3.2.2 Panel to battery

With the following example, it will be illustrated how a single solar panel will effect the charging of a single battery. Figure 3.3, highlights the results of charging a 120 Ah battery by means of a 100W solar panel.

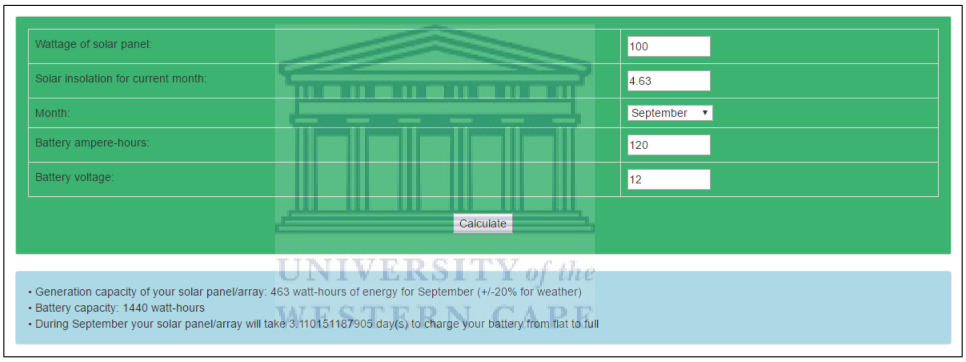


FIGURE 3.3: Solar panel to battery

The above computation is derived as follows. Multiply the solar insolation for your area by the peak wattage of your solar panel. This shows how many watt-hours of energy your solar array will generate on an average day, with values for every month of the year. Then check your battery and find its Amp-hour (Ah) rating. Multiply the Amp-hour rating by the voltage to find its watt-hour rating. Then add around 10% for efficiency levels. Dividing the watt-hours by the generation capacity will reveal how many days it will take to recharge the battery from flat to full. Using a 400W solar panel or four 100W solar panels connected in series, would in affect result in a generation capacity of 1852 watt-hours of energy and a charge from flat to full in 0.78 days.

Algorithm 3 Solar panel to battery computations

$generationCapacity \leftarrow panelWattage * solarInsolation$
$wattHours \leftarrow batAh * batVoltage$
$days \leftarrow wattHours/generationCapacity$

The above algorithm highlights the operation of determining how long it will take to charge a battery from flat to full based on the inputs provided.

3.2.3 Panel wiring

When connecting multiple solar panels in a 12 - 48 volt off-grid system, a few panel configurations are available:

- series
- parallel
- combination

Figure 3.4 details the basics on wiring solar panels in series and in parallel. This takes into account panels that are of the same power.

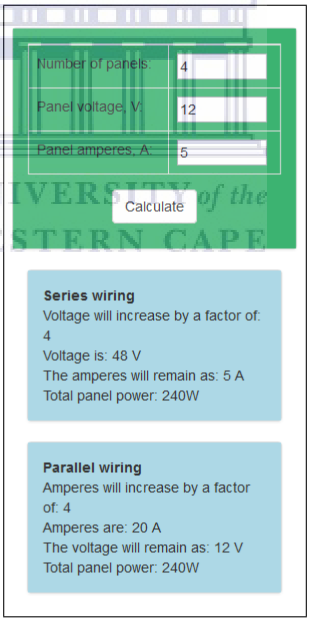


FIGURE 3.4: Panel wiring

Since each panel from the figure generates a voltage of 12 volts and a current of 5 amps, each panel is rated as a 60 watt panel. When four panels are connected in series, the total voltage will increase by a factor of 4, while the amps will remain as 5 amps. In parallel, amps will increase by a factor of 4 and volts will remain as 12 volts. Do note that the total panel power for both configurations is 240 watt.

3.2.4 Battery wiring

Users are often not sure how they are to connect the batteries of their system. The following application will highlight the major differences between series, parallel and combination battery wiring and detail how voltage and current are affected as a consequence.

Figure 3.5 shows a form that allows users to enter their battery specifications.

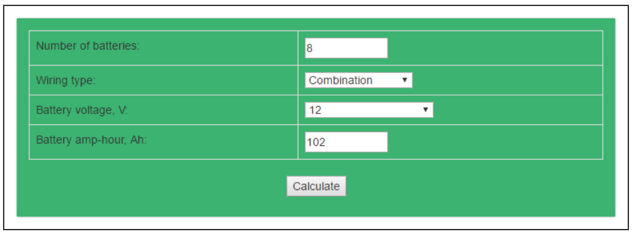


FIGURE 3.5: Battery specifications

Figure 3.6 in particular shows the results of how a combination setup will affect voltage and current.

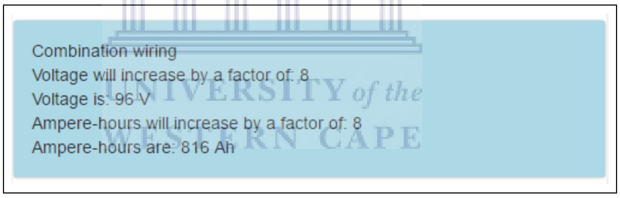


FIGURE 3.6: Results of connection type

Figure 3.7 gives a graphical representation which users can use as a guide to connecting battery wiring.

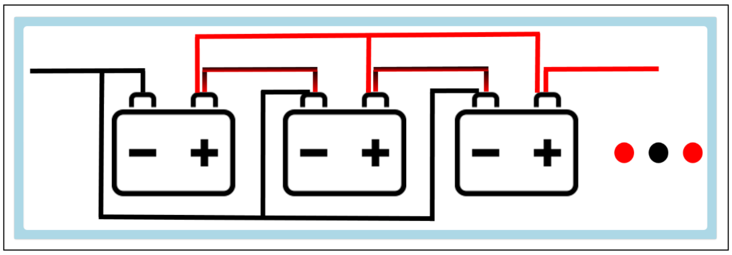


FIGURE 3.7: Wiring specification for use - combination

Current (more power) can be increased by using parallel wiring. Series wiring will increase voltage levels and both can be increased by using a combination of said wiring.

The following table compares the various connection types based on the input taken from the application.

Wiring type	Voltage	Current
Series	Voltage will increase by a factor of 8. Voltage is 96V.	The ampere-hours will remain as 102Ah.
Parallel	The voltage will remain as 12V.	Ampere-hours will increase by a factor of 8. Ampere-hours are 816Ah.
Combination	Voltage will increase by a factor of 8. Voltage is 96V.	Ampere-hours will increase by a factor of 8. Ampere-hours are 816Ah.

TABLE 3.1: Various wiring connections' results based on input

The values derived in the table are calculated with the computations below.

Algorithm 4 Battery wiring configurations

if $wiringType \leftarrow parallel$ **then**
  $Ah\, will\, increase\, by\, a\, factor\, of\, :\, noOfBat$
  $Ah \leftarrow batteryAh * noOfBat$
  $The\, voltage\, will\, remain\, as\, :\, batteryVoltage$
end if

if $wiringType \leftarrow series$ **then**
  $Voltage\, will\, increase\, by\, a\, factor\, of\, :\, noOfBat$
  $V \leftarrow batteryVoltage * noOfBat$
  $The\, ampere - hours\, will\, remain\, as\, :\, batteryAh$
end if

if $wiringType \leftarrow combination$ **then**
  $Voltage\, will\, increase\, by\, a\, factor\, of\, :\, noOfBat$
  $V \leftarrow batteryVoltage * noOfBat$
  $The\, Ampere - hours\, will\, increase\, by\, a\, factor\, of\, :\, noOfBat$
  $Ah \leftarrow batteryAh * noOfBat$
end if

3.2.5 Wind turbine power calculations

Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be supplied via the national grid. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine.

When planning a wind farm, it is important to know the expected power and energy output of each wind turbine to be able to calculate its economic viability. With the knowledge that it is of critical importance to know the power and therefore the energy produced by different types of wind turbine in different conditions and with the aid of this tool, we can calculate the rotational kinetic power produced in a wind turbine at its rated wind speed. This is the minimum wind speed at which a wind turbine produces its rated power.

With the inputs of Figure 3.8, the following power is produced as illustrated by Figure 3.9.

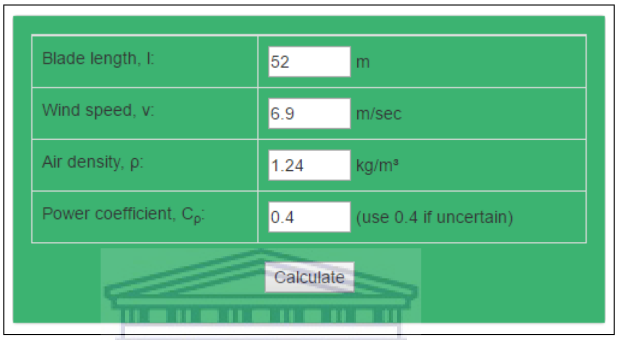


FIGURE 3.8: Wind turbine inputs

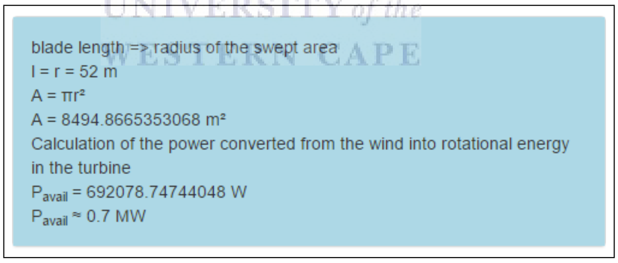


FIGURE 3.9: Wind turbine output

For completeness sake, please see the algorithm[21] below for further clarity.

Algorithm 5 Wind turbine computations

$pi = 3.141592653589793$
$radius \leftarrow l \leftarrow bladeLength$
$area \leftarrow pi * pow(radius, 2)$

$powerAvailableInWatts \leftarrow 0.5 * airDensity * area * pow(windSpeed, 3) * powerCoefficient$
$powerAvailableInMegaWatts \leftarrow round(powerAvailableInWatts * pow(10, -6), 1)$

A German physicist by the name of Albert Betz concluded in 1919 that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. To this day, this is known as the Betz Limit or Betz' Law. The theoretical maximum power efficiency of any design of wind turbine is 0.59 (i.e. no more than 59% of the energy carried by the wind can be extracted by a wind turbine). This is called the "power coefficient" and it is defined as $C_{p_{max}} = 0.59$.

Wind turbines can however not operate at this maximum limit. The C_p value is unique to each turbine type and it is a function of the wind speed that the turbine is operating in. Once the various engineering requirements of a wind turbine, strength and durability in particular, is incorporated the real world limit is well below the Betz Limit with values of 0.35 - 0.45. This is common in even the best designed wind turbines.

3.2.6 Device selections and required energy estimations

Users are often faced with needing to know how the number of devices in their home's affect how much stored power they have available. Said differently, they want to know how many devices they can run based on what is available. The following implementation takes into account the number of devices, their wattage needs and the total wattage from a combination of the devices.

The software will also point out devices that are energy demanding and recommendations will be made to not use them. This is interesting as users might think that any device can be used in conjunction with others without energy costs and storage lifespan. Figure 3.10 presents an idea of low wattage devices as compared to Figure 3.11. This will offer users a selection recommendation and a tally of total wattage as represented by Figure 3.12.

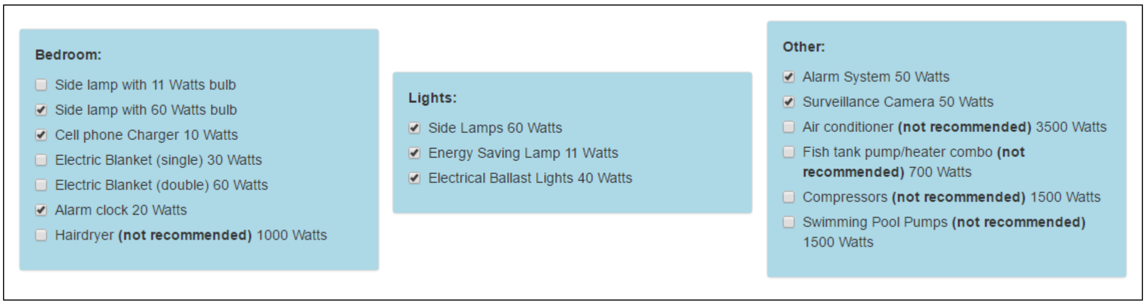


FIGURE 3.10: Low wattage devices selected

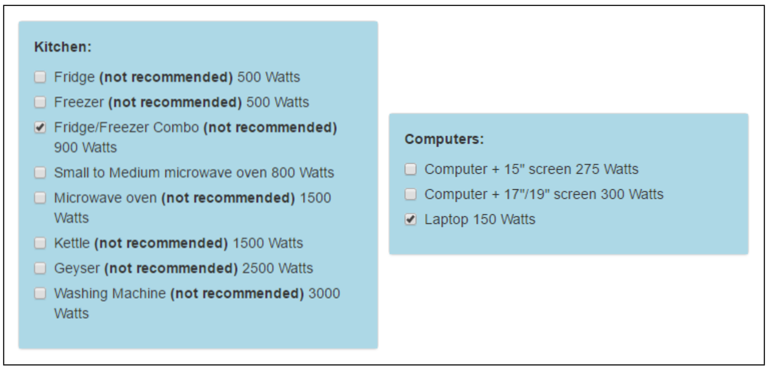


FIGURE 3.11: High wattage devices recommended against

FIGURE 3.12: Total wattage of devices selected

By expanding on this idea of power requirements and taking device wattage, the number of devices and the number of hours used per day / the number of hours that the device is intended to be used, a total for every device can be determined. This is illustrated by Figure 3.13.

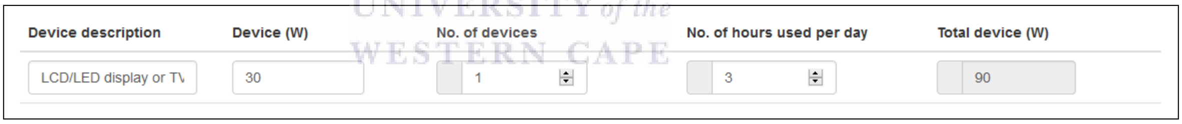


FIGURE 3.13: Device selections based on number of hours used per day

The algorithm below presents the computation for acquiring total device wattage per device and the total computed wattage of all devices selected.

Algorithm 6 Device selections and required energy estimations

$totalDeviceWattage = deviceWattage * noOfDevices * noOfHrs$
$totalComputedWattage = totalComputedWattage + totalDeviceWattage$

3.2.7 Panels based on field size

Flat planes on roofs or open fields are perfect for laying out panels. The examples below will determine the square area of panel dimensions and will compare those to the square area of field dimensions. The technique in use will compute the number of panels row and column-wise and the panels in portrait or landscape layouts. The panels will be stacked against each other and the user will be given the freedom to either install them in that fashion or introduce spacing between them vertically or horizontally. The panels can also be centered in the middle of the field with a margin of 30cm from all ends.

The specifications from Figure 3.14 produce the portrait and landscape calculations and layouts as determined by Figure 3.15, Figure 3.16 and Figure 3.17.

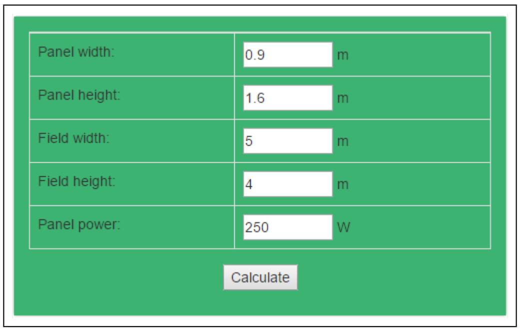


FIGURE 3.14: Panel and field dimensions

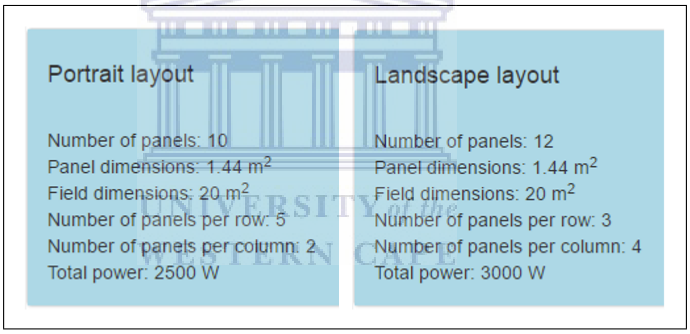


FIGURE 3.15: Layout calculations for portrait and landscape orientations

From Figure 3.15, it is evident that a landscape layout will produce 500W more.

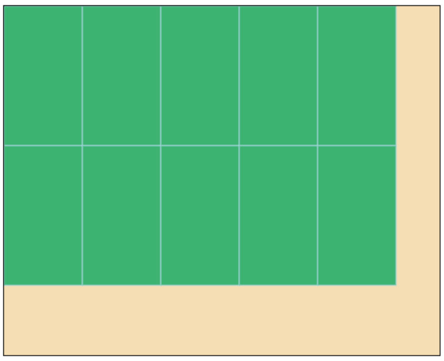


FIGURE 3.16: Portrait layout

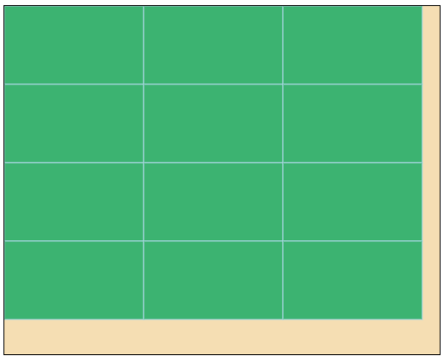


FIGURE 3.17: Landscape layout

Figure 3.17 reveals that a greater area of the $20m^2$ will be used.

The figures are generated with the following parameters defined by the computations below.

Algorithm 7 Portrait layout computations

$panelArea \leftarrow panelWidth * panelHeight$
$fieldArea \leftarrow fieldWidth * fieldHeight$
$rows \leftarrow floor(fieldWidth/panelWidth)$
$cols \leftarrow floor(fieldHeight/panelHeight)$
$noOfPanels \leftarrow rows * cols$
$totalPowerWatt \leftarrow panelPower * noOfPanels$

Algorithm 8 Landscape layout computations

$panelArea \leftarrow panelWidth * panelHeight$
$fieldArea \leftarrow fieldWidth * fieldHeight$
$rows \leftarrow floor(fieldWidth/panelHeight)$
$cols \leftarrow floor(fieldHeight/panelWidth)$
$noOfPanels \leftarrow rows * cols$
$totalPowerWatt \leftarrow panelPower * noOfPanels$

The diagrams displayed are essentially HTML canvas's that are drawn with rectangles row and column-wise. The dimensions of each canvas is derived from the field's dimensions and each rectangle/solar panel to be drawn is derived from the panel's dimensions. This allows a realistic ratio to be maintained, which will grant users a life-like representation of what they can expect.

3.2.8 Panels on map - Google Maps implementation

Being able to estimate the number of solar panels that can be fitted into a drawn Google map polygon can serve as a valuable tool. It can enable a user to find a specific piece of land and simulate the various ways that solar panels can be overlayed. This can be on an empty piece of land or on the roof of a building, house or complex.

For the purposes of this research, the drawn polygon's coordinates will be saved to an array. This will included every point in latitude and longitude form. These polygon points are adjustable and the array will be updated accordingly.

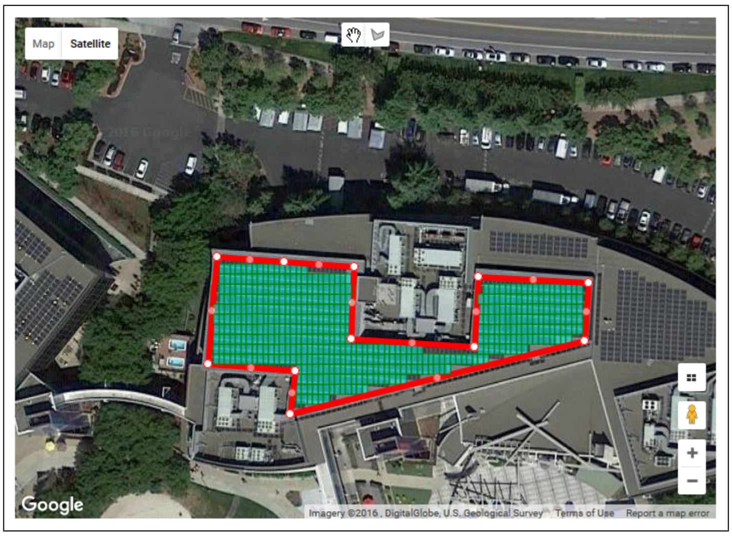


FIGURE 3.18: Map of area and overlayed panels

Figure 3.18 shows an example of a roof that has been mapped with a polygon. The boxes/solar panels drawn in the polygon are of dimensions similar to the solar panels shown in the figure with respect to the zoom/map projection.

Area of polygon/field = 1699.3280447371615 m^2

Area of polygon/field = 19061.170539044146 pixels^2

FIGURE 3.19: Area of polygon drawn

As the polygon is drawn, its area in square meters is calculated. For further usage, the area of the polygon in square pixels is also calculated and it can be used as a measure to determine the number of panels drawn, since a panel's dimensions is set in pixels. These areas are illustrated by Figure 3.19.

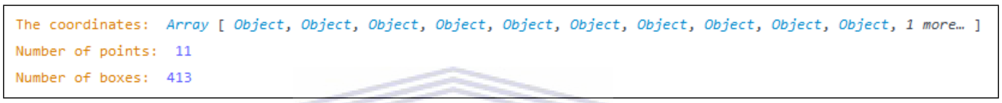
```
The coordinates: Array [ Object, Object, Object, Object, Object, Object, Object, Object, Object, Object, 1 more… ]
Number of points: 11
Number of boxes: 463
```

FIGURE 3.20: Coordinates/points, number of points and number of solar panels

Figure 3.20 shows that the coordinates/points are stored as objects in an array and that 11 objects are present. On the map, they can be seen as the white dots. The number of boxes/panels drawn are 463. With this implementation, there exists no spacing between panels nor panels in string configurations. That functionality will be added at a later stage.

FIGURE 3.21: Adjustment of points/polygon

An added feature is the possibility to adjust the points of the polygon. When the polygon is adjusted, the array is updated and the number of solar panels is re-calculated. This can be seen by Figure 3.21 and Figure 3.22.



```
The coordinates:  Array [ Object, Object, Object, Object, Object, Object, Object, Object, Object, Object, 1 more… ]
Number of points:  11
Number of boxes:  413
```

FIGURE 3.22: Adjusted points/polygon

It is also possible to revert to the previous polygon setup as illustrated by Figure 3.23. By clicking on the revert/back button, the previous polygon dimensions are acquired and the accompanied computations are performed.

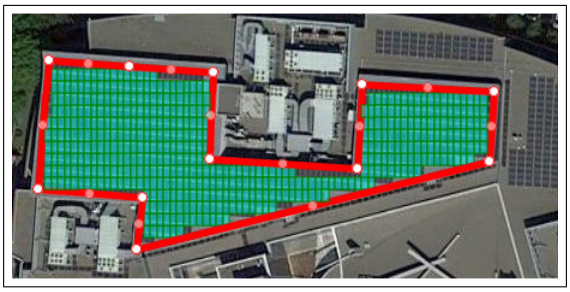
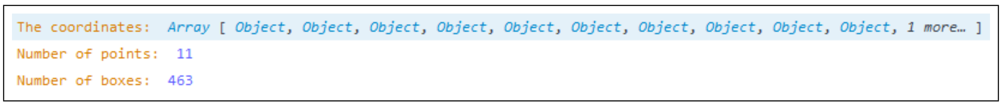


FIGURE 3.23: Result of revert

Figure 3.24 shows the reverted computations and Figure 3.25 shows the latitude and longitude of the first object/point of the polygon.



```
The coordinates:  Array [ Object, Object, Object, Object, Object, Object, Object, Object, Object, Object, 1 more… ]
Number of points:  11
Number of boxes:  463
```

FIGURE 3.24: Reverted computation

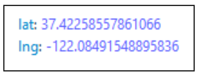


FIGURE 3.25: Latitude and longitude

Delving deeper into the map operations would reveal what is shown by the following :

- Create a Google map - take in coordinates or scroll from current map position
- Create a drawing manager panel that allows the use of a polygon and hand icon
- Deploy an event that fires when the creation of a polygon is completed by a user
  - Set the polygon as editable
  - Call a function to save the polygon as a parameter in order to save its coordinates to an array
  - Add listeners to detect a projection_changed, an insert_at, a remove_at and a set_at

When a polygon is completed the following takes place:

- Calculate the bounds that contains the entire polygon
- Calculate the small box/solar panel size in pixels to populate the polygon
- Detect that the polygon is able to contain a small box/solar panel until the polygon is filled from top left to bottom right
- Draw the small boxes/solar panels in the polygon

Figure 3.26 displays the bounding box that contains the entire polygon. It is shaded in yellow and in this case is only displayed for demonstration/debug purposes.

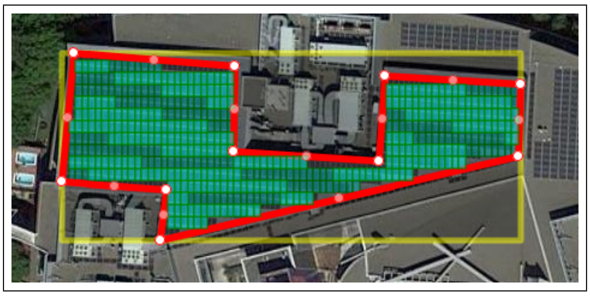


FIGURE 3.26: Bounding box

3.3 Remote Monitoring

It is to be noted that the contents of the remote monitoring section is work continued from my Honours research as illustrated by Figure 3.27. Updates have been applied to the web portal and Android application that enables users of solar systems to view their system's performance.

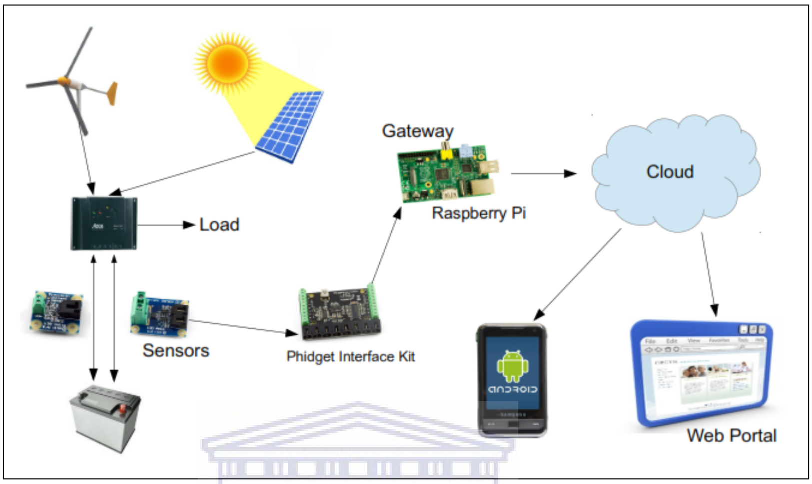


FIGURE 3.27: Remote monitoring system

Users can be offered the services of the solution, that will be described. They will be able to use it to view what their home or business based solar system is producing for them, the energy that is being stored and even what is being used.

In terms of energy production, sensors can be attached between the solar panels and charge controller. These sensors will take into account the voltage, current and subsequently the wattage/power on the panels side. Similarly, voltage, current and power can be computed for the battery bank which a charge controller is optimally charging. Figure 3.28 grants a schematic illustration of the sensors and components of the system.

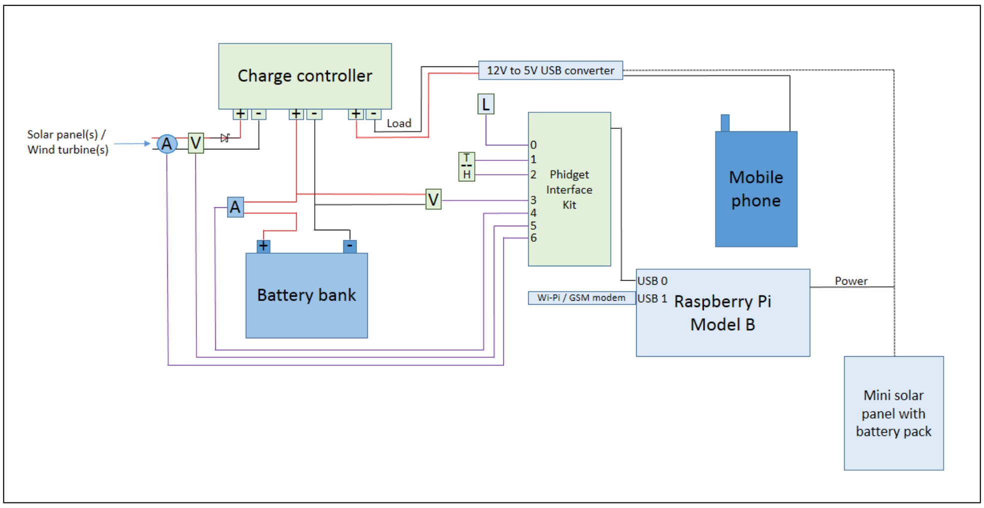


Figure 3.28: Schematic of the remote monitoring system

Since the environment plays a crucial role in the performance of a renewable energy system, ambient temperature, relative humidity and daily luminosity is measured.

3.3.1 Sensor details

- Sensors between the solar panel(s)/wind turbine(s) and charge controller
  - 3586_0 – $CE-IZ04-35A2-1.0/0-250A\ DC\ Current\ Transducer\ (non-ratiometric)$
  - 3509_1 – $CE-VZ02-32MS1-0.5\ DC\ Voltage\ Sensor\ 0-200V\ (non-ratiometric)$
- Sensors between the charge controller and battery bank
  - 1122_0 – $30\ Amp\ Current\ Sensor\ AC/DC\ (ratiometric)$
  - 1135_0 – $Precision\ Voltage\ Sensor\ \pm 30V\ DC\ (non-ratiometric)$
- Environmental sensors
  - 1125_0 – $Humidity/Temperature\ Sensor\ (ratiometric)$
  - 1143_0 – $Light\ Sensor\ 70000\ lux\ (non-ratiometric)$

Sensors that take USB voltage (which can be anywhere from 4.5 - 5.5V) and use that to power themselves and return a result are known to have a ratiometric sensor output type. The resulting sensor value changes in proportion to the USB voltage.

Sensors that have on-board power supplies or voltage regulators, such that they always power themselves off of 5V are known to have a non-ratiometric sensor output type. The sensor value these return does not change in proportion to USB voltage.

In ratiometric mode, the A/D converter on the interface kit references itself to USB voltage. In non-ratiometric mode, the A/D converter references itself to a regulated 5V reference.

With this in mind and making use of both types of sensors, the Phidget Interface Kit will need to be switched into the correct state for each sensor type. There will exist a bit of a delay in the switching. Figure 3.29 presents a state diagram of how the sensing program on the Raspberry Pi will account for both states in the Phidget Interface Kit.

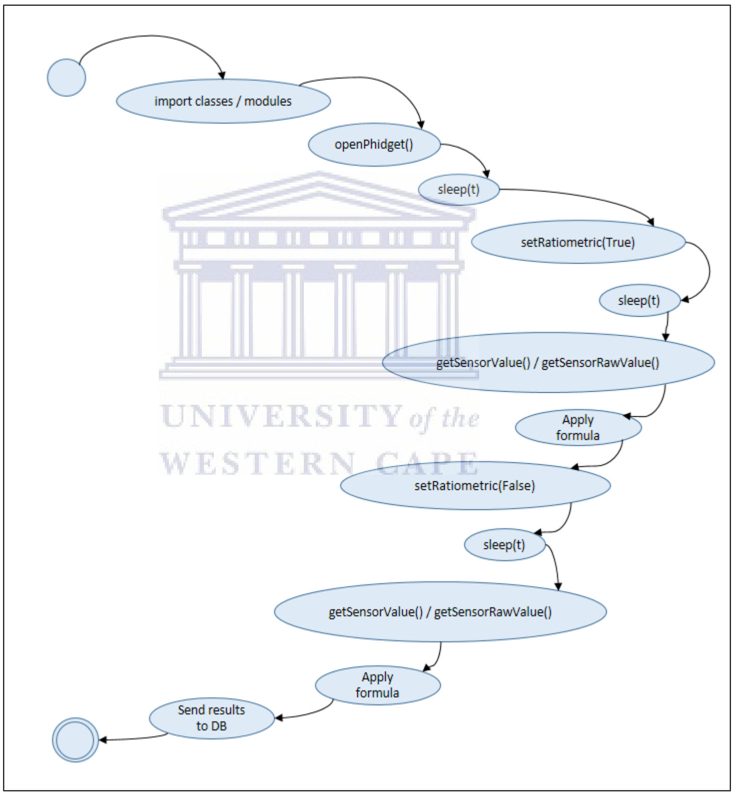


FIGURE 3.29: Sensing state diagram

Ratiometric sensor values will be retrieved first and then the values of all non-ratiometric sensors. The first sleep(t) will give the Phidget Interface Kit time to open. The one's preceding setting the state of the Phidget Interface Kit are responsible for providing enough time for the switching to take place.

3.3.2 Time based measurements

Users of such systems are interested in the performance over time frames that will inform them whether their system is operating optimally with regards to the environment. The readings over these time frames will be present, hourly and daily averages.

The present readings will account for panel voltage, current and power as well as battery voltage, current and power. Present readings for the environment will be ambient temperature, relative humidity, luminosity and a state of charge computation for the battery bank.

3.3.3 Web portal

In order to serve users on personal computers (PCs), laptops, smart phones or tablets with the results of their smart energy system, a web portal has been built to allow connections over the Internet. The portal features a responsive design so that it can scale across various devices. Frameworks and client-side languages that are made use of are Javascript, jQuery, Twitter Bootstrap and jQuery's AJAX requests. Readings are pulled from a MySQL database with PHP as server-side language. The main graphing library in use is FusionCharts.

Figure 3.30 gives an idea of how the portal operates.

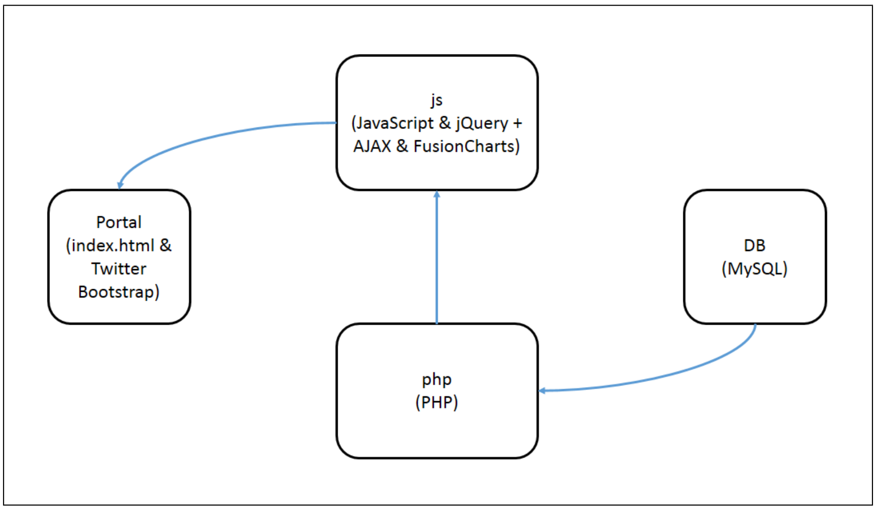


Figure 3.30: Portal operations

The collected sensor data is pulled from a MySQL database via the PHP server-side language. Requests through PHP are handled by a jQuery AJAX request for each

JavaScript application. Every JavaScript application has an associated PHP script for its individual operations.

The data for every application is returned as a JSON object/array by PHP. From the JavaScript side, the JSON object/array is converted into a string value and fed into a FusionCharts graph or chart. These charts are rendered asynchronously on timed intervals and populate the portal front-end. The style and responsiveness of the applications and portal is handled by Twitter Bootstrap.

3.3.3.1 Portal applications

The first section of the portal has applications that display the present or most current readings. They are divided into 3 categories:

- Panel readings
  - Voltage, current, power
- Battery readings
  - Voltage, current, power, battery state-of-charge
- Environmental readings
  - Ambient temperature, relative humidity

The following figures are examples of the live readings displayed.

The second part displays:

- Averages over time - last 7 days
  - Averages of panel/array DC voltage readings
  - Averages of panel/array DC power readings
  - Averages of battery bank DC voltage readings
  - Averages of battery bank DC power readings
- Hourly averages
  - Averages of hourly luminosity readings
  - Averages of hourly panel/array DC voltage readings (5 a.m. - 8 p.m.)
  - Averages of hourly panel/array DC voltage readings (9 p.m. - 4 a.m.)

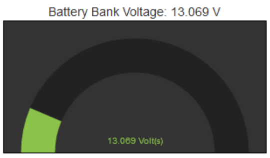


FIGURE 3.31: Battery DC voltage

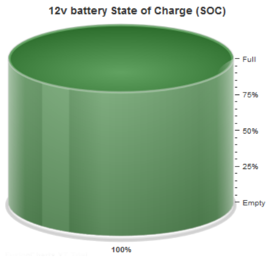


FIGURE 3.32: The State of Charge determined from the battery voltage

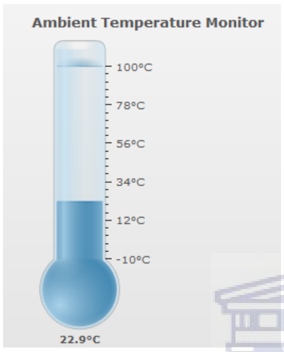


FIGURE 3.33: Ambient temperature

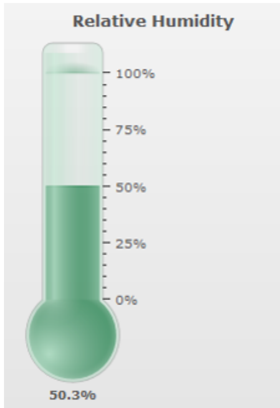


FIGURE 3.34: Relative humidity

  - Averages of hourly battery bank DC voltage readings (5 a.m. - 8 p.m.)
  - Averages of hourly battery bank DC voltage readings (9 p.m. - 4 a.m.)
  - Averages of hourly panel/array DC power readings (5 a.m. - 8 p.m.)
  - Averages of hourly panel/array DC power readings (9 p.m. - 4 a.m.)
  - Averages of hourly battery bank DC power readings (5 a.m. - 8 p.m.)
  - Averages of hourly battery bank DC power readings (9 p.m. - 4 a.m.)

- Last 10 readings
  - Date/Time
  - Ambient temperature
  - Relative humidity
  - Luminosity
  - Battery DC voltage
  - Battery DC current
  - Battery DC Power

Example readings are presented by the images below.

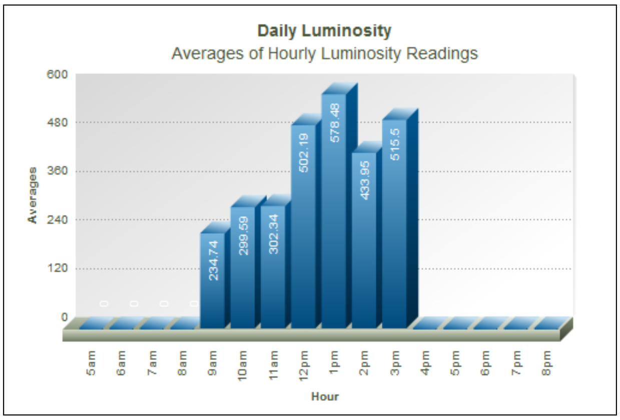


FIGURE 3.35: Hourly luminosity readings

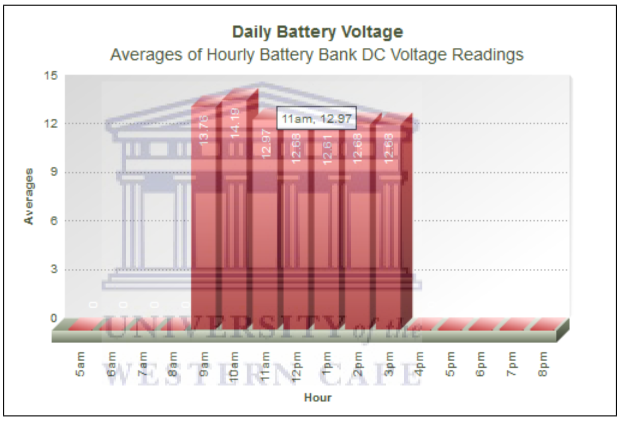


FIGURE 3.36: Hourly battery voltage readings

3.3.4 Android application

The latest Android application will serve as a ready to go tool, as it will allow system owner's mobile or on the go awareness of their system's status. The application will serve to provide:

- A main activity displaying:
  - Date / Time
  - Ambient temperature
  - Relative humidity
  - Luminosity
  - Panel voltage

- Panel current
- Panel power
- Battery voltage
- Battery current
- Battery power
- State of Charge (SOC) See Figure 3.37.

- An activity displaying panel power in watts (5 a.m. - 8 p.m.) See Figure 3.38.
- An activity displaying battery power in watts (5 a.m. - 8 p.m.) See Figure 3.39.

Please see the below figures for examples of the listed functionality.

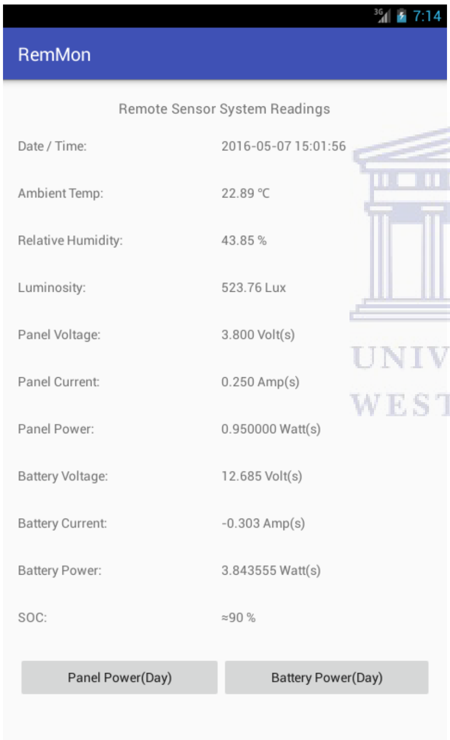


FIGURE 3.37: Main application activity

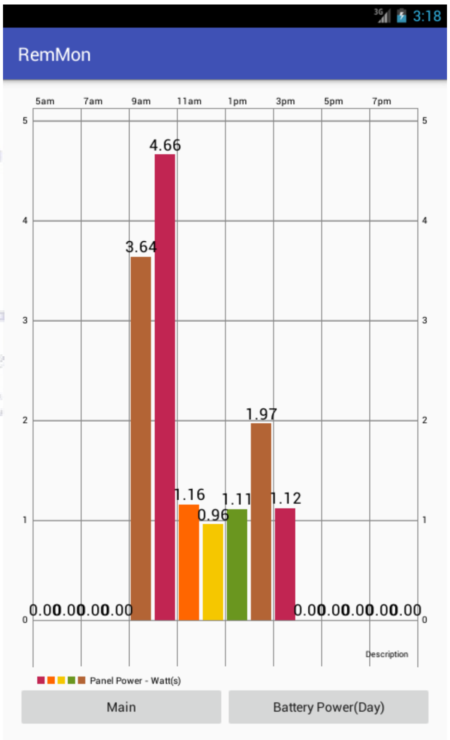


FIGURE 3.38: Panel power during daylight hours

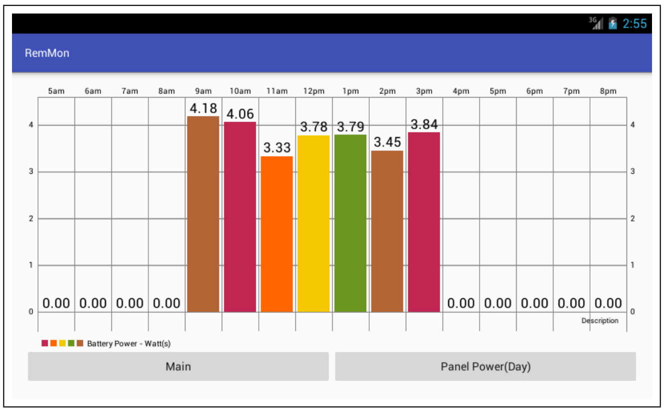


FIGURE 3.39: Battery power during daylight hours

The activities essentially run a background thread which pulls the readings from a remote MySQL database and passes it onto a main thread that populates variables and graphs. The class responsible for running in the background is a JSONTask that extends the AsyncTask class. The function doInBackground(String... params) initiates the HTTP URL connection, buffers the data from an input stream and stores the data contained in the JSON string into individual strings, respectively.

Upon completing the background operations, the values are populated into variables that form part of rendering the user interfaces on the main thread. The JSONTask is executed every minute to fetch the latest readings. This time frame can be adjusted based on user needs.

The MPAndroidChart graphing library is made use of as it offers responsive graphs and charts that provide appeal to the eye. It has support for line- bar- pie- radar- bubble- and candlestick charts as well as scaling, dragging and animations.

3.4 Conclusion

The chapter exposes various architectures of solar systems and introduces tools that would allow users to dimension intended solar and wind systems that would enable the making of informed decisions. The chapter also took into account the updated design for the remote monitoring system that was started during my Honours academic year. This includes a web portal and an Android application that users can make use of to monitor a physical system.

Chapter 4

Results: Presentation and Discussion

4.1 Introduction

The bulk of the chapter will discuss architectural configurations of renewable energy systems and the various tools of the dimensioning software. It will illustrate what is possible within reasonable limits. This chapter will also detail results pertaining to the addition of sensors to the remote monitoring system and show the benefits derived as a result.

4.2 System's Engineering - Architectures and Dimensioning

4.2.1 Panel to battery

The following tables will show how increasing panel wattage over the Cape Town area during the month of September and the solar insolation available for the area determines how long it will take to charge a battery/battery bank from flat to full.

Panel Wattage	Sol. Insolation	Month	Battery	Battery	Generation Capacity	Battery Capacity	Days
W	(kWh/m^2/day)		Ah	V	watt-hours	watt-hours	days
100	4.63	September	120	12	463	1440	3.110
200	4.63	September	120	12	926	1440	1.555
300	4.63	September	120	12	1389	1440	1.037
400	4.63	September	120	12	1852	1440	0.778
500	4.63	September	120	12	2315	1440	0.622
600	4.63	September	120	12	2778	1440	0.518
700	4.63	September	120	12	3241	1440	0.444
800	4.63	September	120	12	3704	1440	0.389

TABLE 4.1: Solar panel(s) wattage comparisons

Panel Wattage	Sol. Insolation	Month	Battery	Battery	Generation Capacity	Battery Capacity	Days
W	(kWh/m^2/day)		Ah	V	watt-hours	watt-hours	days
100	4.63	September	350	12	463	4200	9.071
200	4.63	September	350	12	926	4200	4.536
300	4.63	September	350	12	1389	4200	3.024
400	4.63	September	350	12	1852	4200	2.268
500	4.63	September	350	12	2315	4200	1.814
600	4.63	September	350	12	2778	4200	1.512
700	4.63	September	350	12	3241	4200	1.296
800	4.63	September	350	12	3704	4200	1.134

TABLE 4.2: Effect of increasing battery bank capacity (Ah) - single battery

This takes into consideration battery ampere-hours. The larger the battery ampere-hours, the longer it will take to charge them. The difference in days is made apparent between Table 4.1 and Table 4.2.

Panel Wattage	Sol. Insolation	Month	Battery	Battery	Generation Capacity	Battery Capacity	Days
W	(kWh/m^2/day)		Ah	V	watt-hours	watt-hours	days
100	4.63	September	2800	96	463	268800	580.562
200	4.63	September	2800	96	926	268800	290.281
300	4.63	September	2800	96	1389	268800	193.521
400	4.63	September	2800	96	1852	268800	145.140
500	4.63	September	2800	96	2315	268800	116.112
600	4.63	September	2800	96	2778	268800	96.760
700	4.63	September	2800	96	3241	268800	82.937
800	4.63	September	2800	96	3704	268800	72.570
5600	4.63	September	2800	96	25928	268800	10.367
8000	4.63	September	2800	96	37040	268800	7.257

TABLE 4.3: Effect of increasing battery bank capacity (Ah) - 8 X 12V 350Ah batteries in combination configuration

In Table 4.3, eight 12V 350Ah batteries are connected in a combination configuration. This subsequently increases voltage by a factor of 8 and ampere-hours by a factor of 8. However, even at a panel wattage of 800W, it would still take 72.570 days to charge the battery bank from flat to full, allowing ±20% for weather conditions.

By increasing the number of panels, say by fourteen 400W panels (5600W), it would still take 10.367 days. An even further increase to twenty 400W panels (8000W) would take 7.257 days.

4.2.2 Solar insolation of seven South African metros - 2016

Metro	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
East London	5.68	5.27	4.44	3.69	3.15	2.70	2.85	3.53	4.29	4.78	5.35	5.74
Cape Town	7.93	7.02	5.63	4.06	2.91	2.50	2.67	3.41	4.63	6.16	7.44	7.96
Durban	5.57	5.18	4.75	4.01	3.41	3.01	3.17	3.72	4.32	4.53	4.83	5.44
Johannesburg	6.70	6.10	5.46	4.77	4.21	3.80	4.08	4.78	5.69	5.98	6.29	6.62
Bloemfontein	7.02	6.19	5.28	4.44	3.74	3.32	3.54	4.36	5.29	5.97	6.71	7.07
Port Elizabeth	6.41	5.68	4.63	3.63	2.97	2.50	2.71	3.39	4.29	5.07	5.91	6.55
Pretoria	6.70	6.10	5.46	4.77	4.21	3.80	4.08	4.78	5.69	5.98	6.29	6.62

TABLE 4.4: Solar insolation of seven South African metros

Upon evaluating the solar insolation[22] from Table 4.4, the highest yields are seen from January to March and then again from August to December over the seven metros. This serves as a measure to complement the notion that South Africa is a country that experiences exceptional levels of solar radiance. These levels would allow the use of the Sun's power to top up a portion of the present energy shortfall. The data provided by Gaisma was obtained from the NASA Langley Research Center Atmospheric Science Data Center.

4.2.3 Solar insolation vs temperature vs precipitation vs wet days - Cape Town

Based upon the work of the above subsection, a comparison can be made between the solar insolation for an area against the temperature, precipitation and number of wet days experienced monthly.

Variable	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Insolation	7.93	7.02	5.63	4.06	2.91	2.50	2.67	3.41	4.63	6.16	7.44	7.96
Temperature	22.01	22.40	20.98	18.57	15.85	13.30	12.55	13.11	14.78	17.15	19.11	20.71
Precipitation	32	30	43	82	136	189	164	163	96	61	40	43
Wet days	4.8	4.4	5.1	8.2	12.0	13.3	13.0	13.7	11.1	8.8	5.6	6.3

TABLE 4.5: Solar insolation, $kWh/m^2/day$ vs Temperature, $^{\circ}C$ vs precipitation, mm vs Wet days, d - Cape Town

From January to March, the solar insolation is high as well as the temperature. These months experience low precipitation and number of wet days in comparison with the months April to Sept. From October to December, the precipitation lowers again as well as the number of wet days. August to December sees rising solar insolation again with an increase in temperature.

By taking the precipitation and number of wet days into account, from Table 4.5 it can be seen that the months with the highest precipitation / cloud cover will yield the lowest solar energy since the solar insolation is low.

No. of panels	Wiring type	Panel V	Panel A	Voltage FoI	Total V	A FoI	Total A	Total Panel W
1	Series	30.83	8.11	1	30.83	1	8.11	250.0313
2	Series	30.83	8.11	2	61.66	1	8.11	500.0626
2	Parallel	30.83	8.11	1	30.83	2	16.22	500.0626
3	Series	30.83	8.11	3	92.49	1	8.11	750.0939
3	Parallel	30.83	8.11	1	30.83	3	24.33	750.0939
4	Series	30.83	8.11	4	123.32	1	8.11	1000.1252
4	Parallel	30.83	8.11	1	30.83	4	32.44	1000.1252
32	Series	30.83	8.11	32	986.56	1	8.11	8001.0016
32	Parallel	30.83	8.11	1	30.83	32	259.52	8001.0016
33	Series	30.83	8.11	33	1017.39	1	8.11	8251.0329
33	Parallel	30.83	8.11	1	30.83	33	267.63	8251.0329

TABLE 4.6: Panel wiring configurations

4.2.4 Panel wiring

The results of Table 4.6 are obtained by making use of the specifications of a 250 watt SDDirectPro EnerSol 250 solar panel. The voltage and current properties used in the figure are the panel's voltage and current at maximum power. By multiplying these values, the panel's rated power is obtained. By increasing the number of panels in series or in parallel will result in the same wattage. The difference in configuration allows a user to increase either the voltage or the current to meet their needs.

It must be noted that the maximum system voltage allowed for this panel is 1000VDC. This will limit the use to thirty-two 250 watt panels in series.

4.2.5 Battery wiring

No. of batteries	Wiring type	Battery V	Battery Ah	Voltage FoI	Total V	Ah FoI	Total Ah
1	Series	12	120	1	12	1	120
2	Series	12	120	2	24	1	120
2	Parallel	12	120	1	12	2	240
2	Combination	12	120	2	24	2	240
3	Series	12	120	3	36	1	120
3	Parallel	12	120	1	12	3	360
3	Combination	12	120	3	36	3	360
4	Series	12	120	4	48	1	120
4	Parallel	12	120	1	12	4	480
4	Combination	12	120	4	48	4	480
5	Series	12	120	5	60	1	120
5	Parallel	12	120	1	12	5	600
5	Combination	12	120	5	60	5	600
6	Series	12	120	6	72	1	120
6	Parallel	12	120	1	12	6	720
6	Combination	12	120	6	72	6	720
7	Series	12	120	7	84	1	120
7	Parallel	12	120	1	12	7	840
7	Combination	12	120	7	84	7	840
8	Series	12	120	8	96	1	120
8	Parallel	12	120	1	12	8	960
8	Combination	12	120	8	96	8	960
9	Series	12	120	9	108	1	120
9	Parallel	12	120	1	12	9	1080
9	Combination	12	120	9	108	9	1080
10	Series	12	120	10	120	1	120
10	Parallel	12	120	1	12	10	1200
10	Combination	12	120	10	120	10	1200

TABLE 4.7: Battery wiring configuration comparisons with a 120Ah battery system

From Table 4.7 it is seen that series and combination configurations cause a voltage factor of increase (FoI) / increase by a specific factor, whereas parallel and combination configurations cause an ampere-hour increase by a specific factor. These factors are ultimately determined by the number of batteries that comprise the battery bank / storage.

4.2.6 Wind turbine power calculations

Turbine rating	Blade length	Wind speed	Air density	Power coefficient	Sweap Area	P_{avail}	P_{avail}
KW	m	m/sec	kg/m^3	C_p	m^2	W	KW
2	1.6	8	1.24	0.4	8.042	1021.202	1.021
2	1.6	11	1.24	0.4	8.042	2654.725	2.655
3	2	8	1.24	0.4	12.566	1595.627	1.596
3	2	11	1.24	0.4	12.566	4148.008	4.148
5	2.5	8	1.24	0.4	19.635	2493.168	2.493
5	2.5	11	1.24	0.4	19.635	6481.263	6.481
10	4	8	1.24	0.4	50.265	6382.510	6.383
10	4	11	1.24	0.4	50.265	16592.033	16.592

Table 4.8: Simulation of wind turbines

Table 4.8 highlights the projected rating of 4 wind turbines with regards to wind speed and air density. Based on the wind speed, it can be shown that a turbine can perform below its rated power. It can also produce more energy at higher wind speeds.

Users are advised to check the rated power and maximum/peak power that a turbine can produce. They should also bear in mind that a turbine has rated and working wind speeds and can only survive speeds up until a certain threshold.

4.2.7 Device selections and required energy estimations

Table 4.9 lists the use case of an individual residing in a bachelor flat. Based on the user's computed electrical needs, a suitable solar system can be recommended.

Device	Power use on average (W)	Hours used per day	Total power use (W)	Location/Cat.
LCD/LED Display or TV screen (up to 22")	30	3	90	Lounge
DVD Player	10	2	20	Lounge
Satellite dish and decoder (HD-PVR)	34	24	816	Lounge
Hi-Fi	200	0.5	100	Lounge
Side lamp (CFL)	14	5	70	Bedroom
Cell phone charger	5	3	15	Bedroom
Electric blanket (double)	60	2	120	Bedroom
Alarm clock with radio	2	24	48	Bedroom
Fridge/Freezer combo	40.833	24	980	Kitchen
Home security system	25	24	600	Other
Side lamp	60	3	180	Additional lights
Incandescent light bulb	60	5	300	Additional lights
Energy saving light bulb	14	5	70	Additional lights
Electrical ballast light	40	5	200	Additional lights
Computer + 17"/19" screen	300	2	600	Computers
Laptop	60	3	180	Computers

No. of devices		Battery bank Ah	Devices Power use (W)	Inverter size (W)
16		2800	3573	3000

Table 4.9: Computed energy requirements for a bachelor flat

The recommendation takes into account electrical variations of usage. Certain devices may only be used at various times of a day and others may be added or switched on too. This "sizing" would allow users to determine a suitable system and show them what can be run without complete battery drain.

With the aid of the following formula[23], run time can be calculated for most applications making use of a 12V battery/battery bank system and an inverter.

$$Run\,time\,in\,hours = \frac{10 * (Battery\,capacity\,in\,amperehours)}{Load\,power\,in\,watts}$$

Consider the scenario of 4 devices in use between the hours of 17:00 - 08:00 where there is no charging of batteries in a solar system.

Device	Power use on average (W)	Hours used per day	Total power use (W)	Location/Cat.
Satellite dish and decoder (HD-PVR)	34	15	510	Lounge
Alarm clock with radio	2	15	30	Bedroom
Fridge/Freezer combo	40.833	15	612.495	Kitchen
Home security system	25	15	375	Other
No. of devices		Battery bank Ah	Devices Power use (W)	Inverter size (W)
4		2800	1527.495	3000

Table 4.10: Power usage of 4 devices from 17:00 - 08:00

Running the computation would return the following results:

$$Run\,time\,in\,hours = \frac{10 * (Battery\,capacity\,in\,amperehours)}{Load\,power\,in\,watts}$$

$$= \frac{10 * 2800Ah}{1527.495W}$$

$$= \frac{28000}{1527.495W}$$

$$= 18.3306655668267326570627072429\,04$$

$$= 18.331\,hours\,maximum\,run\,time\,before\,the\,battery\,bank\,is\,completely\,discharged,$$

$$or\,9.165\,hours\,run\,time\,before\,the\,battery\,bank\,is\,50\%\,discharged.$$

With the following information available, users should realise that disconnecting unnecessary devices would improve run time.

4.2.7.1 Inverter peak power vs typical vs average

An inverter essentially needs to supply two needs. This would be peak or surge power and the typical or usual power.

- Surge is the maximum power that the inverter can supply, usually for only a short time frame. This could be for a few seconds up to about 15 minutes.
- Typical is what the inverter has to supply on a steady basis.
- Average power would usually be much less than typical or surge and is not usually a factor in choosing an inverter.

If you were to run a pump for 20 minutes and a small TV for 20 minutes during a one hour period, the average might only be 300 watts, even though the pump requires 2000 watts. Average power is only useful in estimating battery capacity needed. Inverters must be sized for the maximum peak load and for the typical continuous load.

If you are intending on running a device like a submersible well pump, you will need either a very high surge capacity or you will need to oversize the inverter above its typical usage, so that even at maximum surge the inverter will not exceed its surge rating[24].

From Table 4.9 the device with the highest wattage consumption would be the Computer + 17"/19" screen at 300W. Even if it were to surge for a few seconds upon start up, the 3000W inverter will still be able to handle it, since its peak power is 2 times the rating power. This means that it has a surge capacity of 6000W.

4.2.8 Panels based on field size

Table 4.11 shows a condition of a 5x4 meters field. Based on the various dimensions of the SDDirectPro Enersol/AquaSol panels to be simulated, the number of panels that can fit into a given rectangular field can be computed.

As illustrated, making use of twelve 250W panels in landscape orientation would produce the same total power as ten 300W panels in portrait orientation within the given piece of land.

Table 4.12 shows that twelve 250W solar panels at R2997 per panel would cost R35964 and ten 300W panels at R3688.98 per panel would cost R36889.80. This represents a difference of R925.80. Informed options such as this would allow users to make knowledgeable decisions.

Panel power	Panel width	Panel height	Field width	Field height	No. of panels	Panel dimensions	Field dimensions	No. of panels per row	No. of panels per column	Total power
W	m	m	m	m		m^2	m^2			W
50 (portrait)	0.635	0.67	5	4	35	0.42545	20	7	5	1750
50 (landscape)	0.635	0.67	5	4	42	0.42545	20	7	6	2100
100 (portrait)	0.67	1.12	5	4	21	0.7504	20	7	3	2100
100 (landscape)	0.67	1.12	5	4	20	0.7504	20	4	5	2000
120 (portrait)	0.67	1.48	5	4	14	0.9916	20	7	2	1680
120 (landscape)	0.67	1.48	5	4	15	0.9916	20	3	5	1800
140 (portrait)	0.67	1.48	5	4	14	0.9916	20	7	2	1960
140 (landscape)	0.67	1.48	5	4	15	0.9916	20	3	5	2100
150 (portrait)	0.67	1.48	5	4	14	0.9916	20	7	2	2100
150 (landscape)	0.67	1.48	5	4	15	0.9916	20	3	5	2250
180 (portrait)	0.99	1.32	5	4	15	1.3068	20	5	3	2700
180 (landscape)	0.99	1.32	5	4	12	1.3068	20	3	4	2160
250 (portrait)	0.99	1.64	5	4	10	1.6236	20	5	2	2500
250 (landscape)	0.99	1.64	5	4	12	1.6236	20	3	4	3000
300 (portrait)	0.992	1.956	5	4	10	1.940352	20	5	2	3000
300 (landscape)	0.992	1.956	5	4	8	1.940352	20	2	4	2400

Table 4.11: Panels in rectangular field

Panel power	orientation	Cost per panel	No. of panels	Total cost
W		R		R
250	landscape	2997.00	12	35964
300	portrait	3688.98	10	36889.80

Table 4.12: Panel selections and costs involved

4.2.9 Panels on map - Google Maps implementation

With the aid of the Google Maps API V3, the roof of the UWC Computer Science Yellow Sub lab could be placed under evaluation. At map latitude -33.9346077 and longitude 18.6296601, the JavaScript API with zoom level 19 produced Figure 4.1 and Figure 4.2. Due to the zoom limitation, the results are a prediction that could be more accurate.

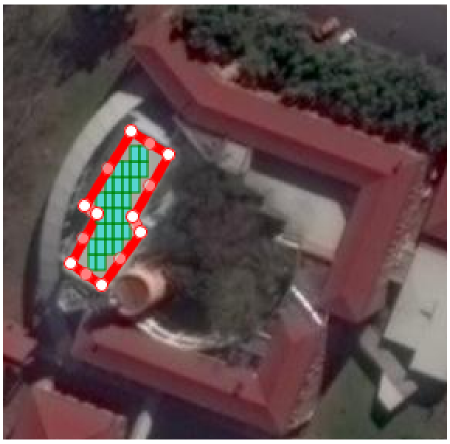


Figure 4.1: UWC CS Yellow Sub Lab portrait orientation

Figure 4.2: UWC CS Yellow Sub Lab landscape orientation

From the two orientations, the following was generated:

Panel power	Orientation	No. of points	No. of panels	Total power
W				W
400	Portrait	8	28	11200
400	Landscape	8	23	9200

Table 4.13: UWC CS Yellow Sub Lab map based estimations

4.3 Remote Monitoring

4.3.1 Partial shading

As solar panels depend on the sun in order to generate electricity, it goes without saying that shading is undesirable for solar systems. A shadow cast on even just part of a solar array can potentially compromise the output of the entire system.

In conventional solar panel strings, shade is a factor that can block the flow of generated electricity. If, for example, shade from trees or surrounding buildings is cast on even one of the panels in a string, the output of the entire string will be reduced to zero for as long as the shadow remains. If a separate, unshaded string exists, this string will continue to produce power normally.

A shadow does not necessarily need to fall on an entire panel, depending on the technology used, in extreme cases. Shading of even just one cell could flatten the output of the panel and in turn the entire string. Modern panels, however, come equipped with devices known as bypass diodes which minimise the effects of partial shading by essentially enabling electricity to flow around the shaded cell or cells[25].

Based on this potential obstacle, an examination into the effect of shading on a 20W Solarflex SA Fold Up Solar Panel reveals the following:

Shading percentage %	Voltage V
0	20.5
25	19.6
50	19.2
75	6.3
100	0.0

TABLE 4.14: Solar panel voltage based on shading percentage

The panel is of type polymer photovoltaic solar cells with a rated output of 18V, 1.1Ah. Based on the results of the partial shading, it can be deduced that the panel does have bypass diodes structurally integrated which enables the flow of electricity around the shaded cells.

Partial shading can be avoided by considering all times of a day for all seasons of a year in order to ensure a nearby object does not cast a shadow over your solar array. When setting up solar panels, also take into account that no trees are planted nearby as they have the potential to grow tall enough to eventually cause shading issues. Since solar panels have decent lifespans and are intended to be used on a long term basis, nearby trees can have plenty of time to grow.

On 26 November 2016, between 2 - 3 p.m. over the Bellville, Cape Town area, a luminosity reading of 70879.75 lux was sensed. It represents the top end of what the sensor is able to determine. Even though this lux reading was present over the area, partial shading of the panel by a nearby tree reduced the panel's ability to generate 20.5V and instead a reading of 18.6V was sensed as the highest voltage reading. In fact, as the wind moved the tree the voltage fluctuated between 13.6 to 18.6V. This further confirms the effect of partial shading on solar panels.

4.3.2 Voltage sensors vs multimeter

The readings from Figure 4.3 are indications of the accuracy of the sensors and multimeter used.

Voltage Sensor 0 - 200V	Top Tronic T820	Precision Voltage Sensor	Top Tronic T820
13.80	13.60	12.922	13.08
Solar panel voltage		Battery voltage	

FIGURE 4.3: A comparison of voltage sensor accuracies

4.3.3 Daily luminosity vs panel voltage vs battery voltage

Based on readings taken from 3 p.m. to 5 p.m. on Tuesday, 23 November 2016, under cloudy conditions, the following is presented by Figure 4.4.

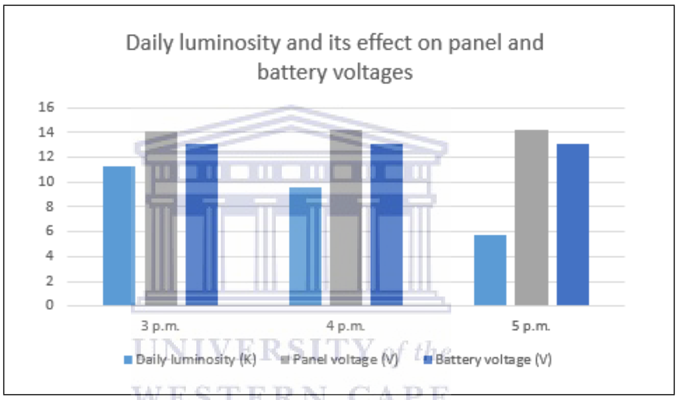


FIGURE 4.4: Daily luminosity vs panel and battery voltages (averages)

Even with dropping luminosity levels based on the time of the day and the added effect of cloud cover, the panel in use was able to generate an average voltage reading of 14.163V. The battery voltage kept stable around 13.067V as there was no draw or load on the system.

4.3.4 Panel power vs battery power

With the same day and time frame in mind, Figure 4.5 presents a case in which the battery power increased as the battery has been steadily charging from 3 p.m. to 5 p.m.

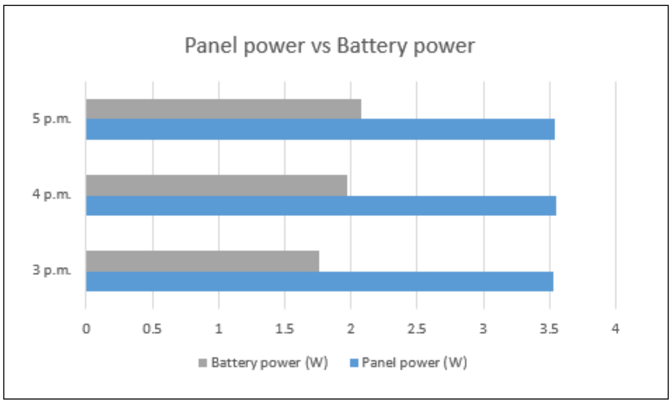


FIGURE 4.5: Panel power vs battery power (averages)

4.3.5 Considerations of solar, wind and generator based systems

This chapter will not be complete without describing the functional use of fuel based generator systems and the scenarios in which they are usable. We will start by comparing the three technologies in Table 4.15 which are interesting, but not always equivalent.

Solar	Wind	Generator
Power produced depends on the hours of sunlight available	Can operate day and night depending on wind availability	Power will range depending on fuel prices and machine efficiency
Inconsistent power	Usage is limited to area	Reliable and convenient to use
Not portable	Can be portable	Relatively portable
Largest footprint	Stronger wind conditions will reduce energy costs	Diesel fuel is the most power dense
Glint and glare	Noise	Noise, non-renewable and produces greenhouse gases
Need to be kept clear of dust/sand, debris	Moving parts need to be lubricated	Internal combustion engines need regular servicing

TABLE 4.15: Considerations of solar, wind and generator based systems

Generators are further divided into different categories:

- Petrol, single phase, air cooled
- Gas (LPG), single phase, air cooled
- Petrol, three phase, air cooled

- Diesel, single phase, air cooled
- Diesel, single phase, water cooled
- Diesel, three phase, air cooled
- Diesel, three phase, water cooled

An electrical supply with only one live phase, plus the neutral is known as single phase[26]. Three phase is the most commonly supplied electricity, 230/400 volts, from which 230 volts can be obtained between a phase and neutral in a four-wire system. This can be higher when used in commercial and industrial applications.

Generators at power stations supply three phase electricity. This is a means of providing three times as much electricity along three wires as can be supplied through two, without having to increase the thickness of the wires[27]. It is used in industry to drive motors and other devices. Three phase electricity is by its very nature a much smoother form of electricity than single phase or two phase power. It is this more consistent electrical power that allows machines to run more efficiently and last years longer than machines running on other phases. Some applications are able to work with three phase power in ways that would not work on single phase at all.

In order to ensure proper maintenance of diesel generator systems, the following must be adhered to:

- The exhaust system, fuel system, DC electrical system and engine require close monitoring for any leaks when the generator is running. This is to prevent hazardous occurrences.
- Regular oil changes for a long and trouble free life just as for any internal combustion engine. This applies towards the oil filter as well.
- Heavy-duty diesel engines require a balanced coolant mixture of water, anti-freeze and coolant additives.
- Deplete stored fuel before it degrades. Diesel is subject to contamination and corrosion within a period of one year.
- Starting batteries must be kept fully charged and well maintained to avoid dwindling by regular testing and inspection.

4.4 Conclusion

This chapter took into account the various tools of the dimensioning software. Use cases were set so that users could determine reasonable expectations and simulate their intended solar and wind installations. Considerations were also presented for generator based systems and their usability. In Chapter 5, recommendations will be made for enhancing the tools listed.

Chapter 5

Conclusions and recommendations

This research has successfully expanded on the work begun during my Honour's academic year. The focus was on the development of a remote sensor network to monitor a solar power system. The monitoring of the system involved the storage of renewable energy, the measurement of readings with sensors, insights into the technology used to take the measurements and the traffic involved. An additional part focused on how users would interact with the system by means of a web portal and an Android application to enable remote monitoring via wireless networks. It further touched on how data was displayed to users in an informative way.

The remote monitoring system, web portal and Android application have seen upgrades that will deliver greater insight to end-users. Both have been built with the ability to scale across multiple devices. An addition to the topic of smart energy systems is the work on dimensioning. It can pave an avenue for users to determine their energy needs based on the number of devices that they intend to run in a household. Users will see what a given system is capable of producing, the time it will take to recharge their battery storage and a host of additional features made available to them.

The major contributions of the dimensioning tool set involve the efficiency comparisons of PWM vs MPPT charge controllers, computations involving solar panel and battery selection, solar panel wiring, battery wiring, wind turbine power, device selections and required energy estimations, solar panels determined for a specified field size and a map based implementation that will still be improved.

Users should take into account the phenomenon of partial shading and the effect it has on energy production in the configuration of solar cells, panels and panel strings.

Likewise, panels should be clear of debris and dust as these environmental factors also effect energy production.

Solar, wind and generator systems are interesting energy technologies, but they are not equivalent. Each features its own benefits and drawbacks that need to be taken into account. It is worth noting that diesel generator systems can basically be run anywhere providing diesel fuel is available for usage. Examples of use include critical services such as life-support equipment and basic operations of a hospital. In mining operations, reliable power is required to control extreme temperatures, provide lighting and keep machines and transport running dependably.

Smart energy systems can make use of the three technologies and combine them into a hybrid system. Solar for the day with turbines to cover the hours that wind energy is available. Generator systems can serve as back-up if the previous two fail. This will ensure smooth and reliable operation with power continuously present.

With the aid of dimensioning software, users can reliably estimate the size of their systems based on their needs. The author intends to use the various tools of the research to continue building a software suite that can cater to inform the common man on energy production, storage and usage in simple and reliable means across solar, wind and diesel generator systems.

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