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An Innovative Microgrid Solution for a Large Housing Development in South Africa

Laurence John Slann

Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Mechanical) in the Faculty of Engineering at Stellenbosch University

Supervisor: Professor J.L. van Niekerk

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Departement Meganiese en Megatroniese Ingenieurswese
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Abstract

An innovative renewable-energy driven microgrid has been developed for a large housing development in the Western Cape of South Africa. The housing project – *Solar City* – is a private development which will eventually consist of 6,000 houses of which half will target low income households and first-time buyers. *Solar City* is aiming to become "the first high tech, sustainable and renewable energy driven city in the world" and to be a good practice model for similar projects in South Africa and beyond. This report has focused on developing an innovative, renewable energy driven smart microgrid with centralised storage for the residential part of *Solar City* and will be provided to the site's developers upon completion for their benefit.

The available renewable energy resources on site – including solar, wind and biomass – have been analysed based on their potential for this project. Energy efficient building practices have briefly been examined in order to help reduce the site's initial energy demand. The microgrid's layout was determined based on previous microgrid pilot programmes and *Solar City's* phases of construction. It was concluded that, in order to match the phased construction of the site, the microgrid would be split into smaller, individual grids.

The overall *Solar City* microgrid will incorporate 530 individual microgrids consisting of distributed, rooftop solar PV modules, centralised Vanadium Redox Flow Battery energy storage systems (VRB-ESS) and smart grid components and it has been assessed from technical, operational and financial perspectives. It was hoped that the microgrid would satisfy the site's entire electricity demand by itself however the cost involved in financing a system of the necessary size has been deemed too high. An affordable 10.78 MWp microgrid has been modelled and additional electricity from the national grid was used to supplement the on-site generation and satisfy the site's demand.

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Nomenclature

AC	Alternating Current
BAU	Business-As-Usual
CPI	Consumer Price Index
CSP	Concentrating Solar Power
c-Si	Crystalline Silicon
DC	Direct Current
DHI	Diffuse Horizontal Irradiation
DNI	Direct Normal Irradiation
EPIA	European Photovoltaic Industry Association
ESCO	Energy Service Company
FIT	Feed-in-Tariff
GHI	Global Horizontal Irradiation
GW	Gigawatt
IRP	Integrated Resource Plan
IDZ	Industrial Development Zone
kW	Kilowatt
kWh	Kilowatt Per Hour
kWp	Kilowatt Peak
MW	Megawatt
MWh	Megawatt per Hour
m/s	Meters per Second
NREL	National Renewable Energy Laboratory
O&M	Operations & Maintenance
PCS	Power Conversion System
PLC	Programmable Logic Controller
PV	Photovoltaic

REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RPP	Renewable Power Plant
SBLM	Saldanha Bay Local Municipality
STC	Standard Test Conditions
USD	United States Dollar
V	Volt
V_{mp}	Maximum Power Voltage
VRB	Vanadium Redox Flow Battery
VRB-ESS	Vanadium Redox Battery-Energy Storage System
W	Watt
ZAR	South African Rand

Chapter 1: Introduction

1.1 Energy Situation in South Africa

Renewable energy, in South Africa as in many parts of the world, is beginning to be earmarked as a major part of the future energy mix. Currently, 91% of South Africa's electricity is derived from large coal mines in the North East prior to being sent via high voltage transmission lines to the rest of the country [Bugaje, 2006]. Furthermore, South Africa is currently the fifth largest producer of coal in the world and is the sixth largest consumer [Greenpeace, 2011]. Having a very large coal resource allowed Eskom, the South African national electricity supplier, to charge consumers very little for electricity in the 1990's and early 21st century in order to provide electrification to as many households as possible after Apartheid [de Groot, van der Veen & Sebitosi, 2013]. Although helpful with aiding development of the country post-apartheid, the low electricity prices have led to many South Africans using electricity unsustainably. This, in turn, has resulted in South Africa being an extremely energy-intensive country and the twelfth highest carbon dioxide emitter in the world [Rogers, 2012]. However, as the coal resource slowly becomes more difficult to mine and with new coal power plants being built, Eskom is having to increase its electricity tariffs relatively sharply in order to fund the investments. Indeed, Eskom recently announced an annual 8% increase on its electricity tariffs for at least the next five years [Eskom, 2013]. This price increase, along with diminishing natural resources and increased consumer energy demand, is slowly making renewable energy more desirable and financially viable in South Africa.

It has been argued that renewable energy systems are not currently sufficiently developed to simply replace existing coal power plants and so their introduction onto the national grid must be gradual [Liserre, Sauter & Hung, 2010]. So far however, there has been little progress with deploying renewables in South Africa and this must change in the coming years to enable the country to continue developing. As such, the South African government recently initiated the Integrated Resource Plan (IRP) 2010-2030 – a detailed report outlining the country's 20-year plan for integrating renewable energy onto the national grid [Department of Energy, 2011]. The report includes goals and targets as well as details as to how these will be achieved and the report will be updated every two years. By 2030, the IRP demands that 9% of South Africa's energy mix be derived from renewables compared to the 0% which renewables represented in 2010. Alongside the IRP report is the Renewable Energy Independent Power

Producer Procurement Programme (REIPPPP) which is also an initiative set up by the South African government. This initiative allows private companies and investors to bid for financial backing from the government for their renewable energy projects on condition that they sell their electricity back to the national grid for a fixed price. The REIPPPP has been designed to contribute to the 3,725 MW of renewable energy which South Africa is targeting to produce in accordance with the IRP 2010-2030 [Department of Energy, 2012]. Along with these initiatives and separate private developments, Eskom is planning to build a 100 MW wind farm and a Concentrating Solar Power (CSP) plant in the coming years. With these movements, it is hoped that renewable energy will begin to gain a significant share of the South African energy mix in years to come.

However, although the resources are available and their potential is known, it is widely agreed that renewable energy systems will never reach their full potential unless the energy they generate can be stored at a large scale when demand is low [Anon, 2013]. Large-scale storage options include pumped storage and compressed air storage systems however many sites lack the necessary geography or the available capital required to install such systems. Batteries are therefore the most common method of storing energy at this moment in time especially for smaller-scale projects. Due to the potential of the battery market for applications such as the renewable energy and electric vehicle industries, more innovative and efficient battery technologies are constantly being developed and released onto the global market. This report will examine South Africa's renewable energy resource and its potential before discussing how to make use of these resources using renewable energy systems and large-scale energy storage to power a residential development.

1.2 Aim and Purpose of Project

As well as the evolving energy mix, another challenge facing South Africa is a lack of affordable housing. Indeed, housing is one of the great infrastructure deficiencies in South Africa as in the rest of the developing world [Ross, Bowen & Lincoln, 2010]. There is a desperate need for affordable housing as well as for electricity in South Africa. As such, this project will attempt to analyse the feasibility of implementing a distributed renewable energy, smart microgrid with centralised storage in order to power a large housing development in the Western Cape of South Africa.

A microgrid incorporates local distributed renewable energy systems and is, in effect, a miniature utility company. Microgrids are connected to the larger macro-grid but have the ability to disconnect from the macro-grid and function autonomously [Asmus, 2012]. Microgrids are seen as a key part of the future energy generation system and a recent study by Pike Research suggests that within the next five years, microgrids will generate a $12.7 billion global industry and be the fundamental building block to the ultimate smart grid and pair naturally with renewable energy generation systems [Settle, 2013]. Whilst various similar developments may exist around the world, no such development has previously been backed in South Africa due to the added capital cost involved with installing a renewable energy microgrid. A significant proportion of South African citizens are unable to afford even the most basic of housing and so this report will not only look into the feasibility of implementing the technical system but will also analyse the financial viability of such a project. The development will generate its power from distributed renewable energy and store excess energy in centralised storage systems. Distributed energy has the potential to "democratise energy, promoting a cultural change in people's attitude to the use of energy and thus helps to stimulate efficient energy use" [No2NuclearPower Briefing, 2007]. Further advantages of using distributed energy include the reduced distribution and transmission losses which result in a higher energy efficiency of the electrical grid as compared to the traditional national electricity network as well as the ability to use local materials, labour and resources. The storage of energy is one of the major challenges facing the renewable energy industry and this report will attempt to find an economically and technologically viable energy storage system for use in a large residential development.

Upon completion, the report and technical and financial models will be presented to the developers of the housing development for their benefit. It is hoped that the groundwork carried out within this project will provide the developers with the information required to decide whether or not to implement such an energy grid.

1.3 Solar City

The housing development which is to be the focus of this project is called *Solar City* and is to be developed on previously used agricultural land strategically located between Vredenburg and Saldanha Bay in the Saldanha Bay Local Municipality (SBLM) in the Western Cape of South Africa. The *Solar City* site is ideally located near the local airport and the area set aside for the development of a new Industrial Development Zone (IDZ) which is anticipated to create tens of thousands of jobs [CK Rumboll, 2012]. Although outside the scope of this project, it is interesting to note that the *Solar City* developers are also planning on creating a renewable energy manufacturing industry and centre of excellence opposite the site. This foresight backs up their statement that the *Solar City* site will contribute heavily to the development of the local area.

Figure 1: Location of *Solar City* Site

Solar City is a sustainable private development with the aim of becoming “the first high tech, sustainable and renewable energy driven city in the world” [CK Rumboll, 2012]. The city is being developed in response to current and future housing demand created by the proposed development of the new IDZ in the surrounding area [Urban-Econ, 2013]. Although the development will eventually incorporate residential, commercial and light industrial buildings, this project has focused specifically on the residential buildings. The developers expect that as much of the city’s energy and electricity demand as possible be satisfied by renewable energy generation systems on site, that the city utilises its domestic waste and that the inhabitants actively pursue energy efficient possibilities. The city will implement its own waste management strategy which it will then aim to incorporate into the surrounding region. It is anticipated that the majority of the required electricity will initially be generated through the use of photovoltaic (PV) modules although all possible options and alternatives will be analysed and discussed. Renewable energy systems will generate electricity which will be used to satisfy residential demand before any excess is stored in centralised energy storage systems. Each house will be equipped with at least one smart meter and smart grid technologies will be implemented throughout the development in order to reduce the site’s electricity and energy demand whilst maintaining high efficiencies.

Solar City currently remains in the planning stage with construction expected to begin in early 2014. Construction of the city will occur in phases with a certain number of houses and buildings being built in each phase. More details of the different phases and how the renewable energy systems, storage systems and smart grid technologies will be implemented within the construction phases will be explained in section 1.4. Upon completion, the city will consist of six thousand houses with half of those being allocated to low-income and subsidised housing. 1,800 houses will be set aside for middle income households with the remaining 1,200 houses being planned for high income households. This provision of in-demand affordable housing as well as the sustainability of the project will benefit the Saldanha Bay/Vredenburg region and help contribute to the development of the surrounding area. The main aim of the project is to analyse how much of the residential energy demand can be satisfied by on-site generation at a reasonable cost and, if required, how much additional electricity must be purchased from Eskom in order to satisfy the site’s demand.

1.4 Construction Phases & Residential Building Information

Solar City is a long-term project and therefore the construction will be phased in over time with the aim of providing economic and financial stability. Four main phases of construction will take place with each phase including a mixture of low, middle and high income houses. The construction of such a development will take into account the economic situation as property sales will be determined by this. Completing the construction in stages allows for times of economic uncertainty and the developers will only proceed with further stages once they are happy that previously built houses are being sold.

As previously stated, one of the major intentions of the *Solar City* developers is to provide affordable housing for first-time buyers and low-income households in particular with half of the planned six thousand houses being aimed at these demographics. An overview of the expected number of houses, the different income levels, the density of units per hectare and the estimated occupancy levels is tabulated in Table 1. This information has been provided by the *Solar City* developers at the end of 2012 and has been used as a basis for this feasibility study. However, it is possible that these figures change slightly over the course of the planning and development stages. In order to cope with any potential change, the technical and financial models have been created in a way that allows for these parameters to be easily altered.

Table 1: Residential Building Information

Income Level	Layout of House	Density (Units/Hectare)	Number of Units	Estimated Occupancy Level (people/house)
Low Income/ Subsidised Housing	3-4 bedroom	35	3,000	5
Middle Income	1-bedroom	25+	250	1
	2-bedroom	20-25	400	2
	2-bedroom	20-25	600	3
	2-bedroom	20-25	450	4
	3-bedroom	20-25	100	4
High Income	2-bedroom	10-15	600	2
	2-bedroom	10-15	200	3
	3-bedroom	10-15	400	4

1.5 Literature Study

There is a strong global backing for renewable energy microgrids to help diversify the electrical grid, reduce CO_2 emissions and electrify rural and remote areas amongst others. In their 2011 report 'The True Cost of Coal', Greenpeace state that "building up clusters of renewable microgrids must be a central tool in providing sustainable electricity to all South Africans" [Greenpeace, 2011]. They go on to say that in order to power large cities, smart interactive girds which are capable of dealing with multiple sources of renewable, intermittent energy sources are essential. In this same report, Greenpeace claim that decentralised energy and smart grids have the potential to "deliver safe, sustainable electricity access and security to all the people of South Africa" whilst arguing that centralised coal power plants have failed to do this [Greenpeace, 2011]. A renewable energy microgrid is one in which, according to the National Renewable Energy Laboratory (NREL) in the United States, renewable energy technologies play the primary role in meeting the energy demand of its residents. NREL state that such renewable energy driven community will incorporate near-zero or zero-energy homes[1], local renewable energy generation and sustainable living practices [Carlisle, Elling & Penney, 2008].

Although *Solar City* aims to become the first "high tech sustainable and renewable energy driven city" in Africa, there are already various examples of

[1] Zero-energy homes are defined by the U.S. Department of Energy as "residential buildings with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable technologies" [Carlisle et al., 2008]

renewable energy driven and sustainable cities and communities around the world. Some cities like Samsø, Denmark and Greensburg, Kansas, U.S.A. are already generating 100% of their electricity demand through renewable energy systems. Both these cities satisfy their entire electricity demand through the use of large onshore and offshore wind turbines [ed. Droege, 2009]. An example of a community which is currently generating more than 100% of its electricity needs through a combination of renewable energy sources is Rhein-Hunsruck in Germany – a district of around 100,000 residents – which incorporates solar, wind and biomass projects into its local grid [Asmus, 2013]. By 2014, the district aims to produce almost 240% of its electricity needs and hence generate significant revenue by selling its excess electricity to the national grid. Although the district has the renewable energy systems in place to generate this electricity, the residents have had to adhere to strict energy efficiency programmes which have reduced the district's energy demand by up to 25% [Asmus, 2013]. Implementing renewable energy systems have the potential to work by themselves, but by incorporating them alongside strict energy efficiency programmes like the ones in Rhein-Hunsruck, the potential for positive results is increased. Interestingly, none of these community examples currently make use of large-scale energy storage systems. Instead they use a combination of renewable sources with back-up diesel generators if required. *Solar City*, by implementing large-scale energy storage onto its electrical network and hence not being required to use a diesel generator, will therefore be a truly unique pilot programme for renewable energy driven communities around the world.

On a smaller scale, and more similarly to *Solar City*, there are villages and small communities which are piloting the use of renewable energy driven microgrids to satisfy their energy demand. Sonoma Mountain Village in California [Carlisle et al., 2008] for instance has incorporated a 1.14 MW centralised solar PV plant along with other sustainable living practices in order to satisfy the majority of its energy demand. Interestingly, there are also many examples of renewable energy driven microgrids being used to power military bases particularly in the United States of America. For example, the Joint Base Pearl Harbour – Hickam military base in Hawaii has seen a 146 kW solar energy system and 50 kW of wind power added to the existing renewable energy systems already on site [Settle, 2013]. The Fort Bragg military base in North Carolina, U.S.A. is another example of a military base with a renewable energy driven microgrid. Here, the base has its own electricity distribution network and monitors the various generation systems through its energy management centre [Galvin Electricity Initiative, 2011].

Globally, initiatives, policies and incentives are being launched in order to accelerate the development of renewable energy and smart microgrids. The most common, and arguably the most effective policy with regards to supporting the introduction of renewable energy is the feed-in-tariff (FIT) scheme [Pegels, 2010]. The feed-in-tariff scheme has been successfully applied in more than forty countries worldwide and the idea is that a feed-in-tariff guarantees producers of renewable energy a fixed tariff for power over a certain period of time [Pegels, 2010]. Since the revenues are known and guaranteed in advance, the investor is able to cover their costs as well as earning a reasonable return on their investment. The REIPPPP scheme which has been introduced in South Africa is indeed based on successful FIT schemes which have been implemented around the world.

Additionally, the European Commission has recently launched a ‘Smart Cities Initiative’ which aims to transform up to thirty European cities into low carbon cities by 2020 [EPIA, 2011]. The concept of a ‘smart city’ is one which the European Photovoltaic Industry Association (EPIA) is actively promoting and they expect solar cities and solar islands to be developed throughout Europe in the coming decade. These, they hope, will “demonstrate the many options for large-scale integration of solar PV in urban and remote environments” [EPIA, 2011] which is exactly what *Solar City* is attempting to achieve. Similarly, the South African government has stated that it will actively support private investment in renewable energy and other clean technologies [Pegels, 2010] which suggests that *Solar City* will receive political and economic backing from its government.

There are however sceptics with regards to the potential of implementing renewable energy driven microgrids for entire cities and districts. Peter Lilienthal of HOMER Energy argues that implementing 100% renewable microgrids for entire cities or communities is too expensive and currently unnecessary [Asmus, 2013]. Without doubt, one of the main barriers to the implementation of renewable energy systems and microgrids is the cost involved, but with the price of PV modules in particular set to reduce in the coming years and the price of fossil fuels increasing, it is expected that renewable energy driven microgrids will flourish [Martin, 2013].

Aside from the technical advantages of implementing renewable energy microgrids, extensive research has been carried out with respect to the social benefits achieved by such microgrids. Since the renewable energy industry in Africa is still young and fragile, should South Africa invest in its local renewable energy industry then it has the potential of becoming Africa's renewable energy manufacturing hub [Greenpeace, 2011] which would result in significant job creation in South Africa. Pilot programmes such as *Solar City* are indispensable with respect to developing the local industry. Furthermore, as previously touched on, *Solar City's* developers are planning on creating a renewable energy excellence and technology centre opposite their housing development in order to promote the renewable energy industry and to train local people into becoming renewable energy specialists.

1.6 Energy Efficient Residential Buildings

Other examples of renewable energy community projects have shown that improving buildings' energy efficiency can lead to a significant reduction in energy demand which, in turn, results in less electricity needed to be generated by renewable energy sources. Rhein-Hunsruck for example, as briefly explained in section 1.5, focused on implementing energy efficient building improvements which resulted in a 25% reduction in heating demand, a 5% reduction in electricity demand and a 26% reduction in water demand with carbon dioxide emissions being cut by 5,400 tons [go100percent, 2013]. One particular example of what effective home design can do is to reduce the energy demand of a building by incorporating passive solar design whilst taking into account natural ventilation and shading [Carlisle et al., 2008]. With *Solar City* aiming to be a sustainable city, the project developers are keen to promote energy efficiency practices during construction and throughout the lifetime of the development. Since construction of the site has yet to begin, the developers have the opportunity to design and construct the residential buildings to be as energy efficient as possible. The developers must communicate effectively with architects and builders to ensure that the proposed energy efficient designs are adhered to. Although outside the scope of this report, certain energy efficient residential building design methods will briefly be mentioned.

There are a number of basic energy efficient building methods and many of these have been well documented. For instance, it will be important to ensure that as many as possible of the homes have a north-facing roof on which PV modules may be installed. This will ensure that the PV modules face as much of the sun as possible throughout the year. Positioning of windows, ensuring the houses are insulated whenever possible and other such energy efficient building methods must also be employed. Information regarding passive ventilation, solar heating and insulation as well as other energy efficient design practices is readily available but will not be explained in great detail in this report. Other sustainable practices which may be incorporated into the *Solar City* residential building plans are the recycling and conservation of rainwater and the design of the site with regards to reducing the need for vehicle use as outlined by *Solar City* developers in an initial structure plan report [CK Rumboll, 2012]. All these factors must be looked into by the site developers if they are determined to achieve their goal of making *Solar City* the first sustainable, renewable energy-driven community in Africa.

Chapter 2: Methodology

2.1 Overview

Technical and financial models have been created in order to simulate the electricity generation and consumption of the *Solar City* site as well as the costs involved with such a system. However, before any modelling could be done, various background research and information had to be gathered. First of all, the renewable energy resources available at the *Solar City* site were analysed for their suitability. All renewable energy resources were considered including solar, solar thermal, wind, hydro and biomass. Once these steps had been covered, the potential technologies involved in the renewable energy systems, local electricity network, smart grid components and the storage of the generated electricity were researched. Since construction is due to begin in early 2014, it was agreed by all parties that only technologies available on the world market today would be considered for this report. The chosen technologies and products will be detailed in this section and reasons for these choices will be provided. Clearly however, as new technologies enter the global market in the coming years, the developers of *Solar City* may be able to retro-fit the buildings built in the initial phases of the development.

2.2 Available Renewable Energy Resources

The renewable energy resources available at and around the *Solar City* site were analysed for the purpose of this report. The solar resource is arguably the renewable resource with the greatest potential in South Africa. With respect to solar PV power, the Global Horizontal Irradiation (GHI) calculation (in kWh/m^2) is the most important parameter when calculating solar PV electricity yield. GHI takes into account all the Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiation (DHI). The majority of the country receives an average GHI of more than 1800 kWh/m^2 per year with some parts of the Northern Cape receiving more than 2600 kWh/m^2 per year as per the solar irradiation map in Figure 2. The Saldanha Bay/Vredenburg region in particular receives an average GHI of around 2150 kWh/m^2 per year which is greater than most parts of the U.S.A. and Europe.

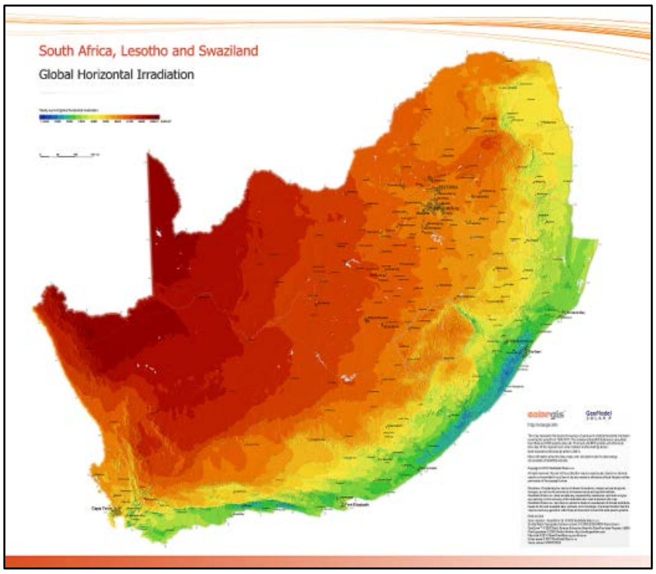

Figure 2: Global Horizontal Solar Irradiation Map of South Africa [GeoModel Solar, 2012]

As the name *Solar City* suggests, the site developers have a strong preference that solar technologies be used to power as much of the site as possible and Figure 2 suggests that the solar resource in the Saldanha Bay region is strong enough to do exactly that. However, to ensure a balanced report and for the purpose of analysis, all renewable resources have been considered.

2.2.1 Solar Resource

Global solar energy has the potential to comfortably supply the entire world's energy demand [EPIA, 2011]. Captured efficiently, solar energy is an extremely useful and powerful renewable resource and South Africa has one of the strongest solar resources in the world. As seen in Figure 2, the Western Cape has a very strong solar resource and the *Solar City* developers wish to harness and use this energy. In the long-term, the *Solar City* developers wish to analyse the feasibility of installing a CSP plant on site but that technology is very new and no such plant currently exists in South Africa. For financial and technological reasons therefore, a CSP plant may not, for the time being, be considered as a suitable electricity generation source at *Solar City*. As such, it has been decided that the initial microgrid will be supplied, at least in part, with electricity generated by roof-mounted PV modules.

GeoModel Solar's *SolarGis PVplanner* software has been used to analyse and determine the photovoltaic potential at the *Solar City* site. The results obtained from the software can be found in Appendix A. In short, the results showed that the annual global in-plane solar irradiation at the *Solar City* site totalled 2229 kWh/m^2 using an inclination of 29° with an azimuth angle of 0°. Using typical crystalline silicon (c-Si) PV modules at an inclination of 29° and taking into account the inverter and Direct Current/Alternating Current (DC/AC) losses, 1kWp of installed PV power would produce, on average, 1793 kWh annually. These results confirmed that a PV power system would be able to generate considerable and reliable levels of electricity throughout the year.

Although the solar resource assessment using GeoModel Solar's *PVplanner* software used historical solar data the results can be taken as a good indication of future yields as solar irradiation tends not to vary significantly from year to year. While this assessment is extremely useful for obtaining a good idea of the potential solar energy has at a particular site, for a report such as this which requires in-depth solar data it is necessary to examine hourly solar data. As such, hourly solar irradiation data for the Saldanha Bay region in 2011 has been used to calculate the expected PV electricity yield for this project. The hourly solar resource data has been provided by MINES ParisTech using the HelioClim-3 Database of Solar Irradiance v3 which is derived from satellite data. In this case, an assumed inclination of 30° has been used and the dataset runs from January 1, 2011 to December 31, 2011.

2.2.2 Other Renewable Energy Resources

Although the *Solar City* developers favour solar energy, the availability of other renewable energy resources at the *Solar City* site has been considered. The renewable energy resource other than solar with the most potential for use at the *Solar City* site is arguably wind energy. The Western Cape is subjected to a yearly average wind speed of 6 meters per second (m/s) [Urban-Econ, 2013] which is strong enough to make engineers look into the possibility of installing wind farms in the area. Additionally, with the *Solar City* site being very close to the Atlantic Ocean, there can be strong winds passing over the site. Also, the development site is situated on the crest of a hill which is well positioned for wind turbines to catch the strong winds coming in from the Atlantic. Although the project developers are not keen on large wind turbines being used on the residential part of the site, the option of using a few wind turbines alongside solar energy is one worth pursuing. An energy mix has the potential to be more reliable than using only one source of energy. As such, historical wind data for 2011 was obtained from the Langebaanweg weather station located just a few kilometres from Saldanha Bay and the proposed *Solar City* site. The historical wind data from Langebaanweg weather station demonstrates that there is potential for the use of wind turbines. Monthly temperature, humidity and wind speed averages are summarised in Table 2 below.

Table 2: Monthly Wind Data at Langebaanweg for 2011

Month	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (km/h)	Mean Wind Speed (m/s)
January	22.20	59.90	16.08	4.46
February	20.79	60.10	16.83	4.67
March	20.21	62.74	15.20	4.22
April	17.80	60.76	14.64	3.93
May	13.59	73.19	10.06	2.79
June	12.41	75.80	11.32	3.14
July	11.69	73.09	11.17	3.11
August	11.12	73.45	12.27	3.41
September	13.25	69.63	10.51	2.92
October	16.27	59.90	15.82	4.39
November	18.20	58.03	16.12	4.47
December	21.65	58.74	15.63	4.34

Interestingly, there is a correlation between wind data in Table 2 and the solar data in Appendix A. Both resources peak during the summer months which is to be expected in the Western Cape of South Africa. This suggests that during the summer months, the site's energy demand has a higher chance of being satisfied by renewable energy sources than during the winter when demand is greater and the resources are weaker. It can therefore be expected that, during the winter, a greater amount of additional electricity may be required from Eskom.

Unfortunately the *Solar City* site is not suitable for any means of on-site hydropower and is too far away from the sea to consider making use of wave or tidal power. There is however, much potential for using biomass as a renewable energy resource on site. Biomass is the oldest form of renewable energy and would be suitable for use at *Solar City* due to the surrounding farm land which could provide much of the necessary resource. As explained, the *Solar City* developers are committed to encouraging sustainable living practices and making use of rainwater and the site's natural waste and making use of biomass energy most certainly falls within this bracket. All these factors could be used alongside the solar and wind resources to help satisfy the site's electrical and heating demand.

2.3 Electricity Generation

After discussion with the developers regarding their preferences and careful consideration of the available renewable resources and electricity generation methods, it was decided that solely PV modules would be used to generate the electricity on site. Although it is widely agreed that a combination of electricity generation sources will result in a more reliable electrical grid, only solar PV will initially be installed at *Solar City*. Since the *Solar City* developers do not want to install large wind turbines on site the option of harnessing the generous wind potential on site has been negated at least for the residential part of the development. This will, however, always remain an option for the site's developers to pursue in the future if their mind-set changes. Additionally, the use of biomass as a form of generating electricity is an option although it would only be supplementary and whilst may be planned for is not a focus of this report. The potential of using biomass to generate electricity or heat energy is more easily calculated once the site has been completed and is inhabited. Furthermore, the cost of centralised control and communication systems for small microgrid networks are much more expensive for hybrid systems that single-source systems [Liserre et al., 2010]. Thus, solar PV, for the time being, has been chosen as the sole source of generating electricity at *Solar City*. It is important to note that whilst it will be the only form of electricity generation, it will be run alongside stringent sustainable and energy efficient practices.

As previously explained, the South African solar resource is one of the best in the world and the *Solar City* developers are keen to harness this resource. Although CSP technology may be the more efficient and powerful solar energy generation method in the future, for the time being, especially on a small scale such as *Solar City*, solar PV is definitely the most suitable electricity generation method. The PV industry is mature and solar PV power is already widely used for residential purposes in South Africa and worldwide. Furthermore, the global PV market has seen massive growth over recent years. Since 2008, the global PV cumulative electricity capacity percent increase from the previous year has been above 60% every year with a peak of 90% in 2010 [Gelman, R., 2011]. A key factor for this sharp rise in installed capacity is that solar PV technology costs have declined over recent years and further cost reduction methods are constantly being explored. A 2011 joint research report between Greenpeace and the EPIA found that, in some areas, unit costs of PV technology had been reduced to one third of where they were five years previously and that historically, PV module prices have reduced by around 22% every time the global cumulative installed capacity has doubled [EPIA, 2011]. Indeed by 2020, solar PV is expected to be financially competitive with retail electricity prices without subsidies for many regions worldwide [Gauntlett, 2013]. Figure 3 illustrates the forecasted growth of the solar PV market in each continent. Africa has very little installed solar PV capacity in 2013 compared to other continents and only begins to register on the chart in 2014. By 2020 though, it is expected and hoped that there will be in the region of 4 GW of installed solar PV capacity within the African continent and South Africa will most likely play a major role in achieving this.

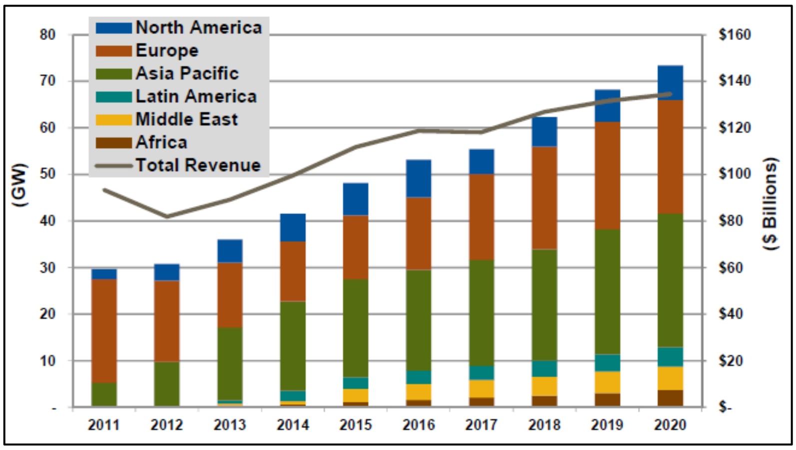

Figure 3: Solar PV Global Market Growth 2011 – 2020 [Gauntlett, 2013]

As well as its potential for generating electricity and capturing the great solar resource available in South Africa, solar PV power has many additional benefits. PV is a decentralised and distributed source of energy. One major advantage of generating electricity close to where it will be consumed is the reduction in distribution and transmission losses compared to traditional centralised electricity generation. The EPIA state that by significantly reducing grid losses in Europe the added value of PV would be approximately 0.5 €ct/kWh [EPIA, 2011]. Furthermore, experience of using PV modules in and around residential buildings is very strong which will enable engineers to efficiently configure the PV power system as well as being able to maintain the modules using local skills and knowledge. Another advantage of PV power for use at *Solar City* is its flexibility. A different number of PV modules can be installed on each house based on their predicted electricity usage which is useful for this project as different income levels and house types will be accommodated. Moreover, the modules are able match the construction of the site as they can gradually be installed whereas if the site were to implement a CSP plant for instance, this would not be the case – a large CSP plant with a very high capital cost would have to be built at a time when there would be few houses occupied on site and thus a low energy demand.

As stated, the proposed *Solar City* electrical grid will be laid out in the form of a microgrid. A microgrid can be defined as an “integrated energy system consisting of distributed energy resources and multiple electrical loads operating as a single, autonomous grid either in parallel to or islanded from the existing utility power grid” [Asmus & Wheelock, 2012]. In effect, a microgrid is essentially a small-scale version of the traditional power grid. Since microgrids are small-scale power grids, “they result in fewer line losses, a lower demand on transmission infrastructure and they rely on localised sources of power generation such as solar or wind energy” [Asmus & Wheelock, 2012]. The microgrid market is slowly beginning to grow in size due to the success of a few pilot programs, the increased need to integrate renewable energy onto the electrical network and the decreasing costs of renewable energy technologies such as solar PV modules [Lawrence, Asmus & Lauderbaugh, 2013]. By designing *Solar City*’s electrical network as a microgrid, the site will be able to function autonomously from the national grid which means that the site will not be affected by national power cuts or outages which may occur more regularly in the future as Eskom’s small reserve margin is put under even more pressure. Also, it means that additional electricity can be purchased from Eskom and bought directly onto the site’s electrical grid through the connection point if required.

2.3.1 Module Type

PV modules are a made up of a collection of solar cells of which there are three main types – monocrystalline, polycrystalline and thin film. PV modules manufactured using the different cell types differ in price and efficiency. Monocrystalline modules tend to be around 15% efficient on average but are more expensive than polycrystalline modules which have efficiencies of around 13%. Thin film amorphous solar cells tend to be the cheapest but have much lower efficiencies. There are a host of PV modules available on the world market and, apart from the wattage, are all very similar. As such, PV modules tend to be distinguished and chosen based on their performance warranty, ease of replacement and maintenance, and their compliance with local electrical and building codes [Keyhani, 2011]. It is also important to choose a single specific type of PV module for use throughout the development since a PV system’s efficiency will drop significantly if there is a mismatch in module power output [Liserre et al., 2010]. The PV modules chosen for use in this project are Kyocera

KD245GH-PB, 245 watt polycrystalline modules which are readily available in South Africa and worldwide. They are available in South Africa with a five-year warranty and a performance guarantee of 10 years on 90% of the specified power under standard test conditions (STC) and 20 years on 80% of the power under STC [Kyocera Solar, 2011]. Although they are polycrystalline modules, they have a module efficiency of 14.8% with a surface area of 1.64m^2. The Kyocera KD245GH-2PB's relatively high efficiency is one of the main reasons behind it being chosen as the PV module for use in this project along with its generous warranty and performance guarantees and availability. The modules are available from various distributors around South Africa with prices ranging from around ZAR 4,000 to ZAR 5,000. However, it is fair to assume that when purchasing these modules in bulk, the *Solar City* site developers will be afforded discounted prices. The price of a single Kyocera KD245GH-2PB module in the financial model for this report has been set at ZAR 4,815 as taken from KG Electric's – a South African solar energy supplier – January 2013 price list [KG Electric, 2013]. As with global PV module prices, it is fair to assume that these prices will fall over the coming years as the market matures and develops. This would mean that modules would become more affordable as the *Solar City* site develops. For the purpose of this report however, the price of the modules have been kept constant for all houses at all stages of construction.

2.4 Grid Technologies

PV modules capture the sun's energy and generate DC electricity which must be converted to AC electricity prior to use with domestic appliances. Inverters are used to complete this conversion and can be located very close to the modules in order to reduce transmission and distribution losses. The power outputs of multiple PV modules are collected by a single, correctly sized inverter. Since a single PV module creates a small power output and voltage, PV systems are typically composed of many PV modules in series or parallel in order to generate sufficient voltage and current levels creating what is known as a PV array. Similarly to PV modules, there are many manufacturers and types of inverters available on the world and South African markets suitable for microgrid applications. Arguably the global leader in the development and production of PV inverters is SMA Solar Technology AG and they have extensive experience with islanded renewable energy projects. SMA has a large presence in South Africa with a headquarters in Pretoria and their products are widely available from most renewable energy distributors. Having a headquarters in Pretoria, there is extensive service support available which will undoubtedly be important considering the amount of equipment which will be required in a project the size of *Solar City*. Being aware of the technical requirements of the South African grid has allowed SMA to ensure that their inverters meet the requirements of the "Grid Connection Code for Renewable Power Plants (RPP's)" [SMA Solar Technology AG, 2013]. This knowledge of South African requirements, along with their wide range of products and global experience are the reasons that SMA inverters have been chosen for this project. Since different houses will be fitted with a different number of PV modules, there will be varying levels of voltages being generated. As such, depending on the voltages produced by the rooftop PV modules, different sizes and specifications of SMA inverters will be required. DC/AC solar inverters will be located at each house and there will be additional AC/DC battery inverters located near to the centralised energy storage systems in order to convert the AC electricity back into DC electricity suitable for storage. The number of AC/DC battery inverters will depend on the predicted peak power and this will vary according to the number of houses connected to each storage system.

As well as the PV modules and inverters, smart residential electricity meters will be installed within the *Solar City* electrical network in order to increase the site's energy efficiency, grid reliability and to reduce electrical losses. Smart electricity meters allow for automatic two-way communication between the home and the energy provider – in this case the *Solar City* Energy Service Company (ESCO). A key benefit of using smart electricity meters is their ability to effectively control and meter the electricity being generated by renewable energy systems. Currently, the smart meter market is entering a low growth phase after previous years of high growth mainly due to large-scale rollouts in the USA [Borska, 2012] but their deployment is expected to continue over the next few years. Navigant Research estimate that 131 million smart electricity meters will be deployed worldwide by 2018 as the renewable energy industry continues to grow. For the purpose of this project, Landis+Gyr E450 smart residential electricity meters have been chosen based on their availability on the global market but also due to Landis+Gyr's reputation. The E450 is compatible with the electrical network which will be installed at *Solar City* as is capable of being modified for various incoming sources. As such, the E450 meter is an all-round, sustainable and high-quality electricity meter and has been chosen for this project based on these merits.

Smart electricity meters are arguably the backbone of a "Smart Grid" – they meter and control the flow of electricity from the home to the utility and this flow can be controlled automatically by a smart communications hub. One such communications hub is Petra Solar's SunWave Communicator which can communicate with up to fifteen separate smart meters. The SunWave Communicator regulates the flow of electricity between the houses and the utility whilst also ensuring that enough electricity is being generated and supplied when required. The *Solar City* ESCO will be able to examine the data obtained by each SunWave Communicator device in order to control the site's electricity supply and demand status and thus know when to purchase additional electricity from Eskom.

Controlling the many separate parts of a microgrid is extremely important. Should the PV modules, inverters and smart meters not be properly controlled, the microgrid may become unstable and even fail [Liserre et al., 2010]. However, by using central communications hubs such as the SunWave Communicator along with the smart residential electricity meters, *Solar City's* electricity network controllers should be able to effectively manage the flow of electricity throughout the site. Indeed, a smart microgrid has the potential to achieve higher availability and quality compared to the conventional method of generating electricity through effective control and monitoring. Furthermore, the microgrid's security can be improved by reacting to short-term demand variations and dispatching electricity to those users who require it [Liserre et al., 2010]. The communication systems must be able to make effective, split-second decisions in order to retain the microgrid's reliability since renewable energy sources are intermittent and their power outputs change constantly. Implementing effective control of a smart microgrid has the potential to therefore achieve higher availability and quality compared to the conventional power generation system as well as improving grid security and reliability.

2.5 Energy Storage

One of the main stumbling blocks towards implementing large-scale renewable energy systems is the fact that it is currently very difficult, and relatively inefficient, to store energy on a large-scale. Indeed, it is widely agreed that without more efficient large-scale energy storage, renewable resources will never fulfil their potential. It can be argued that, once it becomes possible to store electricity efficiently, all the arguments against using renewable energy due to capacity and productivity issues lose their sway [Scheer, 2005]. However, as set out at the beginning of this project, only technologies which have been thoroughly tried and tested and are currently available on the world market will be considered for use in *Solar City* and so new, innovative and un-tested energy storage solutions have not been considered. Currently, the most efficient ways of storing large-scale electricity are in the form of pumped hydro or compressed air storage schemes. However these schemes require extremely large areas of land and the correct geography. Furthermore, as electricity generation is being decentralised, it is equally as important that decentralised energy storage systems are developed. Therefore, much work is being carried out on new storage technologies and batteries in particular. At this moment in time, the most common battery used for PV applications is the flooded lead-acid battery [Stine & Geyer, 2001]. Although the lead-acid battery is a proven and mature technology, it is not ideal for storing renewable energy since they have low energy densities, short life spans and do not cope well with repeated charge-discharge cycles [Lindley, 2010]. As such, new battery technologies have been, and are being, developed specifically with a view to being used alongside renewable energy systems and microgrids in particular.

One such technology is redox flow batteries. Redox flow batteries store and discharge energy through a reversible electrochemical reaction between two electrolytes [Baxter, 2006]. These batteries are typically comprised of cell stacks, electrolyte tanks, a control system and a power conversion system (PCS). Arguably, the main advantage of flow batteries is their flexibility – the power and energy ratings of flow batteries are independent of one another which mean that the power output can be increased by adding further cell stacks whilst the energy capacity can be increased by expanding the electrolyte tanks [Baxter, 2006]. This flexibility results in flow batteries being one of the most promising types of batteries for intermittent grid storage at this moment in time [Ross, 2013] since they can be sized and designed appropriately for many different applications and projects.

One type of flow battery is the Vanadium Redox Flow Battery (VRB) which operates with V(4+)/V(5+)/V(3+)/V(2+) redox couples [Hawkins & Robbins, 2001]. The VRB has been said to be one of the “most promising electrochemical energy storage systems deemed suitable for a wide range of renewable energy applications” [Parasuraman et al., 2012]. This technology has been around for a couple decades and the VRB Energy Storage System (VRB-ESS) has been patented by Prudent Energy – a Chinese Energy company – and is currently the most commercialised redox flow battery used for large-scale energy storage [Kear, Shah & Walsh, 2012]. VRB systems have high capacities, independent power and energy ratings, a cycle life of greater than 100,000 cycles and round-trip efficiencies of between 70 and 80% [Rahman, Rehman & Abdul-Majeed, 2012]. It is the VRB systems' efficiency which is one of the main stumbling blocks slowing their commercial development. It has been argued that if the efficiency of an energy storage technology is less than 75%, then the PV module system will have to be over-sized by up to 25% [Brunet, 2011]. Even so, VRB systems have been trialled and adopted commercially for renewable energy applications in many countries including Australia, the United States, Germany, China and also South Africa. Indeed, a 250 kW/520 kWh VRB system was trialled at the University of Stellenbosch, South Africa in 2001 [Hawkins & Robbins, 2001]. This particular trial resulted in a round-trip efficiency of 78% for the VRB-ESS which is relatively high considering the efficiencies found in other literature.

Prudent Energy supply VRB-ESS systems in 10-kW rated cell stacks which allows for the assembly of modular, flexible systems. Each VRB-ESS is controlled by a Programmable Logic Controller (PLC) which controls the times and rates of charging the system [Prudent Energy, 2012]. Additionally, Prudent Energy's VRB systems make use of local parts, supplies and labour during construction and operation which would fit in well with *Solar City*'s wish to use local labour and skills where possible. Although these batteries are technically suitable for use within the *Solar City* microgrid, they may be too expensive to use. Various costs have been published and Prudent Energy has suggested the use of $500/kWh as a benchmark price for the financial model for this project (Price suggestion as of October 2012). Other publications have stated the cost of VRBs at around $0.08/kWh per cycle [Kumar, 2012] to $620-740/kWh [Crabtree et al., 2011]. This cost, as with any new technology, will eventually drop to more affordable prices and it is expected that VRB systems will play a major role in integrating renewable energy into the current electricity grid. Although the cost of these systems may still be too high, this feasibility project will attempt to use VRB systems as the storage option at *Solar City*. A thorough financial model will be created to allow the site developers to determine if VRB-ESS's are financially viable for this application or not.

Chapter 3: Technical Model & Results

3.1 Overview

Although *Solar City* will eventually be comprised of 3,000 low income, 1,800 middle income and 1,200 high income houses, construction of the site will be completed in stages. In order to more closely match the gradual development of the site, the technical model has broken the site into ‘blocks’ of houses. Blocks of houses will be comprised of solely low income, middle income or high income houses in order to model the fact that similar income level houses tend to be built close together. Individual microgrid networks have been designed for each block of houses with the expectation that upon completion, each separate microgrid will join together to form a combined *Solar City* site microgrid. Two simulations were run per income level in order to analyse the effect of implementing different system sizes.

Each house will be allocated a certain number of roof-mounted PV modules based on its income and occupancy levels and forecasted electricity demand. The electricity generated by these modules will be converted from DC to AC electricity by an SMA inverter within the house before satisfying the domestic loads at that moment in time. At this point, any excess electricity will be sent to the block’s communal VRB-ESS via SMA battery inverters which convert the AC electricity back into DC electricity for storage. When the generated electricity does not satisfy the houses’ demand, electricity will be discharged from the VRB-ESS and the process reversed. Smart meters will be used to meter the electricity flow at three different points throughout the process. The electricity generated by the roof-top modules, the electricity remaining after loads are satisfied at the houses and the incoming and outgoing electricity at the communal VRB-ESS will all be metered separately. By metering the electricity flow at each of these stages, the electrical grid can be effectively controlled and monitored.

Although the PV modules, inverters and smart meters will all be installed in and around each house and be paid for by the homeowners, they will not own the equipment. Instead, the equipment will belong to the *Solar City* ESCO and the homeowners will receive shares in this company when they pay for the system. The homeowners will also receive a pre-determined amount of electricity per month which they may use free of charge. Homeowners will be allowed to use as much of this amount as they require and will be credited for using less than this limit. However, should they exceed the limit, the ESCO will charge the homeowners per extra kWh used. The benefits of implementing this system include encouraging energy efficient practices whilst also raising important finances for the ESCO which is responsible for maintaining the electrical grid in working order. The amount of PV modules, type of inverter and electricity allowance will vary depending on the type of house and income level. For instance, a high income household will receive a higher monthly electricity allowance and more PV modules but will have to pay a higher initial cost and higher monthly costs than a low income household.

If the site's electricity demand is not met through the use of renewable energy resources, additional electricity will be purchased from Eskom at utility rates. This is possible since the *Solar City* microgrid will be connected to the national grid. Since electricity storage will be available, the *Solar City* ESCO will be able to purchase any necessary additional electricity from Eskom overnight when electricity prices are at their lowest. The purchased electricity can then be stored on-site for a certain number of hours and used the next day during peak times or at times of shortage. Being able to purchase additional electricity from Eskom prior to it being needed is only possible with effective control, monitoring and planning of the electrical grid which is why two-way communication hubs and smart electricity meters will be implemented within the microgrid.

Since construction of *Solar City* has yet to begin, there are many technological and logistical details which are as yet unknown. Various assumptions have thus had to be made in order to create a model which can generate useful results. These assumptions are listed below and any extra detail, if required, has been provided.

- Summer months: October – April; Winter months: May - September
- VRB-ESS Round-Trip Efficiency: 75%
- All the houses in one block will be constructed at the same time
- Energy demand load profiles were created and forecasted for each house and income level

In order to calculate how much electricity must be generated on-site, the site's electricity demand first had to be forecasted. With *Solar City* being a sustainable development and promoting energy efficient practices and behaviours, it cannot be classed as a business-as-usual (BAU) case. It would therefore be unsuitable to use standard electricity consumption levels for typical households. As such, energy demand load profiles have been created based on previous research, communication with *Solar City* developers and knowledge of the local area. Although forecasting the energy demand is necessary, projected energy demands often deviate from the actual demands due to limitations in the model or unsuitable assumptions [Bhattacharyya & Timilsina, 2009]. Indeed, a 2002 study found that the majority of projected energy demands in the United States overestimated demand by up to 100% [Bhattacharyya & Timilsina, 2009]. Keeping in mind the limitations of forecasting energy demand load profiles, a selection of load profiles were created for each income level, with different profiles for different occupancy types and work patterns as well as for summer and winter seasons. Considering the many potential factors affecting energy demand load profiles, the forecasted demand models used within the technical models can easily be modified should more concrete data become available.

Twenty-nine different load profiles were created and their details can be found in Table 3 and the daily profile plots in Appendix C. The work patterns selected are based on the most common household occupancy patterns and a combination of these was chosen per income level. As expected, the energy demand in winter is greater than that in summer and demand peaks tend to occur in the morning and the evening both of which are outside the period during which PV modules generate their maximum electricity. It is precisely for this reason that energy storage is so important for solar PV applications.

Table 3: Type and number of Load Profiles

Income Level	Layout of House	Number of Units	Estimated Occupancy Level (people/house)	Work Patterns
Low Income/ Subsidised Housing	3-4 bedroom	3,000	5	At work 08:00 – 17:00
			5	At home all day
			5	At work 06:00 – 13:00
			5	At work 13:00 – 20:00
			5	On holiday all day
Middle Income	1-bedroom	250	1	At home all day
	2-bedroom	400	2	At work 08:00 – 17:00
	2-bedroom	600	3	At work 08:00 – 17:00
				At work 06:00 – 13:00
	2-bedroom	450	4	At work 08:00 – 17:00
	3-bedroom	100	4	At work 06:00 – 13:00
High Income	2-bedroom	600	2	At work 08:00 – 17:00
				At work 13:00 – 20:00
	2-bedroom	200	3	At work 06:00 – 13:00
	3-bedroom	400	4	At work 08:00 – 17:00

Figure 4 illustrates the average seasonal energy demand per house type and it has been used to determine the monthly household electricity allowances. Electricity allowances were selected based on the electricity usage of each house but, as with the energy demand load profiles, these limits may be altered by the *Solar City* developers. Low income households will receive an allocation of 220 kWh per month whilst the middle and high income households will be allocated 450 kWh and 500 kWh per month respectively. The *Solar City* developers could implement more aggressive electricity limits in an attempt to make *Solar City's* residents even more energy efficient or to raise more income from electricity charges but for the purpose of the models in this report, the aforementioned limits have been used.

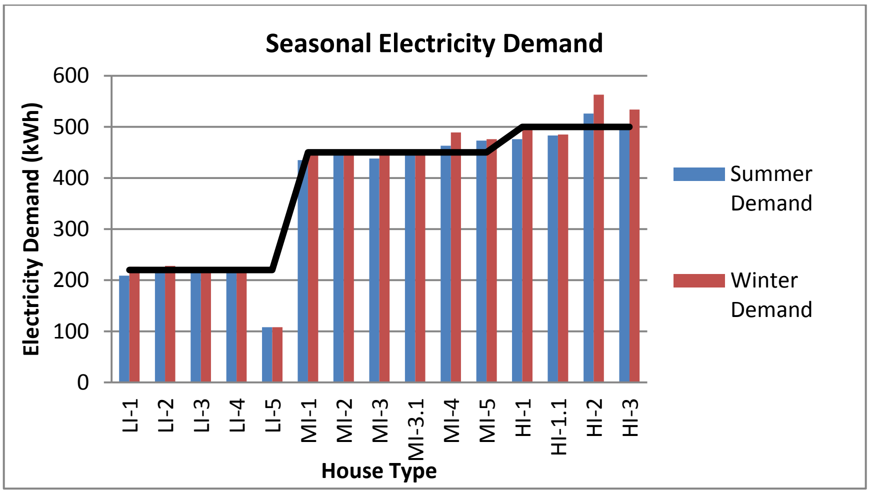

Figure 4: Seasonal Electricity Demand

Once the energy demand load profiles were obtained, it was possible to build the power generation models. As previously stated, slightly different simulations were run for each block of houses and these models will be explained in further detail in the following sections.

3.2 Low Income Blocks

The low income block model is arguably the most important with respect to this project since it is mainly low income homeowners and first-time buyers which *Solar City* is targeting. The developers wish to provide affordable homes for up to 3,000 families who are classified as low income households. It is therefore essential that these houses are as affordable as possible and that the PV power generation system does not add too significant a cost to the overall price of the house. Two low income block simulations were run: one with four PV modules and one with five modules per house.

3.2.1 Low Income Block Option 1

The first block option was comprised of twenty low income houses with four PV modules per house equating to eighty modules per block. The power generation system for this block has been set out as follows: four roof-mounted PV modules capture the solar energy and convert this to DC electricity which is directly converted to AC electricity by an SMA Sunny Boy 1200 inverter located close to the modules. The four modules create a maximum power voltage of 59.6 V_{mp} which is converted to the standard 230V by the inverter. The AC electricity satisfies the domestic loads at that moment in time before any excess is sent to the communal VRB-ESS via four SMA Sunny Island 5048 inverters which convert the AC electricity back to DC for storage. In order to be stored at the VRB-ESS, the communal battery inverters convert the 230V AC electricity to 48V DC electricity. The electricity is metered after it has been through the DC/AC inverter, after the real-time domestic loads have been satisfied and prior to going through the AC/DC battery inverters. This entire process is controlled and monitored by a SunWave communications hub. A wire diagram of the block's electrical layout, as well as those for all other block options, can be found in Appendix D. Datasheets for all equipment used in this block option, as well as all options yet to be discussed, can be found in Appendix B.

Eighty 245W modules per block equate to a 19.6 kWp PV system or 0.98 kWp per house which will generate just under 42.9 MWh/year before taking into account the process' losses. However, the anticipated electricity demand for this block is just over 50.5 MWh/year. Therefore, additional electricity will have to be purchased from Eskom in order to make up this deficit. Due to the process' various efficiency losses, a total of 23.15 MWh/year will have to be purchased from Eskom in order to completely satisfy the block's demand. Essentially therefore, a total of 66.05 MWh/year of electricity is required to satisfy the 50.05 MWh/year demand which results in a system efficiency of 75.7%. The reason for such an efficiency level is mainly attributable to the VRB-ESS which has been simulated as having a round-trip efficiency of 75%.

The peak battery capacity over the course of the year has been calculated to be 96 kWh and the peak electricity demand calculated at 42 kW. Taking these results into consideration, a 50 kW/130 kWh VRB-ESS will be sufficient to cope with the demands of this block of houses. Such a VRB-ESS layout is available due to the flexibility of the battery system. Importantly, an advantage of the VRB-ESS is that its size can be increased in the future should it be required. For instance, if the project developers wish to combine one or more blocks, they can quite simply combine both VRB-ESS or even extend each battery system to cope with the extra demand.

3.2.2 Low Income Block Option 2

A second simulation was run for the low income blocks to investigate the use of five PV modules per house as opposed to the four used in option one. Installing an extra module per house results in a greater on-site generation and thus less electricity having to be bought in from outside. The potential downside to installing the larger system is the required larger storage system which may become too expensive. Indeed, a system with six PV modules per house was also modelled but this resulted in a very large VRB-ESS which would have cost far too much.

This block option is also comprised of twenty houses and the power generation process is exactly the same as in section 3.2.1 apart from the fact that there is an extra module per building. The extra twenty modules result in a block PV system of 24.5 kWp or 1.225 kWp per house. In this case, each house will be fitted with an SMA Sunny Boy 2000HF inverter with four SMA Sunny Island 5048 inverters located close to the VRB-ESS. The five modules per building generate a maximum power voltage of 89.4 V_{mp}. The SMA Sunny Boy 2000HF inverters are necessary to deal with the greater power and voltage output created by the additional PV module compared with the first option.

Due to the extra PV module per house, this block option will generate 53.62 MWh/year before losses and therefore less electricity will have to be purchased from the national grid in order to satisfy the block's demand of 50.5 MWh/year. Option 1 required 23.15 MWh/year from Eskom whereas option 2 will only require an additional 12.04 MWh/year from Eskom which is a significant reduction. Since the same load profiles were used for both low income models, the peak demand in both options is the same – 42 kW. The size of the VRB-ESS is the major difference and in this case the peak battery capacity increases to 143 kWh which means that a 50 kW/200 kWh VRB-ESS must be implemented. The VRB-ESS necessary for this option will therefore cost significantly more than that required for option one and the impact of this has been analysed in the financial model in section 4.3.

3.3 Middle Income Blocks

1,800 houses are to be assigned to middle income households and two different block options have been examined. Both options are composed of ten houses with option 1 having ten modules per house and option 2 having eleven modules.

3.3.1 Middle Income Block Option 1

The first option is comprised of ten houses with ten PV modules per house equating to 100 modules per block. Due to the larger power and voltage outputs of the roof-mounted PV modules, a larger inverter was required compared to the ones used for the low income block options. With a maximum power output of 2450W and a maximum voltage output of 149 V_{mp}, an SMA Sunny Boy 2500HF will be required per house. These inverters are suitable up to a maximum power input of 2600W. Unlike the low income block options, only three SMA Sunny Island 5048 inverters will be required to convert the AC electricity into DC electricity for storage due to the smaller peak energy demand of the block.

The combined load profiles of all ten houses produced a yearly demand of 55.3 MWh/year with a peak demand of 25.6 kW occurring in the late evening. This first block option was modelled with 10, 245W PV modules per house which result in a 24.5 kWp PV system. The block's PV system will generate 53.62 MWh/year before any system losses are taken into account which is just short of the overall demand. However, due to electrical system losses, 19.72 MWh/year would still need to be purchased from Eskom in order to completely satisfy the block's demand. To cope with the block's own electricity generation and the necessary additional electricity from Eskom, a 30 kW/250 kWh VRB-ESS will be required since the peak energy demand and battery capacity have been calculated as being 25.6 kW and 181 kWh respectively.

3.3.2 Middle Income Block Option 2

The second block option also modelled ten houses but with each house being fitted with eleven modules as opposed to the ten in option one. In this case, the PV system's size is 27 kWp with each PV array creating a maximum voltage output of 178.8 V_{mp}. As with the first middle income block option, three SMA Sunny Island 5048 battery inverters will be required to cope with the peak demand. However, due to the increased power and voltage output of the PV modules in this option, SMA Sunny Boy 3000HF inverters will be required for each house which are able to cope with the higher power output generated by the extra module.

Such a system will generate 58.98 MWh/year before losses which is greater than the block's electricity demand of 55.3 MWh/year. Again, due to losses, the PV system does not completely satisfy the demand and therefore additional electricity will still have to be purchased from Eskom. In this case, to entirely satisfy the block's demand, 14.2 MWh must be purchased from Eskom over the course of the year. To deal with the expected peak demand and generation, a 30 kW/310 kWh VRB-ESS will be necessary for blocks of this type since the model has predicted a peak energy demand and battery capacity of 25.6 kW and 227 kWh respectively. Again, the impact of requiring a larger VRB-ESS has been analysed in the financial model.

3.4 High Income Blocks

Although *Solar City*'s main aim is to provide affordable housing for low income households, there will be 1,200 houses built for high income households. These houses will be larger and more energy intensive and will therefore require a larger PV system. Again, two different block layouts have been analysed. This time however, the number of houses per block has been altered – not the number of PV modules. Houses in both block options will be fitted with twelve PV modules but option 1 will be dealing with a block of twelve houses whereas the second option will deal with a six-house block. Comparing the following two options therefore will consider whether a larger or smaller number of houses per block will be more advantageous with regards to electricity generation and energy efficiency.

3.4.1 High Income Block Option 1

The first model examined a block of twelve houses with twelve modules per roof creating a 35.3 kWp PV system with a maximum power voltage output of 178.8 V_{mp} per array. Due to the high power and voltage outputs generated by the PV arrays, an SMA Sunny Boy 3000HF inverter will be required per house as well as four SMA Sunny Island 5048 battery inverters located at the communal VRB-ESS.

The system will generate 77.21 MWh/year which is greater than the block's demand of 73.99 MWh/year. Again though, due to losses, the PV system is not capable of satisfying the entire demand alone and additional electricity must be bought in. An additional 20.45 MWh of electricity will be required from the national grid in order to satisfy the demand. The round-trip efficiency of this particular system has been calculated to be 75.8% which again is heavily influenced by the VRB-ESS. With a peak energy demand of just under 41 kW and a peak battery capacity of 256 kWh, a 50 kW/350 kWh VRB-ESS will be required for this particular block of houses.

3.4.2 High Income Block Option 2

The second option for the high income houses considers a block of six houses with twelve modules per house. This results in a 17.6 kWp PV system for the entire block which equates to 2.93 kWp per house. Since the same number of modules will be installed on each house in this option as in the first high income block option, the maximum output voltage and the associated inverters which will be required are the same: a maximum output voltage of 178.8 V_{mp} requiring an SMA Sunny Boy 3000HF inverter per house with four SMA Sunny Island 5048 inverters by the communal VRB-ESS.

In total, 38.61MWh/year will be generated by this option’s system which is slightly greater than the demand of 37.58 MWh/year. In this case, 11.15 MWh/year of additional electricity will be required in order to satisfy the block’s demand. Taking into account all the losses throughout the process, this system has a calculated round-trip efficiency of 75.5%. The block’s peak energy demand is just under 20 kW and its peak battery capacity is 115.7 kWh which suggests a 30 kW/160 kWh VRB-ESS will be necessary to satisfy the block’s needs.

3.5 Summary

Each block’s specifications are summarised in Table 4. Although important, the decision of which block layouts to choose may not be made solely using the results from the technical models. The financial implications of each block layout are equally as important in projects such as *Solar City* especially when considering such a development in South Africa. The next section will therefore explain the financial models created and their associated results. Only by combining the results of the technical and financial models will a decision be possible.

Table 4: Summary of Block Specifications

	LI Block 1	LI Block 2	MI Block 1	MI Block 2	HI Block 1	HI Block 2
Houses	20	20	10	10	12	6
PV Modules/House	4	5	10	11	12	12
Total PV Modules	80	100	100	110	144	72
System Size (kWp)	19.6	24.5	24.5	27.0	35.3	17.6
Size of VRB-ESS (kW/kWh)	50/130	50/200	30/250	30/310	50/350	30/160
Total Annual Generation (MWh)	42.89	53.62	53.62	58.98	77.21	38.61
Eskom Electricity Required (MWh)	23.15	12.04	19.725	14.2	20.45	11.15
Total Annual Demand (MWh)	50.51	50.51	55.3	55.3	73.99	37.58
Efficiency of Process (%)	76.5	77.0	75.4	75.6	75.8	75.5

Chapter 4: Financial Model & Results

4.1 Overview

It has been shown that, from a technical point of view, implementing a PV microgrid with centralised storage at *Solar City* is possible. However, the greatest challenge for projects of this kind at this moment in time is making such systems affordable. With *Solar City's* developers wishing to provide affordable homes for low income households and first-time buyers, it is even more important that any renewable energy power generation system is made as affordable as possible. As such, financial models have been created on the back of the technical models to analyse how expensive each system would be and where specific issues or challenges lay. The financial models take into account all expenditure and income associated with the PV systems from the homeowners' and *Solar City* ESCO's points of view.

As previously determined, homeowners will be responsible for paying the capital cost associated with the PV system although all the equipment will belong to the *Solar City* ESCO. In return, each homeowner will own shares in the ESCO and be provided with a pre-determined amount of electricity per month. The ESCO will be in charge of monitoring the electricity supply and demand and thus be responsible for buying additional electricity from Eskom as and when required. The ESCO will also be responsible for crediting or charging homeowners should they go under or over their monthly electricity allowance. The charges, along with the monthly service fees received from each household, will be collected by the ESCO and used to pay for the additional electricity from Eskom as well as operation & maintenance (O&M) and inverter replacement costs.

4.2 Assumptions

As with the technical models, various assumptions have had to be made in order to generate useful results. Many assumptions, such as currency conversion and interest rates, have been made according to rates at the time of writing but can easily be modified within the models. All the assumptions made within the financial models are listed below and will be referred to later in the report.

- Eskom 2013/2014 electricity tariffs (from 01 July 2013) have been used to calculate the cost of buying additional electricity from Eskom
- Eskom electricity tariffs increase by 8% per annum until 2018

- Saldanha Bay Municipality electricity rates have been used for the BAU comparison
    - 0 – 50 kWh/month: ZAR 0.92/kWh
    - 51 – 350 kWh/month: ZAR 1.04/kWh
    - 351 – 600 kWh/month: ZAR 1.28/kWh
    - 600+ kWh/month: ZAR 1.49/kWh
- Consumer Price Index (CPI): 5.5%
- Bond interest rate: 8.5%
- Homeowners will pay for the system through a bond over the course of twenty years
- Equipment prices per unit have been assumed as follows:
    - Kyocera PV module: ZAR 4,815
    - Landis+Gyr E450 smart meter: ZAR 1,952
    - Prudent Energy VRB-ESS: ZAR 4,435/kWh
    - SMA Sunny Island 5048 inverter: ZAR 33,617
    - SMA Sunny Boy 1200 inverter: ZAR 7,943
    - SMA Sunny Boy 2000HF inverter: ZAR 12,348
    - SMA Sunny Boy 2500HF inverter: ZAR 13,229
    - SMA Sunny Boy 3000HF inverter: ZAR 14,110
- A 15% discount was deducted from the cost of all equipment to simulate buying in bulk and hence being afforded wholesale price
- 1 USD = ZAR 8.87 (Correct as of January 21, 2013)
- Monthly service charges: ZAR 25 for low income, ZAR 50 for middle income and ZAR 75 for high income households
- O&M cost has been assumed as ZAR 500/kWp [South African Photovoltaic Industry Association, 2011]
- Users will be charged ZAR 4/kWh over their monthly electricity allowance and will be credited with ZAR 1/kWh under their allowance

4.3 Low Income Blocks

The two block options for low income blocks as detailed in sections 3.2.1 and 3.2.2 have been analysed from a financial perspective and the short and long-term costs calculated. The costs of the systems have been analysed from both the homeowners' and the ESCO's points of view and the two options have been compared.

4.3.1 Homeowner Costs

Both options' capital costs per house are shown below as well as the breakdown of the costs. The breakdown of the costs show the percentage of the overall cost attributable to the PV modules, the VRB-ESS and the balance of plant which includes all the inverters, smart meters and all electrical wiring.

Table 5: Breakdown of Capital Costs for Low Income Blocks

Block Option	Overall Capital Cost per house [ZAR]	PV Modules [%]	Balance of Plant [%]	VRB-ESS [%]
Option 1	56,659.22	28.89	27.86	43.25
Option 2	77,690.34	26.34	25.14	48.52

As Table 5 indicates, and as is expected, the majority of the capital cost is attributable to the energy storage system. Block option 2 costs around ZAR 20,000 more per house than option 1 and this is attributable mainly to the larger VRB-ESS which is required due to the larger system size. With the estimated price of a typical low income house on *Solar City* set to be around ZAR 85,000, these two capital costs may be deemed too expensive without any outside help for the low income demographic of South Africa.

Apart from the initial capital cost, homeowners will have to make other payments towards the PV system on a regular basis. Homeowners will be responsible for paying their electricity charges and service fee on a monthly basis. The service fee is intended to help cover the O&M costs as well as other costs associated with installing and maintaining a PV microgrid system. A monthly service fee of ZAR 25.00 has been assumed for low income households and this will be paid directly to the ESCO. On their monthly bill, alongside the service fee, homeowners will see their electricity charge or credit amount. Low income houses will receive 220 kWh of electricity from the local ESCO per month. However, as is currently the norm in South Africa, low income households receive their first 50 kWh 'free' from the local municipality/government every month. In effect therefore, the ESCO will only be providing *Solar City*'s low income homeowners with 170 kWh/month – the other 50 kWh/month will be paid for by a third party organisation. This will not affect the technical system since the additional third party electricity can be bought onto site through the Eskom grid connections or the third party can simply pay the *Solar City* ESCO for each 'free' allocation of electricity which will then be generated on site. However, this will affect the financial comparisons with BAU cases as will be shown later in section 4.3.4.

Using the assumed energy demand load profiles, it has been calculated that over the course of a year, a typical low income household will receive just over ZAR 200 in credit from the local ESCO. This relates to each house using, on average, 200 kWh per year less than their allotted amount and being credited with ZAR 1/kWh. On average therefore, a typical low income household will receive ZAR 16.80 in credit each month which results in their overall monthly ESCO bill being around ZAR 8.20 for year one. This is less than they would be paying for electricity each month using the conventional power generation system which shows that, once the capital has been paid for, the PV system has the potential to save homeowners significant amounts of money.

For the purpose of this report it is assumed that homeowners will take out a bond to pay for the capital cost of the microgrid up-front. Homeowners will then pay monthly bond repayments over the course of twenty years with a bond interest rate of 8.5% and a CPI of 5.5%. The estimated total monthly payments – bond repayments, monthly service fees and electricity charges – for both block options over the course of the twenty years are plotted below.

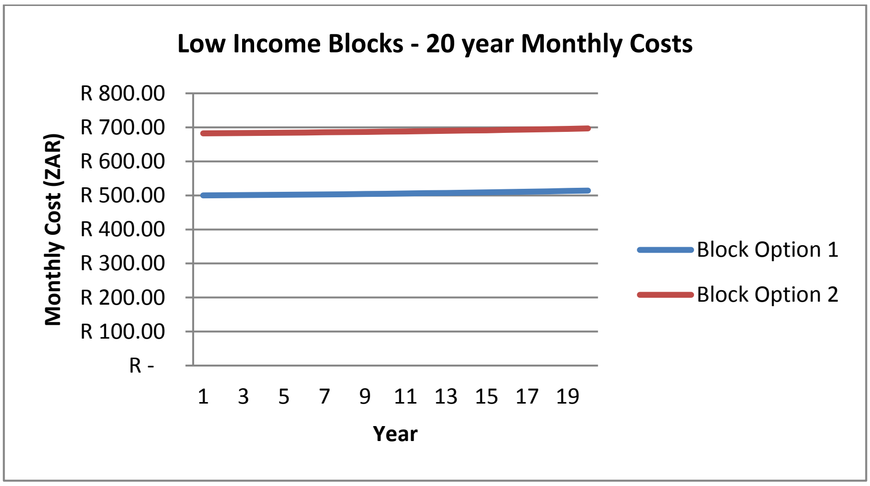

Figure 5: 20 Year Monthly Costs for Low Income Homeowners

The reason for the significant difference in homeowners' monthly payments is due to the higher capital cost associated with the second block option which results in a higher monthly bond repayment being required. Homeowners would be required to pay monthly bond repayments of approximately ZAR 491 and ZAR 674 for block options 1 and 2 respectively. The slight increase in monthly payments from year to year is due to the CPI increase.

4.3.2 ESCO Costs

As outlined previously, the *Solar City* ESCO will be responsible for purchasing additional electricity from Eskom as and when required as well as paying all O&M costs, upgrading and replacing faulty equipment and charging or crediting the homeowners for their electricity usage. The yearly Eskom bills based on July 2013 tariffs and the O&M costs which will need to be paid by the ESCO for each low income block option are given in Table 6.

Table 6: Eskom and O&M Annual Costs - Low Income Blocks

Block Option	Additional Eskom Electricity Required per Year [MWh]	2013/2014 Eskom Bill per Block [ZAR]	Annual O&M Bill per Block [ZAR]
Option 1	23.15	7,081.01	9,800
Option 2	12.04	3,682.74	12,250

Although the second block option requires less electricity to be purchased from Eskom and hence a lower annual expenditure, its greater system size requires a greater annual O&M cost which will almost nullify the benefits of the lower Eskom bill in year one. However, Eskom have stated that, for the next five years at least, a minimum annual price increase of 8% will be attributed to electricity tariffs. Therefore, it is fair to assume that having to buy less electricity from Eskom will become more financially attractive as time goes by. Using an 8% increase on electricity prices over the next five years, the increase in the annual Eskom bill using the 2013/2014 bill as a starting point is illustrated in Figure 6 and it shows how the difference in the Eskom bill increases between block options 1 and 2 with each passing year. Although Eskom's tariffs are unknown from 2018 onwards, it is fair to assume that they will not decrease which would strengthen the idea that having to purchase less electricity from Eskom is more desirable than having a slightly lower capital cost at the beginning.

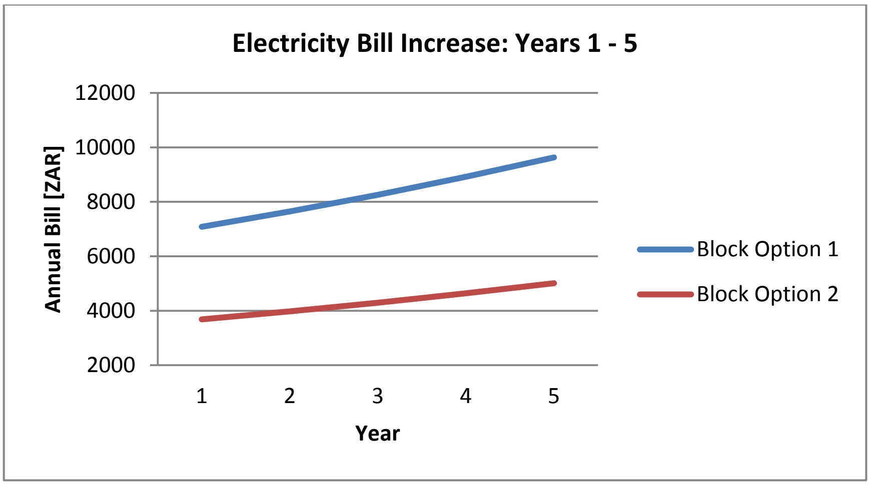

Figure 6: Projected Electricity Bill Increase Years 1 - 5

A significant source of expenditure for *Solar City's* ESCO will be concerned with the site's inverters. A major drawback of using inverters is that they have a relatively short lifetime. They must be replaced after ten to twelve years of use and it will be the responsibility of *Solar City's* ESCO to pay for the replacements. In order to finance such an overhaul, the plan is for the ESCO to use the income they receive from all service fees and electricity charges. Although the inverter technology and price per unit will undoubtedly improve over the course of a decade, for modelling purposes the exact same inverter type and price per unit has been used to calculate the replacement cost. In order to replace all the inverters, the ESCO will require ZAR 249,330 for block option 1 and ZAR 324,215 for block option 2.

The financial model however does not predict that the ESCO will receive enough income per block in order to completely finance the inverter replacements. It is difficult to charge low income households even more for the system which raises the issue of how the ESCO will afford to replace the inverters. Options include taking out a bank or government loan, setting more aggressive electricity allowances or using some of the predicted income from the industrial and commercial sectors of *Solar City*. Indeed, using some of the income of the industrial and commercial businesses to help with the running costs of the residential buildings and PV system is a viable option available to the site's developers. As the industrial and commercial sectors are out of scope for this report, the potential income generated is unknown but is most certainly something which can be examined further by site developers.

4.3.3 Comparison with Business-as-Usual Case

In order to assess the financial feasibility of implementing a solar PV microgrid in place of the traditional electrical system, it is important to compare the costs of both cases over the long-term. A period of twenty years was chosen and both low income block options were assessed against a BAU case using the conventional power system. As stated in section 4.3.1, it was assumed that homeowners would pay for the capital cost of the systems using financial bonds with an interest rate of 8.5% and a CPI of 5.5%. The planned 8% increase on electricity tariffs was also included for the first five years. The BAU costs include the 220 kWh/month of electricity using Saldanha Bay municipality rates (See section 4.2) which increase over time due to the planned hike in electricity tariffs and CPI. Also, the BAU case where homeowners receive their first 50 kWh of the month free has been analysed. The low income block costs are comprised of the homeowners' monthly bill (electricity charges/credit and service fees) and monthly bond repayments. Figure 7 illustrates the variation in monthly bill for each case over the course of twenty years.

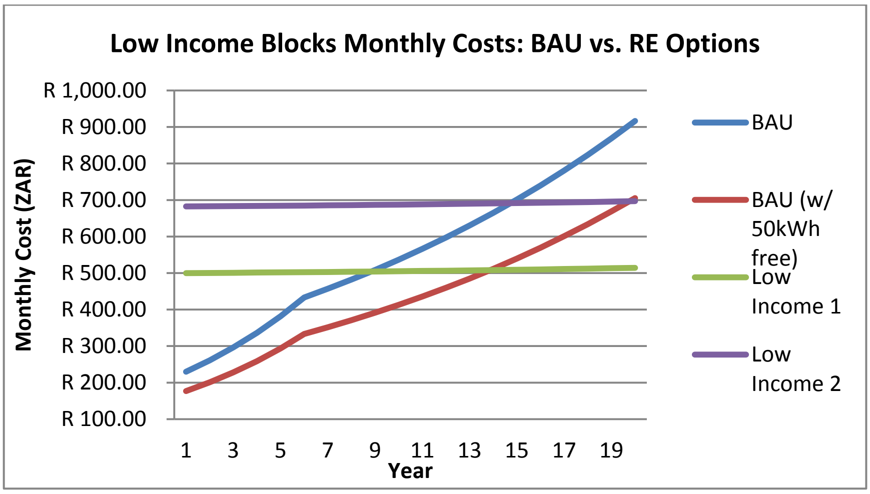

Figure 7: Microgrid vs. BAU Case - Low Income Blocks' Monthly Costs

As Figure 7 shows, it is currently more affordable for homeowners to pay for a conventional grid connection system than the PV microgrid with centralised storage as outlined in this report. However, as electricity prices rise, the solar PV microgrid becomes more attractive to the homeowner and to the ESCO. Although the two cases become closer in terms of price, it is not until year 9 that block option 1 breaks even with the BAU case and not until year 14 that it breaks even with the BAU case with 50 kWh/month free. These timescales are significantly larger when considering the second block option. However, what this does show is that in the long-term, and certainly by the next decade, the solar PV options will be more affordable and financially viable than conventional power systems. The issue is whether it is financially feasible for low income homeowners to pay “over-the-odds” for their electricity for the next ten years and unfortunately for *Solar City*, without any outside help, it is not. However, it is important to note, that should Eskom keep the 8% annual increase on electricity prices in place after year 5, the solar PV cases would break-even earlier than they do in Figure 7 above.

4.3.5 Summary

Implementing a PV electrical system for low income houses is technically possible but the costs associated with it may prove to be too expensive for homeowners without any outside help. Although in the long-term the PV system has the potential to be more affordable than the traditional electrical system, it may be difficult to persuade low income homeowners to pay more than they would otherwise for a few years before seeing the benefits of the renewable energy system. The financial model has concluded that the costs per watt installed for block options 1 and 2 are ZAR 57.82/W and ZAR 63.42/W respectively. These costs are approximately three times greater than the ZAR 21.07/W estimated by John Quiggin for solar PV projects [Quiggin, J., 2012]. However, the ZAR/W costs modelled in this project include the storage of electricity which has been shown to be the most expensive part of the system. The greater cost per watt installed is therefore expected and understandable.

Options are available to *Solar City's* developers in order to make these PV systems more affordable and desirable to prospective low income homeowners and these will be explained and discussed in section 5.1.

4.4 Middle Income Blocks

The two middle income block options as detailed in sections 3.3.1 and 3.3.2 have been analysed financially in terms of the capital and long-term costs associated with homeowners and the local ESCO.

4.4.1 Homeowner Costs

According to *Solar City*'s developers, a typical middle income house at the site will cost in the region of ZAR 600,000. The two middle income PV system options' capital costs and breakdown of costs are summarised in Table 7. The capital costs for both options account for around 30% of the overall price of a typical middle income house.

Table 7: Middle Income Block Options Capital Costs and Breakdown of Costs

Block Option	Overall Capital Cost per house [ZAR]	PV Modules [%]	Balance of Plant [%]	VRB-ESS [%]
Option 1	158,306.64	25.85	14.61	59.53
Option 2	181,673.99	22.53	13.15	64.33

Again, the VRB-ESSs account for the bulk of the capital cost and the significant difference in price between the two options can be attributed to the necessary increase in VRB-ESS size due to the extra power output of the system in the second block option. In both options the VRB-ESS is responsible for around 60% of the overall price whereas it only represents around 45% of the low income block options' system price. A reduction in the price of VRB systems therefore has the potential to make a significant improvement to the overall cost of the two middle income block options.

A monthly service fee of ZAR 50.00 has been assumed for all middle income households which is twice as much as for low income households and reflects the added equipment involved in the middle income electrical systems. The model predicts that middle income households will be charged for using more electricity than the 450 kWh they will be allocated. Over the course of the year, the model predicts that a typical household for both system options would be charged ZAR 198.40 by the ESCO equating to ZAR 16.5 per month resulting in an average monthly bill of ZAR 66.5 when combining the pre-determined service fee and electricity charges for year one.

As in section 4.3.1, it is expected that homeowners will take out a bond in order to pay for the capital cost of the PV system. As such, they will have to pay monthly bond repayments on top of the ZAR 66.5 monthly bill as previously discussed. The total monthly payments that homeowners can expect to make for both options are shown in Figure 8.

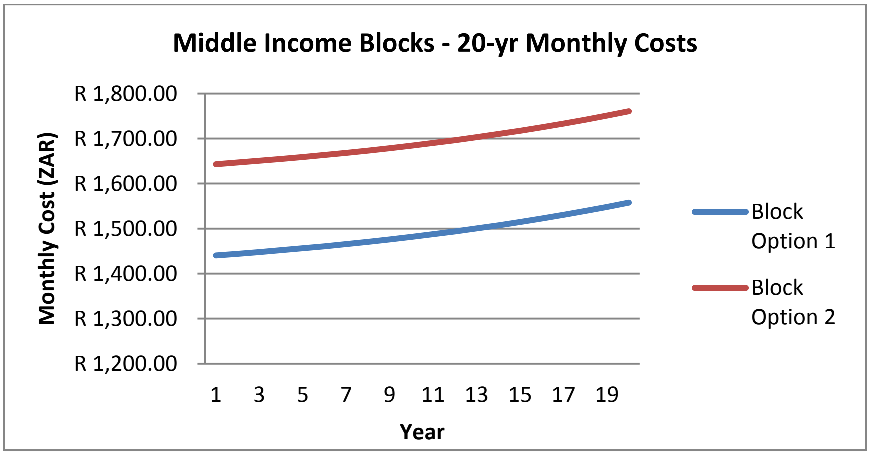

Figure 8: 20 Year Monthly Costs - Middle Income Homeowners

Again, there is a significant difference between the monthly costs of both options which is attributable to the different bond repayment amounts. Bond repayments of approximately ZAR 1,374 and ZAR 1,576 per month have been calculated for block options 1 and 2 respectively.

4.4.2 ESCO Costs

The amount of additional electricity required per block option and their associated 2013/2014 cost can be seen in Table 8 as well as the O&M costs per block option.

Table 8: Eskom and O&M Annual Costs - Middle Income Blocks

Block Option	Additional Eskom Electricity Required per Year [MWh]	2013/2014 Eskom Bill per Block [ZAR]	Annual O&M Bill per Block [ZAR]
Option 1	19.72	6,033.38	12,250
Option 2	14.2	4,343.43	13,500

Again, the larger on-site PV system reduces the amount of electricity required from Eskom but demands a greater annual O&M cost. As explained in section 4.3.2 however, with electricity tariffs set to rise over the coming years, requiring less additional electricity is an advantage and will become more beneficial in future years.

With respect to replacing all the blocks' inverters after ten or so years of use, the financial model has calculated that the ESCO will need approximately ZAR 198,170 and ZAR 205,658 per block for options 1 and 2 respectively in order to finance the replacements. With service fees and electricity charges as detailed in this report, the ESCO will receive around ZAR 87,000 per block over the course of the first ten years for both options which clearly shows that the

ESCO will have to either charge the homeowners even more, set more aggressive monthly electricity allowances, take out an additional bank or government loan, or receive financial help from the industrial and commercial parts of the site.

4.4.3 Comparison with Business-as-Usual Case

The two block options have been compared to a conventional grid connection case. As in section 4.3.3, the BAU case has been created by taking Saldanha Bay Municipality electricity rates for the 450 kWh/month of electricity which will be allocated to each middle income homeowner at *Solar City* and adding on the CPI, interest rate and electricity price hike over a period of twenty years.

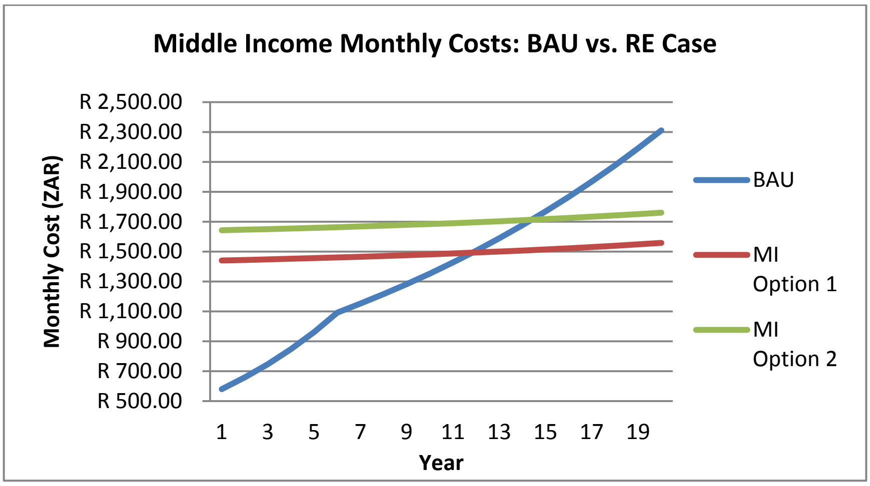

Figure 9: Microgrid vs. BAU Case - Middle Income Blocks' Monthly Costs

Figure 9 shows that the monthly costs for *Solar City* block options 1 and 2 will not break-even until years 12 and 14 respectively. It is extremely unlikely that homeowners will be prepared to pay over the odds for at least a decade before seeing any return on their investments. However, there are certain methods available to shorten the period before breaking even. For instance, the monthly payments may be reduced by paying off some of the capital cost up front. Also, by structuring the loan over a period of fifteen years as opposed to twenty years, the homeowners will end up paying a lower overall price. The monthly payments will be very similar for the first fifteen years but from year sixteen onwards, the monthly payments will be virtually insignificant. Another option – the government's "Green Fund" initiative – will be explained and discussed in section 5.2.

4.4.5 Summary

The technical system has the potential of being affordable for the majority of middle income households. However, the financial analysis has shown that the *Solar City* renewable energy case will cost more to homeowners than a BAU case for at least the first decade. As such, it may be difficult to persuade homeowners to part with their money when they know they could be paying less elsewhere. Homeowners may be persuaded to opt for *Solar City* by altering the conditions of any loan or by paying off some of the capital cost initially which would result in lower monthly payments. As with the low income blocks, the ZAR/W installed cost of both options is about three times greater than the typical cost per watt installed of a PV system. The costs per watt installed of block options 1 and 2 are ZAR 64.61/W and ZAR 67.41/W respectively. There is not much difference between the two which is expected considering the capital costs of both options and only the one additional module per house in option 2.

The overriding conclusion is that a capital cost equal to about 30% of a typical middle income house price could well be affordable for the majority of middle income homeowners but it may be difficult to persuade homeowners to buy into the system considering the fact that for at least the next decade or so, the conventional power system is more affordable. In order to make the solar PV system more appealing and financially viable, certain financial incentives may be required.

4.5 High Income Blocks

4.5.1 Homeowner Costs

As per the *Solar City's* developers' estimations, a typical high income house on site will cost in the region of ZAR 800,000. The technical systems as detailed in sections 3.4.1 and 3.4.2 have been analysed from a financial perspective and the capital costs as well as the breakdown of these costs are listed in Table 9 below. Considering the average expected price of a high income house at *Solar City*, the capital costs of both systems will cost just over 20% of the typical house price.

Table 9: High Income Block Options Capital Costs and Breakdown of Costs

Block Option	Overall Capital Cost per house [ZAR]	PV Modules [%]	Balance of Plant [%]	VRB-ESS [%]
Option 1	183,900.76	26.71	13.51	59.79
Option 2	174,476.38	28.15	14.24	57.62

The VRB-ESS again accounts for most of the capital cost and the slightly lower capital cost involved with option 2 is due to the smaller VRB-ESS size. Although both options include twelve PV modules per house, the second block option is only comprised of six houses compared to the twelve houses in the first option. The results therefore show that even though there are the same number of PV modules per house, having a smaller block will be more financially viable to homeowners with respect to initial capital costs.

High income homeowners will be charged a monthly service fee of ZAR 75.00 which they will pay directly to the ESCO. On top of this, they will be subject to electricity charges should they exceed the 500 kWh/month electricity cap which they are allocated. The financial model has calculated that a house in block option 1, on average, will be charged ZAR 27.50 per month in year one whereas an average house in the second block option will only be charged ZAR 9.50 per month in the first year. This results in an average house having a monthly bill of ZAR 102.50 and ZAR 84.50 in block options 1 and 2 respectively without the capital cost repayments.

Again, similarly to previous income level examples, high income homeowners have the option of paying for the installed PV system through the use of a bank bond which they will then pay back over the course of twenty years. Homeowners in block options 1 and 2 will have to make monthly bond repayments of ZAR 1,595 and ZAR 1,514 respectively based on the capital costs and loan repayment terms. The total monthly costs associated with homeowners for both block options are plotted below.

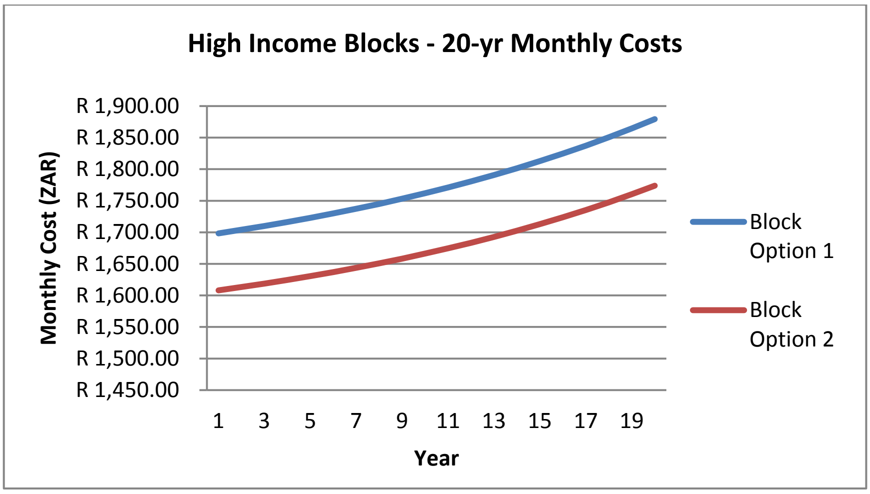

Figure 10: 20 Year Monthly Costs - High Income Blocks

4.5.2 ESCO Costs

The costs associated with the additional electricity required from Eskom and the annual O&M per block are summarised in Table 10. As both block options are identical apart from the fact that there are only six houses in option one compared to twelve in the second option, it may be fair to assume that if the second option's details in Table 10 were doubled they would be identical to the first option's details. However, this is not exactly the case – when the information is doubled, the second block option requires more additional electricity from Eskom which results in a higher bill but, on the other hand, its O&M cost is slightly lower than the first option.

Table 10: Eskom and O&M Annual Costs - High Income Blocks

Block Option	Additional Eskom Electricity Required per Year [MWh]	2013/2014 Eskom Bill per Block [ZAR]	Annual O&M Bill per Block [ZAR]
Option 1	20.45	6,255.14	17,650
Option 2	11.15	3,410.51	8,800

As with both low income and middle income blocks, all the inverters must be replaced after ten years of use. The cost of replacing the inverters in block option 1 is ZAR 258,220 and ZAR 129,110 in block option 2. The ESCO should be able to afford up to ZAR 160,300 and ZAR 72,020 for block options 1 and 2 respectively from the service fees and electricity charges obtained throughout the first ten years. These are just over half the necessary cost and thus additional money will have to be found from elsewhere.

4.5.3 Comparison with Business-as-Usual Case

The total monthly costs which prospective homeowners will be subjected to for either of the solar PV systems are compared to those costs which they would be paying for a conventional BAU case and the results are shown in Figure 11.

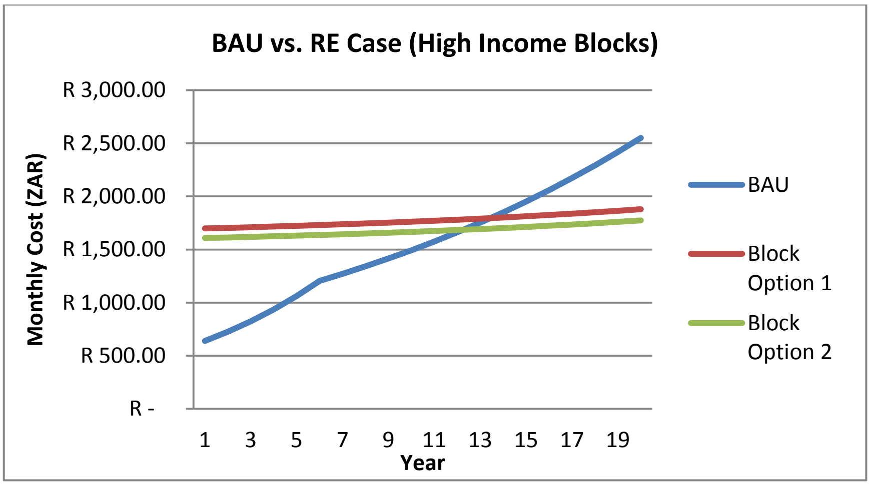

Figure 11: Microgrid vs. BAU Case - High Income Blocks' Monthly Costs

As Figure 11 shows, both high income blocks will not break even with a conventional BAU case until around years 12 and 13. Although this suggests that homeowners will be paying more than they could be for at least a decade, higher income homeowners may be more prepared to pay 'over-the-odds' for a certain period of time if they are guaranteed a significant return on their investments within twelve to thirteen years.

4.5.4 Summary

Both block options for the prospective PV system have been found to be financially viable for the majority of high income households since the capital cost for both options is only around 20% of the overall house price. High income homeowners may also be prepared to pay a little more for a decade or so with the knowledge that they would then begin to save money. The costs per watt installed of both block options have been calculated to be ZAR 62.55/W and ZAR 59.35/W for block options 1 and 2 respectively.

Chapter 5: Discussion

5.1 Low Income Blocks

The results obtained from the technical and financial models for both low income block options have shown that, from a technical point of view, implementing a PV microgrid with centralised storage and smart grid components as opposed to the more conventional power generation system is feasible. All the equipment required to implement such a system is currently available on the world market and most of it is also readily available on the South African market which suggests that the *Solar City* developers would have no problem installing the system if they chose to do so. Although incapable of satisfying the entire blocks' electricity demand alone, the two block options for the PV microgrid system are capable of satisfying the demand as long as additional electricity is purchased from the national grid. Currently, the model predicts a total system efficiency of 76.5% and 77% for block options one and two respectively. The major reason for this level of efficiency is the VRB-ESS which has a cycle efficiency of around 75%. However, with technological advancements and improvements over the next few years, it is fair to expect the efficiency of the VRB-ESS, and hence the overall system, to improve. Increasing the efficiency of the process would reduce the amount of additional electricity required from Eskom as well as potentially reducing the size of the PV system required.

The major issue with implementing the PV microgrid for low income households concerns the finances of the project. The capital and monthly costs are too expensive for the majority of low income homeowners and it would be almost impossible to persuade such homeowners to part with more of their money to pay for this system than they would be required to pay for the conventional power system. However, by taking advantage of certain government schemes such as the 'housing subsidy', it may be possible to make the PV microgrid option more affordable for the majority of homeowners. A subsidy of up to ZAR 96,362 per house is available for homeowners who earn less than ZAR 3,500 per month [Western Cape Government, 2013]. A large proportion of low income homeowners at *Solar City* are expected to earn less than this value and therefore will be eligible to receive this subsidy. The subsidy would be available to be put towards the price of a house and the capital cost of the installed PV system. With the average price of a low income house on *Solar City* expected to be around ZAR 75,000, the housing subsidy will comfortably cover this cost and the remainder can be used to help reduce the capital cost of installing the PV system.

In effect, as opposed to paying capital costs of ZAR 56,659 and ZAR 77,690 for block options one and two respectively on top of the house price, homeowners may only be required to spend ZAR 35,298 and ZAR 56,328 respectively for the installation of their PV power generation system. When one considers that the average price of installing all the necessary wiring and transformers for connecting a house close to an available line to the Eskom grid is ZAR 10,000 for overground cabling and ZAR 15,000 for underground cabling as confirmed by Mr Steven Levy of Power Construction – a civil engineering contractor – in South Africa, the homeowners at *Solar City* will be paying ZAR 20,000 to 40,000 more than they would otherwise. Furthermore, the cost of connecting a house to an Eskom line rises rapidly the further away it is from an available line. Prices of up to ZAR 50,000 are quite common and for more remote areas these rise even higher. With no available Eskom lines currently in place around the *Solar City* site it is possible that a conventional grid connection system would cost as much as, if not more, than the predicted PV system as detailed in this report. This comparison suggests that the capital costs of ZAR 35,398 and ZAR 56,328 for the PV system are not too different to the capital costs required to be paid by the average homeowner wishing to connect to the Eskom grid.

The effect the housing subsidy has on homeowners' monthly payments is illustrated in Figure 12. Without the advantage of the housing subsidy, the break-even point for the *Solar City* case compared to a BAU case would occur in years 9 and 15 for block options one and two respectively. By taking advantage of the housing subsidy however, the break-even point can be reached by years 4 and 9 respectively. This makes implementing the *Solar City* system, in particular the first block option, more appealing and affordable to the homeowners. If homeowners know that after four years of using the rooftop PV modules they would be paying less than they would have been had they been paying for a conventional system, it makes the system much more appealing.

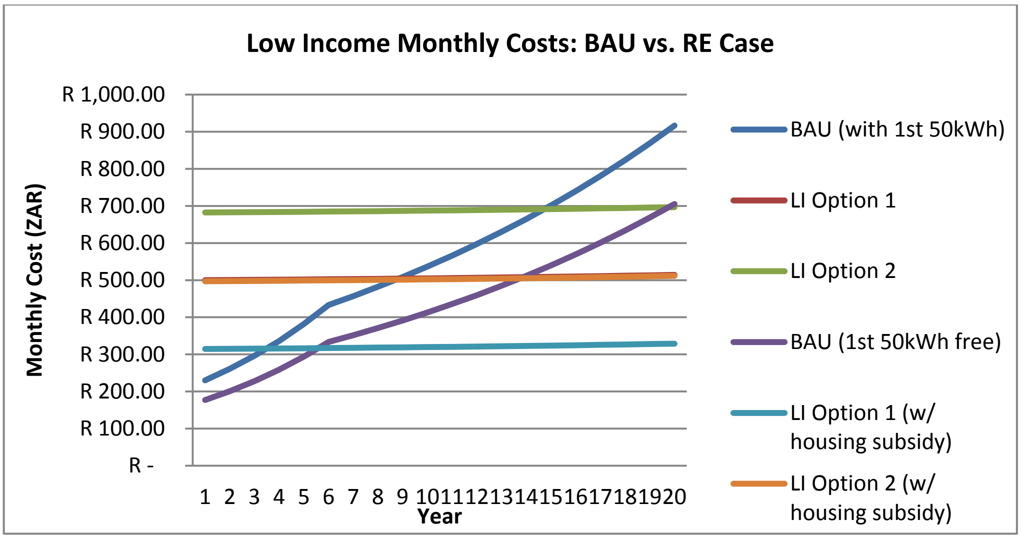

Figure 12: Effect of Housing Subsidy on Break-Even Point

The decision of which option to choose for the low income blocks is heavily influenced by whichever option is the most affordable over the lifetime of the system with regards to both the homeowners and the *Solar City* ESCO. Figure 12 shows that compared to a conventional BAU case and with the help of the housing subsidy, the first block option reaches the break-even point after only four years and becomes significantly more affordable to the homeowners after this point. The first block option is more affordable for homeowners since there is one fewer PV module per house and a smaller VRB-ESS but these result in more electricity being required from Eskom than for the second option. This additional electricity will influence the decision as to which option to choose since it is widely expected that electricity prices will continue to increase over the coming years. However, in a few years' time, the *Solar City* developers will have the option of increasing the size of the on-site solar PV system should the electricity prices become too expensive.

Another key issue which has been raised by the financial models is how the ESCO will afford to replace all the inverters after ten years or so as is expected. It was anticipated that the monthly service fees and electricity charges would create enough income for the ESCO to be able to finance the inverter replacements but after having run the models, this has proved not to be the case. There is a significant shortage of income which means that the ESCO must find other sources of income to finance the replacement parts. Options available to *Solar City's* developers for raising additional funds to pay for the replacement of the site's inverters have been detailed in section 4.3.2. Depending on which method of fund raising is chosen, additional costs may well be passed onto the homeowner or the developers – both of which are unwanted. This issue of replacing inverters after ten years of use is a serious challenge to the site's developers and will have to be seriously considered. It may well be that the service fees used in these models are too low and must be raised should *Solar City* decide to implement the system.

Taking both technical and financial models into consideration, it may be advisable to choose the first block option and reassess the situation in five to ten years' time as the electricity prices continue to rise. By implementing the first block option, it allows the project developers to learn about the PV system before making it larger but it also makes the system more affordable and appealing to customers in the short-term.

5.2 Middle Income Blocks

As with the low income blocks, the two options modelled with respect to the middle income blocks are technically feasible. The challenge however is making the system financially viable for both the homeowners and the *Solar City* ESCO.

With the capital costs for both block options being around 30% of the price of a typical middle income house on *Solar City*, it can be argued that the capital costs involved with installing the PV system are affordable to the majority of middle income households. The issue arises when the homeowners' monthly payments are analysed. As seen in section 4.4.3, the PV system will only break-even when compared to the conventional BAU case in years 12 and 15 for block options one and two respectively. This may dissuade potential homeowners from going to live at *Solar City* for the time being at least. As with the low income blocks therefore, some financial changes must be made in order to make the PV system more desirable.

Making use of government schemes such as the "Green Fund" initiative for instance may alleviate some of the financial pressure put on homeowners. The "Green Energy Efficiency Fund" is a government-backed scheme which provides loans of between ZAR 1.0m and ZAR 50.0m at prime minus 2% for a term up to 15 years for energy efficient and/or renewable energy projects in South Africa [Industrial Development Corporation, 2013]. Although making use of the "Green Fund" would result in homeowners paying less interest than they would have done without it, they would still be paying a similar monthly cost than they would be over 20 years with a normal bond since the "Green Fund" has a maximum term of

15 years. The key advantage of using the “Green Fund” is that after 15 years, the monthly cost to homeowners would drop dramatically and they would be making big savings compared to the Eskom electricity prices since they would then only be paying their service fees and electricity charges. Figure 13 illustrates the effect that the “Green Fund” would have on a homeowner’s monthly payments.

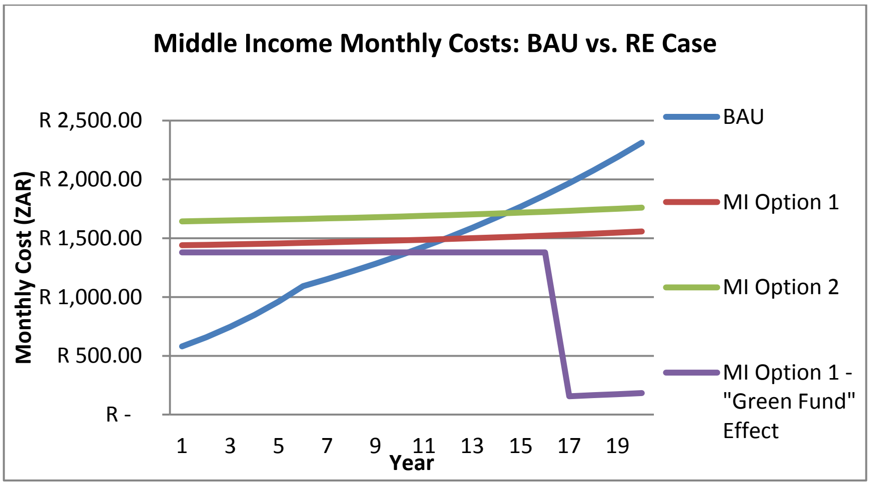

Figure 13: Effect of "Green Fund" on Long-Term Monthly Payments

The effect of the “Green Fund” has only been illustrated for the first block option but it is a similar story for the second option. Due to the lower interest rate and shorter lease period, initially the monthly payments are very similar although the break-even point occurs in year ten as opposed to year 12. From year fifteen onwards however, there is a significant difference between the two payment methods since the “Green Fund” loan has been paid off and the homeowners only pay for their electricity charges and monthly service fees which is a minimal amount. For homeowners to know that by making use of the “Green Fund” scheme they can be making significant savings after fifteen years is very appealing and will no doubt help market the *Solar City* system.

Choosing which technical system option to implement is again heavily influenced by the financial models. Technically, both systems work and the only major difference is the extra PV modules in option two which result in a greater on-site electricity generation and thus a larger VRB-ESS. The greater on-site electricity generation, although costing more initially, results in less additional electricity needing to be purchased from the national grid and thus cheaper electricity bills for the ESCO.

Similarly to the low income blocks, it may be advantageous to implement the first block option to start with since it is the smallest and initially most affordable option. Then, once utility electricity bills continue to rise in the coming years as is expected, it may become more financially viable for the *Solar City* developers to install one or two more PV modules per house and implement larger storage systems as are modelled in option two. Installing the smaller system is beneficial for all parties: it is more affordable for the homeowner but also allows *Solar City's* ESCO and developers to enlarge the system in due time should there be the need, and finances available, to do so.

5.3 High Income Blocks

As expected, the systems modelled for both high income block options are also technically feasible and the decision as to whether or not implementing these systems would be viable is again down to the finances involved. Capital costs for both options are around 22% of the typical high income house price as expected at *Solar City*. As such, it is fair to assume that a high income household would be able to afford the additional costs associated with implementing a PV power generation system. However, the finances have been analysed with the goal of making the *Solar City* system even more affordable for high income households. Initially, a loan term of twenty years was used as a loan repayment period but it has been suggested that by shortening the loan period, the overall repayment cost will be reduced. In order to analyse the effect a different loan period would have on the finances and the overall cost to the homeowners, a loan period of ten years has been compared to the original twenty-year period. Figure 14 illustrates how varying the loan period can reduce the financial pressure on homeowners over the long-term even though for the first ten years they would be paying more than they would be were they to take out a twenty-year loan.

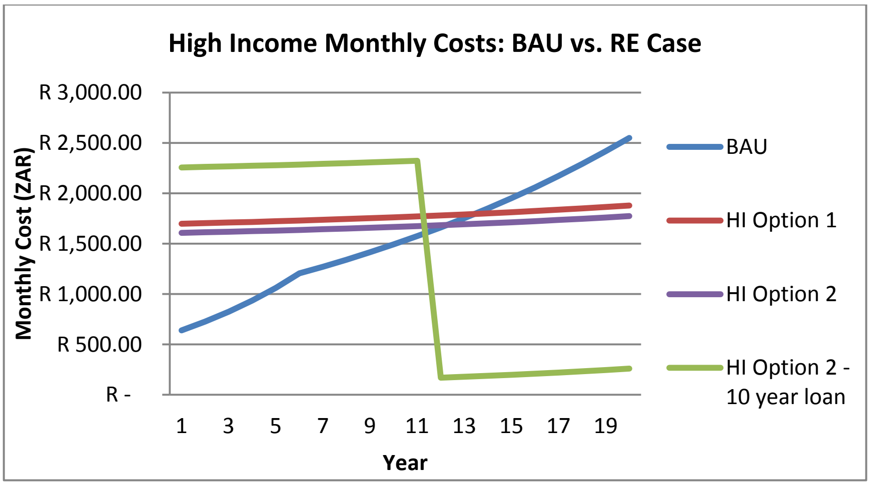

Figure 14: 15 Year Loan Period vs. 20 Year Loan Period

This would be an option available to homeowners who would have to make this decision themselves but it shows that options are indeed available to manage the cost of the PV system and that the *Solar City* system can be made affordable to high income homeowners no matter their financial situation.

Unlike the block options analysed for low and middle income houses, the two high income block options are both modelled using an equal number of PV modules per house – twelve. The difference between the two options is the number of houses which make up each block – option one is made up of twelve houses whilst option two consists of six houses. The effect, if any, that the number of houses has on the technical and financial results of a block of houses has been examined because it is expected that high income houses will sell slower than low or middle income houses. Grouping fewer houses together to form a block of houses could mean that fewer houses remain unsold in periods of financial uncertainty. Furthermore, high income homeowners may not wish to be surrounded by many other houses, and so keeping the block size to a minimum would provide each house with more individual space which is considered desirable. By grouping six houses together as opposed to twelve, the size of the VRB-ESS can be more than halved which results in a reduced capital cost per house making the second block option more attractive to homeowners from a financial perspective also. Having a smaller block size would also be more attractive to the *Solar City* developers and planners since high income houses cost more to construct and take longer to build. It would be therefore beneficial to be able to implement a power generation system for six houses rather than twelve and so the second block option is recommended.

5.4 Overall *Solar City* Electricity Network

Sections 5.1 to 5.3 have shown that implementing a PV microgrid with centralised VRB-ESSs and smart grid components is technically and, with some outside help, financially possible. In both the low and middle income block options, the smaller system has been the most feasible option due to lower initial costs allied with the possibility of extending it in future years. The 6-house block option for high income households has been chosen based on its lower capital and running costs as well as other construction and lifestyle benefits. In total therefore, using the block options as outlined above, *Solar City's* overall electricity network will be composed of 530 individual microgrids (150 low income blocks, 180 middle income blocks and 200 high income blocks) which combined create a 10.78 MWp network.

Although the models created for this project do not allow for any sharing of electricity between individual blocks, once the site has been completed this can be examined. Each individual microgrid will be connected to one another since they all have to be able to receive electricity from the national grid, and this means that they can potentially share electricity between themselves if required. In effect, *Solar City* will be one large microgrid split into 530 smaller microgrids which, with efficient management and control, has the potential to work very efficiently and could become a defining pilot project for residential renewable energy microgrids worldwide.

5.5 Social Issues

The technical and financial models draw up hard facts and numbers which can be understood relatively easily and are the crux of this project. However, it is important to understand and mention the social issues which may arise by installing this power generation system. One of the major social issues expected to arise from such a project is the issue of ownership. As explained, the *Solar City* ESCO will purchase, install and own all the PV modules and other equipment installed on-site. However, strict guidelines and rules must be distributed to all homeowners to stop them selling, replacing or altering the modules or other equipment at their homes. Although people may own the building, they will not own the power generation equipment installed on that building and this may create certain problems if guidelines and rules are not clearly set out. The ESCO must also respond quickly to technical problems associated with the power generation equipment – it will be the ESCO's responsibility to maintain and ensure that the modules, inverters and meters are in working order. For instance, if a module is not working then that house will be generating less electricity than it should be and this will affect the whole block's electricity generation and demand flow.

Another widespread issue in South Africa is the problem of electricity theft. It has been publically stated that electricity theft was costing South Africa around ZAR 4 billion every year and Eskom has recently set up a campaign in order to raise awareness of the issue [South African Government News Agency, 2010]. People have worked out a way to bypass current standard electricity meters in order to provide themselves and others with more electricity than they are paying for. By metering the electricity generated by the PV modules, the remaining electricity after the demand has been met at the houses, and the electricity flowing in and out of the VRB-ESSs, *Solar City's* control software will be able to pick up any issues with any smart meter on-site. The benefits of using smart meters are that they are in constant communication with the control hub and as such any disturbances with the meters or electricity flow will be flagged which should hopefully help minimise electricity theft.

Another social issue which may arise is the fact that homeowners will know how much electricity they are being provided with and how much they are paying, but they will also find out how much a different income level homeowner is receiving and how much they are paying for it. Thus, it is important to align the cost to each homeowner correctly in terms of the electricity they will receive each month and the O&M costs associated with it. Any discrepancies in this cost alignment and there will be social tension. The technical and financial models run for this project have, in some cases, used assumed values. Prior to implementing a renewable energy system such as the one outlined in this project, *Solar City's* developers must ensure that electricity allowances as well as all homeowner costs are fair to each individual homeowner.

5.6 Improvements

Even though the PV microgrid with centralised storage and smart grid properties detailed in this report has been modelled to satisfy the majority of *Solar City*'s electricity demand, aiming to satisfy the entirety of the site's demand is and should be the developers' goal. There are options available to achieve this but again, it will be a few more years until such options become financially viable. The first option would be to increase the size of the PV grid as outlined in this report. The problem with doing so at this moment in time is the size of the VRB systems which would be required to store the generated electricity. In a few years' time, when this technology becomes more affordable and more efficient, increasing the size of the PV system would possibly become more viable. It has been shown through the use of the technical models used for this report that the entirety of *Solar City*'s electricity demand can indeed be met by PV modules should viable storage be available. Another improvement available to *Solar City* developers is to add other renewable energy sources into the site's microgrid as touched on briefly earlier in the report. Adding wind turbines or making use of biomass would help grid reliability and enable greater electricity generation. The issues of adding these systems at this moment in time are related to capital costs and the site developers wanting to focus on solar power.

Finally, another option available to *Solar City* developers is to build an on-site CSP plant as briefly discussed in section 2.2.1. CSP is more powerful and more efficient than PV but the technology is much newer than PV and thus costs significantly more at this moment in time. There is also extremely limited knowledge of CSP technologies in South Africa and the African continent as a whole which also makes PV more feasible for this project. Theoretically though, a correctly designed CSP plant should be able to comfortably satisfy the entire *Solar City* electricity demand. Fortunately for the developers, there is plenty of space available on site which can be set aside for such a power plant in the next decade or so but again, this is not currently a viable option from both a technical and financial point of view.

Chapter 6: Conclusions

Solar City's developers are hoping to create a sustainable development with the aim of becoming “the first high tech, sustainable and renewable energy driven city in the world”. In order to achieve this goal they are interested in generating as much as possible of the site's electricity and energy demand on-site through renewable energy resources. This report has focused on the development of an innovative solar PV driven microgrid for the residential part of the development. *Solar City*'s electrical network will be split up into individual microgrid networks, each supplying one block of houses. Each block's microgrid will include roof-top PV modules, inverters, smart electrical meters and VRB-ESSs. Upon completion, *Solar City* as a whole will act as one large microgrid composed of hundreds of smaller individual microgrids.

Due to the Western Cape's rich solar resource and the maturity of the PV industry, solar PV power has been identified as the most feasible power generation source. Kyocera KD245GH-2PB PV modules will convert the sun's energy into electricity prior to satisfying real-time domestic demand with any excess electricity being stored on-site by Vanadium redox flow batteries. The block networks will eventually all be connected together which will allow for electricity sharing between blocks although this property has not been modelled. Simulations were run for each income level and each of these groups was modelled separately and an optimised block option for each income level was obtained. The analysis of the technical and financial models has resulted in the following block layouts being recommended.

Table 11: Final Block Layout Results

Income Level	Block Option Chosen	Layout of Block Option
Low Income Blocks	Block Option 1	20 houses, 4 PV modules/house
Middle Income Blocks	Block Option 1	10 houses, 10 PV modules/house
High Income Blocks	Block Option 2	6 houses, 12 PV modules/house

The results in Table 11 have been obtained with the assumption that construction of *Solar City* begins in 2014. The particular block options above have been chosen based largely on the initial capital and long-term homeowner costs as well as those costs attributable to the on-site ESCO. In each case, the block options chosen were the more affordable of the two modelled options in year 1. By choosing the smaller and more affordable options, it makes it easier for *Solar City* to attract buyers initially but also allows for expansion in future years. Using the block options as detailed in Table 11, *Solar City*, upon completion, will be composed of 530 individual microgrids (150 low income, 180 middle income and 200 high income blocks) resulting in an overall system size of 10.78 MWp.

All the equipment required to implement the power generation system as outlined in this report is available today either on the South African or global markets and there have been similar projects around the world which have demonstrated that such microgrids work. Additionally, there are many companies with extensive knowledge of renewable energy systems and PV power available in the Western Cape of South Africa. From a technical point of view, the power generation system is fairly simple and can be easily installed and maintained by local engineers and technicians. Additionally, a VRB-ESS was trialled fairly extensively at the University of Stellenbosch, South Africa in 2001 and this experience and knowledge will be useful if *Solar City* do indeed decide to implement VRB systems within their power generation microgrid.

Advantages of creating an electrical grid in the form of individual microgrids are many. First of all, it allows for the electrical grid to be built alongside the construction of each block which eases the financial pressure on the project developers. Secondly, the network will be able to deal with any interior and/or exterior grid disruptions and will comfortably function autonomously from the national grid. Other advantages include the possibility of electricity sharing between blocks, increased energy efficiency and energy security.

As expected, although the project is technically feasible, the financial models have shown that the *Solar City* microgrid may not be financially viable for all cases. Certainly, without any government-backed schemes or loans, the project would not be viable for low income homeowners. Indeed, even with the housing subsidy and government-backed initiatives such as the “Green Fund”, the PV microgrid may still be out of reach financially for the majority of low income households. This is an extremely important issue since *Solar City*’s main target demographic is low income earners and first-time buyers. Without these financial tools, it must be concluded that implementing such a power generation system at *Solar City*, for the time being at least, is unfeasible for the majority of low income homeowners. However, in four or five years’ time, when Eskom’s electricity tariffs have risen and the technology required for storing electricity in particular has become more affordable and efficient, a renewable energy microgrid will almost certainly be beneficial and affordable for *Solar City* homeowners and developers. The PV system discussed in this report however does have the potential to be financially viable for all middle and high income homeowners as of today. With this in mind, and due to the way the microgrids will be installed, *Solar City's* developers could implement the renewable energy microgrids for middle and high income buildings only for the time being. Then, once it becomes more financially feasible, the developers could look at retrofitting the low income houses with the renewable energy power generation system.

This report has concluded that implementing a solar PV microgrid with VRB-ESSs and smart meters at *Solar City* is technically feasible for all building types. Nevertheless, implementing such a system is currently too expensive, especially without any government schemes or subsidies, for low income homeowners who are the target demographic of this development and will make up half of the site's population. In order for low income homeowners to be able to afford the costs of such a system, *Solar City's* developers may have to wait another four or five years until they can implement it. The system is however financially feasible for middle and high income homeowners and could be installed on all these houses from the beginning of construction.

Appendix A – Yield Assessment of Photovoltaic Site

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RENEWABLE & SUSTAINABLE ENERGY STUDIES

YIELD ASSESSMENT OF THE PHOTOVOLTAIC POWER PLANT

Report number: PV-1235-1211-91
Issued: 22 November 2012 08:05 CET (GMT +0100)

1. Site info

Site name:	West Coast Peninsula West Coast DC, Western Cape, South Africa
Coordinates:	**32° 57' 14.46" S, 17° 57' 43.98" E**
Elevation a.s.l.:	23 m
Slope inclination:	1°
Slope azimuth:	270° west

Annual global in-plane irradiation: **2229 kWh/m²**
Annual air temperature at 2 m: **16.7 °C**

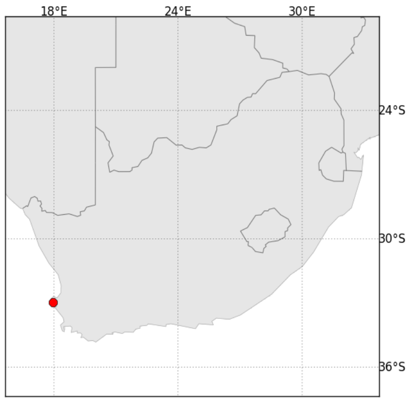
2. PV system info

Installed power:	**1.0 kWp**
Type of modules:	crystalline silicon **(c-Si)**
Mounting system:	**fixed mounting, free standing**
Azimuth/inclination:	**0° (north) / 29°**
Inverter Euro eff.:	97.5%
DC / AC losses:	5.5% / 1.5%
Availability:	99.0%

Annual average electricity production: **1793 kWh**
Average performance ratio: **80.5%**

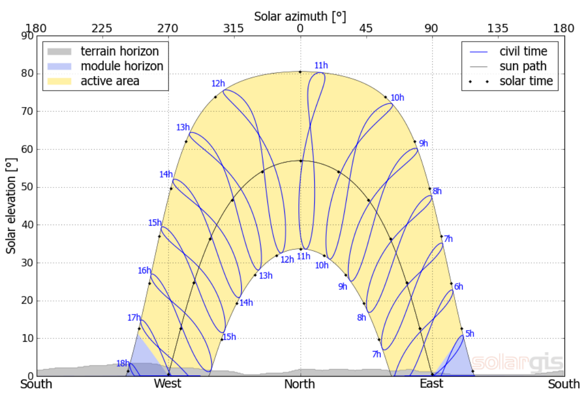
Location on the map: http://solargis.info/imaps/#loc=-32.954016,17.962217&tl=Google:Satellite&z=14

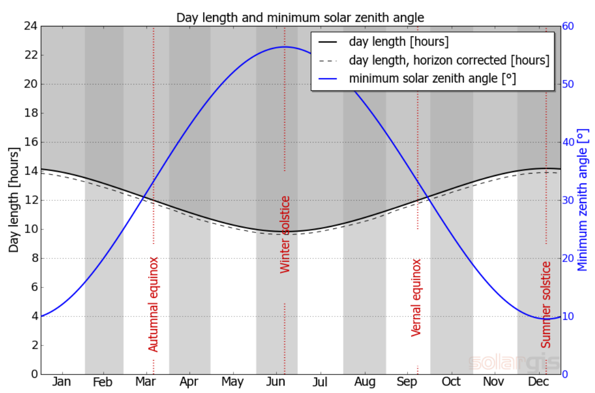
3. Geographic position



Google Maps © 2012 Google

4. Terrain horizon and day length

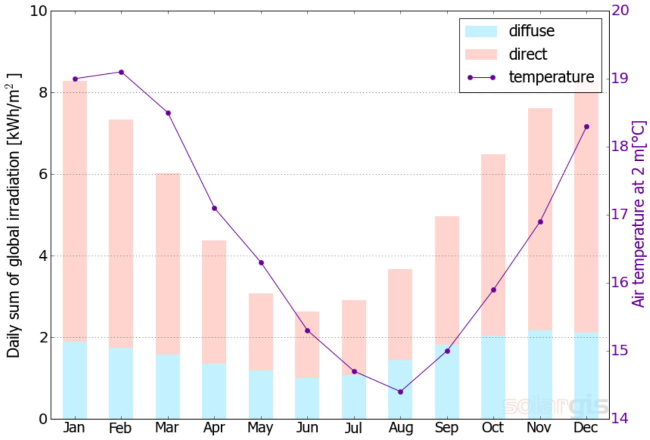




Left:	Path of the Sun over a year. Terrain horizon (drawn by grey filling) and module horizon (blue filling) may have shading effect on solar radiation. Black dots show True Solar Time. Blue labels show Local Clock Time.
Right:	Change of the day length and solar zenith angle during a year. The local day length (time when the Sun is above the horizon) is shorter compared to the astronomical day length, if obstructed by higher terrain horizon.

5. Global horizontal irradiation and air temperature - climate reference

Month	Gh_m	Gh_d	Dh_d	T_{24}
Jan	257	8.27	1.89	19.0
Feb	205	7.33	1.74	19.1
Mar	187	6.02	1.57	18.5
Apr	131	4.37	1.36	17.1
May	95	3.07	1.19	16.3
Jun	79	2.63	1.00	15.3
Jul	90	2.90	1.08	14.7
Aug	114	3.67	1.44	14.4
Sep	149	4.97	1.82	15.0
Oct	201	6.49	2.04	15.9
Nov	228	7.61	2.17	16.9
Dec	257	8.28	2.11	18.3
Year	**1993**	**5.46**	**1.62**	**16.7**



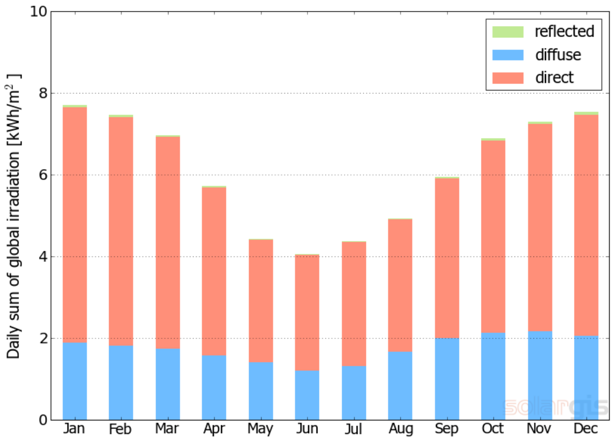
Long-term monthly averages:

Gh_m Monthly sum of global irradiation [kWh/m^2]
Gh_d Daily sum of global irradiation [kWh/m^2]
Dh_d Daily sum of diffuse irradiation [kWh/m^2]
T_{24} Daily (diurnal) air temperature [°C]

6. Global in-plane irradiation

Fixed surface, azimuth 0° (north), inclination. 29°

Month	Gi_m	Gi_d	Di_d	Ri_d	Sh_{loss}
Jan	239	7.71	1.88	0.07	0.0
Feb	209	7.47	1.81	0.06	0.0
Mar	216	6.97	1.75	0.05	0.0
Apr	172	5.72	1.57	0.03	0.0
May	138	4.43	1.40	0.02	0.1
Jun	122	4.06	1.20	0.02	0.0
Jul	136	4.37	1.31	0.02	0.1
Aug	153	4.93	1.66	0.03	0.0
Sep	178	5.94	2.00	0.04	0.0
Oct	213	6.88	2.13	0.05	0.0
Nov	219	7.30	2.16	0.06	0.0
Dec	234	7.54	2.05	0.07	0.0
Year	**2229**	**6.10**	**1.74**	**0.04**	**0.0**



Long-term monthly averages:

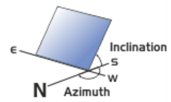
Gi_m Monthly sum of global irradiation [kWh/m^2]
Gi_d Daily sum of global irradiation [kWh/m^2]
Di_d Daily sum of diffuse irradiation [kWh/m^2]
Ri_d Daily sum of reflected irradiation [kWh/m^2]

Sh_{loss} Losses of global irradiation by terrain shading [%]

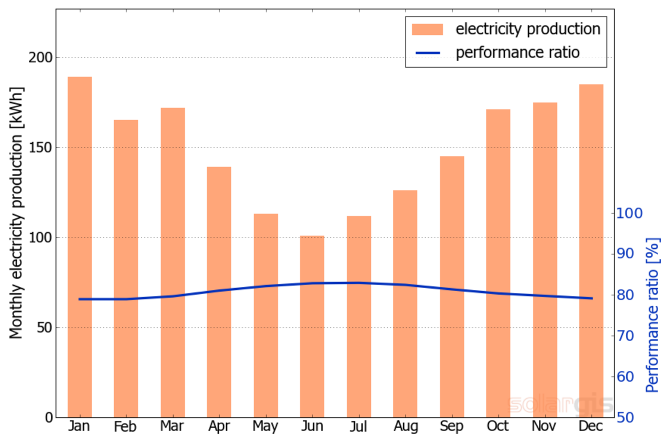
Average yearly sum of global irradiation for different types of surface:

	kWh/m^2	relative to optimally inclined
Horizontal	1993	89.5%
Optimally inclined (29°)	2228	100.0%
2-axis tracking	2994	134.4%
Your option	**2228**	**100.0%**

7. PV electricity production in the start-up



Month	Es_m	Es_d	Et_m	E_{share}	PR
Jan	188	6.09	189	10.5	78.9
Feb	165	5.90	165	9.2	78.9
Mar	171	5.55	172	9.6	79.6
Apr	139	4.64	139	7.8	81.0
May	113	3.65	113	6.3	82.1
Jun	101	3.37	101	5.6	82.8
Jul	112	3.63	112	6.3	82.9
Aug	125	4.05	126	7.0	82.4
Sep	145	4.84	145	8.1	81.3
Oct	171	5.53	171	9.6	80.3
Nov	174	5.82	175	9.7	79.7
Dec	184	5.96	185	10.3	79.1
Year	**1792**	**4.91**	**1793**	**100.0**	**80.5**



Long-term monthly averages:

Es_m Monthly sum of specific electricity prod. [kWh/kWp]
Es_d Daily sum of specific electricity prod. [kWh/kWp]
Et_m Monthly sum of total electricity prod. [kWh]
E_{share} Percentual share of monthly electricity prod. [%]
PR Performance ratio [%]

8. System losses and performance ratio

Energy conversion step	Energy output [kWh/kWp]	Energy loss [kWh/kWp]	Energy loss [%]	Performance ratio [partial %]	Performance ratio [cumul. %]
1. Global in-plane irradiation (input)	2228	-	-	100.0	100.0
2. Global irradiation reduced by terrain shading	2228	0	0.0	100.0	100.0
3. Global irradiation reduced by reflectivity	2170	-58	-2.6	97.4	97.4
4. Conversion to DC in the modules	1996	-174	-8.0	92.0	89.6
5. Other DC losses	1886	-110	-5.5	94.5	84.6
6. Inverters (DC/AC conversion)	1839	-47	-2.5	97.5	82.5
7. Transformer and AC cabling losses	1811	-28	-1.5	98.5	81.3
8. Reduced availability	1793	-18	-1.0	99.0	80.5
Total system performance	**1793**	**-435**	**-19.5**	**-**	**80.5**

Energy conversion steps and losses:

1. Initial production at Standard Test Conditions (STC) is assumed,
2. Reduction of global in-plane irradiation due to obstruction of terrain horizon and PV modules,
3. Proportion of global irradiation that is reflected by surface of PV modules (typically glass),
4. Losses in PV modules due to conversion of solar radiation to DC electricity; deviation of module efficiency from STC,
5. DC losses: this step assumes integrated effect of mismatch between PV modules, heat losses in interconnections and cables, losses due to dirt, snow, icing and soiling, and self-shading of PV modules,
6. This step considers euro efficiency to approximate average losses in the inverter,
7. Losses in AC section and transformer (where applicable) depend on the system architecture,
8. Availability parameter assumes losses due to downtime caused by maintenance or failures.

Losses at steps 2 to 4 are numerically modeled by pvPlanner. Losses at steps 5 to 8 are to be assessed by a user. The simulation models have inherent uncertainties that are not discussed in this report. Read more about simulation methods and related uncertainties to evaluate possible risks at http://solargis.info/doc/pvplanner/.

9. SolarGIS v1.8 - description of the database

SolarGIS is high-resolution climate database operated by GeoModel Solar s.r.o. with geographical extent covering Europe, Africa and Asia. Primary data layers include solar radiation, air temperature and terrain (elevation, horizon).

Air temperature at 2 m: developed from CFSR data (© NOAA NCEP); years: 1991 - 2009; recalculated to 15-minute values. The data are spatially enhanced to 1 km resolution to reflect variability induced by high resolution terrain.

Solar radiation: calculated from Meteosat satellite data; years: 1994 - 2010; 15-minute or 30-minute values at 90 m spatial resolution - global horizontal and direct normal irradiance; the uncertainty of annual global horizontal irradiation typically ranges between ±3% and ±5%; 99% data coverage for the analysed time period.

This estimation assumes year having 365 days. Occasional deviations in calculations may occur as a result of mathematical rounding and cannot be considered as a defect of algorithms. More information about the applied data and algorithms can be found at: http://solargis.info/doc/pvplanner/.

10. Service provider

GeoModel Solar s.r.o., Milana Marečka 3, 84107 Bratislava, Slovakia; Registration ID: 45 354 766, VAT Number: SK2022962766; Registration: Business register, District Court Bratislava I, Section Sro, File 62765/B

11. Mode of use

This report shows solar power estimation in the start-up phase of a PV system. The estimates are accurate enough for small and medium-size PV systems. For large projects planning and financing, more information may be needed:
1. Statistical distribution and uncertainty of solar radiation
2. Detailed specification of a PV system
3. Interannual variability and P90 uncertainty of PV production
4. Lifetime energy production considering performance degradation of PV components.

More information about full PV yield assessment can be found at: http://solargis.info/doc/pvreports/.

12. Disclaimer and legal information

Considering the nature of climate fluctuations, interannual and long-term changes, as well as the uncertainty of measurements and calculations, GeoModel Solar s.r.o. cannot take full guarantee of the accuracy of estimates. The maximum possible has been done for the assessment of climate conditions based on the best available data, software and knowledge. GeoModel Solar s.r.o. shall not be liable for any direct, incidental, consequential, indirect or punitive damages arising or alleged to have arisen out of use of the provided report.

13. Contact information

This report has been generated by Centre for Renewable and Sustainable Energy Studies (CRSES), Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Private Bag X1, 7602 Matieland, South Africa, http://www.crses.sun.ac.za

Appendix B – Equipment Datasheets

SPECIFICATIONS

Standard Test Conditions (STC)
*STC = 1000 W/M² irradiance, 25°C module temperature, AM 1.5 spectrum**

	KD320	KD250	KD245	KD240	KD220	KD215	KD140
Maximum Power	320W	250W	245W	240W	220W	215W	140W
Number of Cells	80	60	60	60	54	54	36
Tolerance	+5% / -3%	+5% / -3%	+5% / -3%	+5% / -3%	+5% / -0%	+5% / -0%	+7% / -0%
Maximum System Voltage	600V	600V	600V	600V	600V	600V	600V
Maximum Power Voltage	40.1V	29.8V	29.8V	29.8V	26.6V	26.6V	17.7V
Maximum Power Current	7.99A	8.39A	8.23A	8.06A	8.28A	8.09A	7.91A
Open Circuit Voltage	49.5V	36.9V	36.9V	36.9V	33.2V	33.2V	22.1V
Short Circuit Current	8.60A	9.09A	8.91A	8.59A	8.98A	8.78A	8.68A
Series Fuse Rating	15A	15A	15A	15A	15A	15A	15A
Length	65.4″	65.4″	65.4″	65.4″	59.1″	59.1″	59.1″
Width	52.0″	39.0″	39.0″	39.0″	39.0″	39.0″	26.3″
Depth	1.8″	1.8″	1.8″	1.8″	1.8″	1.8″	1.8″
Weight	60.6 lbs	46.3 lbs	46.3 lbs	46.3 lbs	41.0 lbs	41.0 lbs	28.4 lbs
Termination Method	Locking Plug-in Connectors						

* Subject to simulator measurement uncertainty of +/- 3%.
KYOCERA reserves the right to modify these specifications without notice.
For more detailed specifications, visit www.kyocerasolar.com

NEC 2008 COMPLIANT
UL 1703 LISTED
CERTIFIED IEC61215 ED2 IEC61730 BY JET

WARNING: Read the instruction manual in its entirety prior to handling, installing & operating Kyocera Solar modules.

040513

Advanced meter

- Single- and polyphase direct connected meter
- MID B bi-directional active and IEC-class 2 reactive energy measurement
- Rated registers controlled by real-time clock and calendar
- Energy profiling: three independent profiles for electricity configurable by content
- Four independent profiles for multi-energy values
- Logging for meter events, power quality, disconnector states, anti-tamper and multi-energy events
- Standardized security system
- Demand supervision unit
- Firmware upgrade possibility
- Integrated disconnector and up to two relays for appliance load controls

Communication

Power line carrier (PLC)

The E450's communication system is based on International Electrotechnical Commission (IEC) open standards (IEC 61334) and DLMS/COSEM protocols. The integrated PLC modem will provide the best cost of ownership in large scale smart metering rollouts.

GPRS/UMTS

The E450 meter provides a modular GPRS/UMTS communication solution. The communication module is exchangeable and has an integrated antenna. Alternatively, one can use an external antenna that is easy to install and maintain. The solution is designed to deliver a wide range of services at a low communication cost.

Local communication

Meter has an additional optical port supporting IEC 62056-21 and DLMS readout commands. Parameterization can be handled locally according to predefined security settings.

End user interaction

The E450 meter enables real time interaction with end users. With an elegant and timeless design your customer will have a new experience when looking at the energy meter. The front cover slider allows you to personalize the look of the meter, while your installers can access the technical nameplate and optical interface by moving it down.

An optional integrated wireless interface enables bi-directional communication with our ecoMeter in home display. Customized messages can be shown on the meter display or sent to the ecoMeter.

Multi-energy data collector

The E450 meter can act as a gateway for collecting data and interacting with other energy meters, like gas, water or heat.

		E450 (1phase) PLC	**E450** (3phase) PLC	**E450** (3phase) 2G/3G
Connection type	Direct connection 5 (80) A	available	not available	not available
	Direct connection 5 (100) A	not available	available	available
Accuracy class	Combined meter active energy class 1 (IEC); A (MID), reactive energy class 2	available	available	available
System interface	PLC interface	available	available	not available
	2G/3G interface	not available	not available	available
User and wireless interface	Optical + wireless M-Bus (868MHz)	available	available	available
Local interface (daughter board)	Wired M-Bus	optional	optional	optional
Disconnector	1-pole disconnector (live only)	available	not available	not available
	3-pole disconnector (live only)	not available	available	available
Digital output	with 90mA releay option	available	available	available
Digital input	1 digital input	available	available	available
Outputs	1 Bistable relay 8 A, 230VAC + 1 digital output 100 mA, 230VAC	available	available	available
	1 Bistable relay 8 A, 230VAC + 1 latching relay 5 A, 230VAC	optional	optional	optional

available
not available
optional

Prudent Energy
VRB™ Systems

VRB™ Battery System Specifications

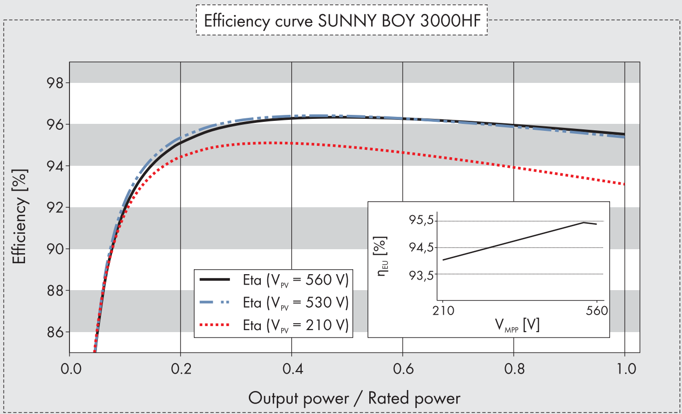
Note: Battery System performance specifications are based on preliminary testing; actual measured values may vary.

Performance Characteristics	
Open circuit voltage at 0% and 100% capacity	50 VDC to 56 VDC
Maximum charge voltage (at battery terminals)	58.9 VDC
Minimum voltage on discharge	42 VDC
Maximum charge current	140 ADC
Maximum discharge current (continuous)	140 ADC
Maximum discharge current (< 300 s)	175 ADC
Continuous power at beginning of discharge	7.0 kW
Continuous power at end of discharge	5.25 kW
Duty cycle	100%
Physical Specifications (Approximate)	
Dimensions (D x W x H) (power module only) Dimensions (D x W x H) (with 40 kWh storage)	1.0 m x 1.2 m x 1.1 m 1.3 m x 1.15 m x 1.90 m
Mass (power module) Mass (power module plus 40 kWh storage)	510 kg 5,300 kg
Operating Limits	
Electrolyte Temperature range	10°C to 35°C
Humidity	0% to 95%, non-condensing
Altitude range (no derating)	0 m to 3,000 m
Environmental Limits – Shipping and Storage (Class 2K3 in IEC 60721-3-2)	
Allowable temperature range	-25°C to 70°C
Humidity	0% to 95%, non-condensing
Altitude range	0 m to 3,000 m
Reliability and Design Life	
Cycle life	> 10,000 cycles
Service life	100,000 hours

Maintenance Intervals	**Frequency**	**Offline Duration**
Maintenance interval "A"	9,000 hours	< 2 hours
Maintenance interval "B"	27,000 hours	< 8 hours
Service life	90,000 hours	N/A

SUNNY BOY 2000HF / 2500HF / 3000HF

Technical Data	Sunny Boy 2000HF	Sunny Boy 2500HF
Input (DC)		
Max. DC power (@ cos φ=1)	2100 W	2600 W
Max. input voltage	700 V	700 V
MPP voltage range / rated input voltage	175 V – 560 V / 530 V	175 V – 560 V / 530 V
Min. input voltage / initial input voltage	175 V / 220 V	175 V / 220 V
Max. input current	12 A	15 A
Max. input current per string	12 A	15 A
Number of independent MPP inputs / strings per MPP input	1 / 2	1 / 2
Output (AC)		
Rated output power (@ 230 V, 50 Hz)	2000 W	2500 W
Max. apparent AC power	2000 VA	2500 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V – 280 V	220 V, 230 V, 240 V / 180 V – 280 V
AC power frequency / range	50 Hz, 60 Hz / −4.5 Hz ... +4.5 Hz	50 Hz, 60 Hz / −4.5 Hz ... +4.5 Hz
Rated power frequency / rated power voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	11.4 A	14.2 A
Power factor at rated power	1	1
Adjustable displacement factor	–	–
Feed-in phases / connection phases	1 / 1	1 / 1
Efficiency		
Max. efficiency / European efficiency	96.3 % / 95 %	96.3 % / 95.3 %
Protection		
Input-side disconnection device	●	●
Ground-fault monitoring / grid monitoring	● / ●	● / ●
DC surge arrester Type II, can be integrated	–	–
DC reverse-polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / ●	● / ● / ●
All-pole sensitive residual current monitoring unit	–	–
Protection class (according to IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III	I / III
General Data		
Dimensions (W / H / D)	348 / 580 / 145 mm (13.7 / 22.8 / 5.7 in)	348 / 580 / 145 mm (13.7 / 22.8 / 5.7 in)
Weight	17 kg / 37.4 lb	17 kg / 37.4 lb
Operating temperature range	−25 °C ... +60 °C / −13 °F ... +140 °F	−25 °C ... +60 °C / −13 °F ... +140 °F
Noise emission (typical)	38 dB(A)	38 dB(A)
Internal consumption (night)	1 W	1 W
Topology	HF transformer	HF transformer
Cooling concept	Convection	OptiCool
Degree of protection (according to IEC 60529)	IP65	IP65
Degree of protection of connection area (according to IEC 60529)	IP54	IP54
Climatic category (according to IEC 60721-3-4)	4K4H	4K4H
Maximum permissible value for relative humidity (non-condensing)	100 %	100 %
Features		
DC terminal	SUNCLIX	SUNCLIX
AC terminal	Connector	Connector
Display	Graphic	Graphic
Interface: RS485 / *Bluetooth*	○ / ●	○ / ●
Warranty: 5 / 10 / 15 / 20 / 25 years	● / ○ / ○ / ○ / ○	● / ○ / ○ / ○ / ○
Multi-function relay	○	○
Certificates and approvals (more available on request)	CE, VDE0126-1-1, G83/1-1, RD 1663/2000, PPC, AS4777, EN 50438*, C10/11, PPDS, IEC 61727, ENEL-Guida, SI4777, UTE C15-712-1, VDE-AR-N 4105	
Type designation	SB 2000HF-30	SB 2500HF-30



Accessories

SMA Plug-in Grounding
PLUGIN-GRD-10-NR

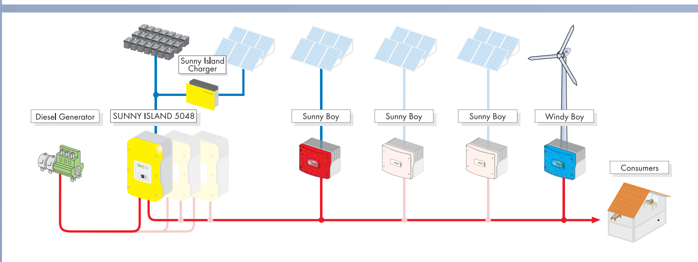
Quick Module RS485 + multi-function relay
485QM-10-NR

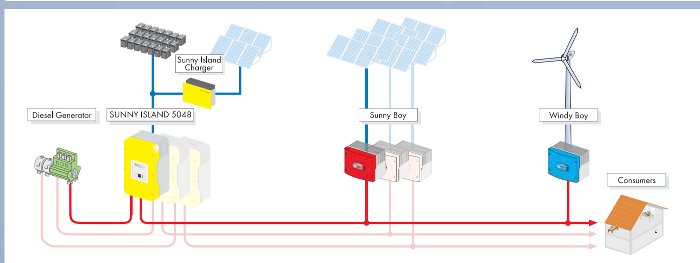
* Does not apply to all national deviations of EN 50438
** Only applies to V option
● Standard features ○ Optional features – Not available
Data at nominal conditions

Technical Data	Sunny Boy 3000HF	
Input (DC)		
Max. DC power (@ cos φ=1)	3150 W	
Max. input voltage	700 V	
MPP voltage range / rated input voltage	210 V – 560 V / 530 V	
Min. input voltage / initial input voltage	175 V / 220 V	
Max. input current	15 A	
Max. input current per string	15 A	
Number of independent MPP inputs / strings per MPP input	1 / 2	
Output (AC)		
Rated output power (@ 230 V, 50 Hz)	3000 W	
Max. apparent AC power	3000 VA	
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V – 280 V	
AC power frequency / range	50 Hz, 60 Hz / −4.5 Hz ... +4.5 Hz	
Rated power frequency / rated power voltage	50 Hz / 230 V	
Max. output current	15 A	
Power factor at rated power	1	
Adjustable displacement factor	–	
Feed-in phases / connection phases	1 / 1	
Efficiency		
Max. efficiency / European efficiency	96.3 % / 95.4 %	
Protection		
Input-side disconnection device	●	
Ground-fault monitoring / grid monitoring	● / ●	
DC surge arrester Type II, can be integrated	–	
DC reverse-polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / ●	
All-pole sensitive residual current monitoring unit	–	
Protection class (according to IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III	
General Data		
Dimensions (W / H / D)	348 / 580 / 145 mm (13.7 / 22.8 / 5.7 in)	
Weight	17 kg / 37.4 lb	
Operating temperature range	−25 °C ... +60 °C / −13 °F ... +140 °F	
Noise emission (typical)	38 dB(A)	
Internal consumption (night)	1 W	
Topology	HF transformer	
Cooling concept	OptiCool	
Degree of protection (according to IEC 60529)	IP65	
Degree of protection of connection area (according to IEC 60529)	IP54	
Climatic category (according to IEC 60721-3-4)	4K4H	
Maximum permissible value for relative humidity (non-condensing)	100 %	
Features		
DC terminal	SUNCLIX	
AC terminal	Connector	
Display	Graphic	
Interface: RS485 / *Bluetooth*	○ / ●	
Warranty: 5 / 10 / 15 / 20 / 25 years	● / ○ / ○ / ○ / ○	
Multi-function relay	○	
Certificates and approvals (more available on request)	CE, VDE0126-1-1, G83/1-1, RD 1663/2000, PPC, AS4777, EN 50438*, C10/11, PPDS, KEMCO**, IEC 61727, ENEL-Guida, SI4777, UTE C15-712-1, VDE-AR-N 4105	
Type designation	SB 3000HF-30	

Technical Data
SUNNY ISLAND 5048 / 5048U

	SI 5048	SI 5048U
Output data		
Nominal AC voltage (adjustable)	230 V (202 – 253 V)	120 V (105 – 132 V)
Nominal grid frequency (adjustable)	50 / 60 Hz (45 – 65 Hz)	60 Hz (55 – 65 Hz)
Continuous AC power at 25 °C / 45 °C	5000 / 4000 W	5000 / 4000 W
Continuous AC power at 25 °C for 30 / 5 / 1 min	6500 / 7200 / 8400 W	6500 / 7200 / 8400 W
Max. AC power for 3 s	12000 W	11000 W
Nominal AC current	21.7 A	41.7 A
Max. AC current	120 A (60 ms)	180 A (60 ms)
Output voltage harmonic distortion factor	< 3 %	< 3 %
Power factor	-1 to +1	-1 to +1
Input data		
Input voltage (range)	230 V (172.5 – 250 V)	120 V (80 – 150 V)
Input frequency	50 / 60 Hz (40 – 70 Hz)	60 Hz (54 – 66 Hz)
Max. AC input current (adjustable)	56 A (2 – 56 A)	56 A (2 – 56 A)
Max. input power	12.8 kW	6.7 kW
Battery data		
Nominal battery Voltage (range)	48 V (41 – 63 V)	48 V (41 – 63 V)
Max. battery charging current	120 A	120 A
Continuous charging current	100 A	100 A
Battery capacity	100 – 10 000 Ah	100 – 10 000 Ah
Charge control	IU_0U with automatic full and equalization charge	IU_0U with automatic full and equalization charge
Efficiency/power consumption		
Max. efficiency (typical)	95 %	95 %
Own consumption with no load (standby)	25 W (< 4 W)	25 W (< 4 W)
Protection type (DIN EN 60529)	IP30	NEMA 1
Certification	CE	UL
Device protection	short-circuit, overload, overtemperature	short-circuit, overload, overtemperature
Interfaces	2 LEDs, 4 buttons, 2-line display, 2 multifunction relays, RS485, SD card	2 LEDs, 4 buttons, 2-line display, 2 multifunction relays, RS485, SD card
Mechanical data		
Width / height / depth	467 / 612 / 235 mm	467 / 612 / 235 mm
Weight	63 kg	63 kg
Ambient conditions		
Ambient temperature	-25 °C ... +50 °C	-25 °C ... +50 °C
Warranty (EU)	5 years	5 years
Accessories		
Ext. battery temperature sensor	included	included
"GenMan" generator start manager	optional	optional
Multicluster-Box	optional	–
"BatFuse" battery connection box	optional	optional
	Version: December 2008	

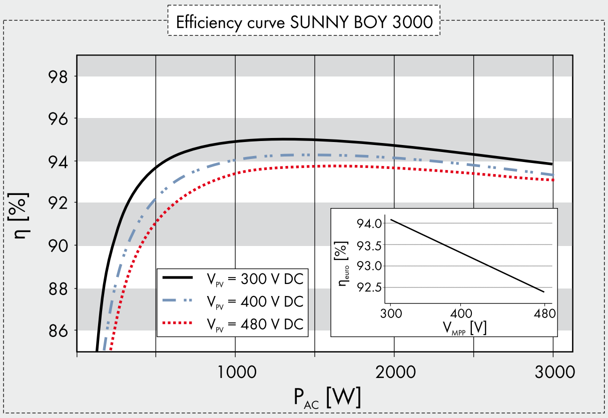




Website: www.alphatrononline.com
Email: sales@alphatrononline.com
Australia Phone: 1800 148 793
New Zealand Phone: +64 9 414 5520

SMA Solar Technology AG

Technical data	Sunny Boy 1200	Sunny Boy 1700	Sunny Boy 2500	Sunny Boy 3000
Input (DC)				
Max. DC power (@ cos φ = 1)	1320 W	1850 W	2700 W	3200 W
Max. DC voltage	400 V	400 V	600 V	600 V
MPP voltage range	100 V – 320 V	147 V – 320 V	224 V – 480 V	268 V – 480 V
DC nominal voltage	120 V	180 V	300 V	350 V
Min. DC voltage / start voltage	100 V / 120 V	139 V / 180 V	224 V / 300 V	268 V / 330 V
Max. input current / per string	12.6 A / 12.6 A	12.6 A / 12.6 A	12 A / 12 A	12 A / 12 A
Number of MPP trackers / strings per MPP tracker	1 / 2	1 / 2	1 / 3	1 / 3
Output (AC)				
AC nominal power (@ 230 V, 50 Hz)	1200 W	1550 W	2300 W	2750 W
Max. AC apparent power	1200 VA	1700 VA	2500 VA	3000 VA
Nominal AC voltage; range	220, 230, 240 V; 180 V – 265 V	220, 230, 240 V; 180 V – 265 V	220, 230, 240 V; 180 V – 265 V	220, 230, 240 V; 180 V – 265 V
AC grid frequency; range	50, 60 Hz; ± 4.5 Hz	50, 60 Hz; ± 4.5 Hz	50, 60 Hz; ± 4.5 Hz	50, 60 Hz; ± 4.5 Hz
Max. output current	6.1 A	8.6 A	12.5 A	15 A
Power factor (cos φ)	1	1	1	1
Phase conductors / connection phases	1 / 1	1 / 1	1 / 1	1 / 1
Efficiency				
Max. efficiency / Euro-eta	92.1 % / 90.9 %	93.5 % / 91.8 %	94.1 % / 93.2 %	95.0 % / 93.6 %
Protection devices				
DC reverse-polarity protection	●	●	●	●
ESS switch-disconnector	●	●	●	●
AC short circuit protection	●	●	●	●
Ground fault monitoring	●	●	●	●
Grid monitoring (SMA Grid Guard)	●	●	●	●
Galvanically isolated / all-pole sensitive fault current monitoring unit	●/–	●/–	●/–	●/–
Protection class / overvoltage category	I / III	I / III	I / III	I / III
General data				
Dimensions (W / H / D) in mm	440 / 339 / 214	440 / 339 / 214	440 / 339 / 214	440 / 339 / 214
Weight	23 kg	25 kg	28 kg	32 kg
Operating temperature range	–25 °C ... +60 °C	–25 °C ... +60 °C	–25 °C ... +60 °C	–25 °C ... +60 °C
Noise emission (typical)	≤ 41 dB(A)	≤ 46 dB(A)	≤ 33 dB(A)	≤ 30 dB(A)
Internal consumption (night)	< 0.1 W	< 0.1 W	< 0.25 W	< 0.25 W
Topology	LF transformer	LF transformer	LF transformer	LF transformer
Cooling concept	Convection	Convection	Convection	Convection
Electronics protection rating / connection area (as per IEC 60529)	IP65 / IP65	IP65 / IP65	IP65 / IP65	IP65 / IP65
Climatic category (per IEC 60721-3-4)	4K4H	4K4H	4K4H	4K4H
Features				
DC connection: SUNCLIX	●	●	●	●
AC connection: screw terminal / plug connector / spring-type terminal	–/●/–	–/●/–	–/●/–	–/●/–
Display: text line / graphic	●/–	●/–	●/–	●/–
Interfaces: RS485 / *Bluetooth*®	○/○	○/○	○/○	○/○
Warranty: 5 / 10 / 15 / 20 / 25 years	●/○/○/○/○	●/○/○/○/○	●/○/○/○/○	●/○/○/○/○
Certificates and permits (more available on request)	CE, VDE 0126-1-1, UTE C 15-712-1, DK 5940*, RD 1663 , G83/1-1, CER/06/190 (only SB 1700), PPC, AS4777, EN 50438**, C10/C11, PPDS, IEEE 929		CE, VDE 0126-1-1, DK 5940*, RD 1663 , G83/1-1, CER/06/190, PPC, AS4777, EN 50438**, C10/C11, PPDS	
*Only applies to IT variants, ** Does not apply to all national deviations of EN 50438				
● Standard features ○ Optional features – not available Data at nominal conditions				
Type designation	SB 1200	SB 1700	SB 2500	SB 3000



Accessories


RS485 interface of type 485PB-NR


Bluetooth® Piggy Back BTPBINV-NR


Grounding set "Positive" ESHV-P-NR


Grounding set "Negative" ESHV-P-NR

LAN	
Technology/Standard	802.15.4
Frequency	2.4 GHz
Modulation	Direct Sequence Spread Spectrum (DSSS)
Network Configuration	Self-Healing Mesh
Transmit Output Power	
North America & Australia International	63 mW (+18 dBm) 10 mW (+10 dBm)
RF Data Rate	250 kbps
Receiver Sensitivity	-102 dBm
Security	128 Bit AES Encryption Link and Network Keys
Antenna Gain	2 dBi
No. of Channels	15
WAN	
Technology	Cellular/EVDO/1xRTT/ HSDPA/EDGE/GPRS/ Wi-Fi/Gobi
Security	SSL tunnels, SSHv2, FIPS 197 (serial port) VPN-IPsec with IKE/ISAKMP, multiple tunnel support, DES, 3DES, up to 256 bit AES Encryption, VPN Pass-through, GRE Forwarding
Management	HTTP/HTTPS web interface Password access control IP service port control
Compliance / Agency	
North America	FCC 47 CFR PT 15-B UL 60950-1 CSA C22.2 #60950-2 NEMA4
Global (passed)	IEC 60950-1, CB REPORT IEC 60950-22, CB REPORT IEC 60529, IP66 EN55022 CLASS B Cenelec EN 55024 IEC 61000-6-4
Global (pending)	A-Tick

Power	
Average Operating Current	< 0.1A
Supply Voltage	
North American International	100 - 140 VAC 100 - 240 VAC
Power Consumption Idle (W)	3.9 W at 120 VAC
Power Consumption Max (W)	13.4 W at 120 VAC
Surge Protection	
North American International	10 kA Inominal, 36 kA Ipeak 20 kA Inominal, 50 kA Ipeak
Environmental	
Operational Temperature Range	-35 °C to +70 °C
Storage Temperature Range	-40 °C to +85 °C
Relative Humidity	5 - 95% (Non-condensing)
Mechanical	
Dimension (L x W x H)	12" x 10" x 6" (31 cm x 25 cm x 15 cm)
Weight	10 lbs. (4.5 kg)
Mounting Options	Wood pole, metal pole, concrete pole, rooftop
Internal Flash Storage	> 1GB

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Appendix C – Projected Energy Demand Load Profiles

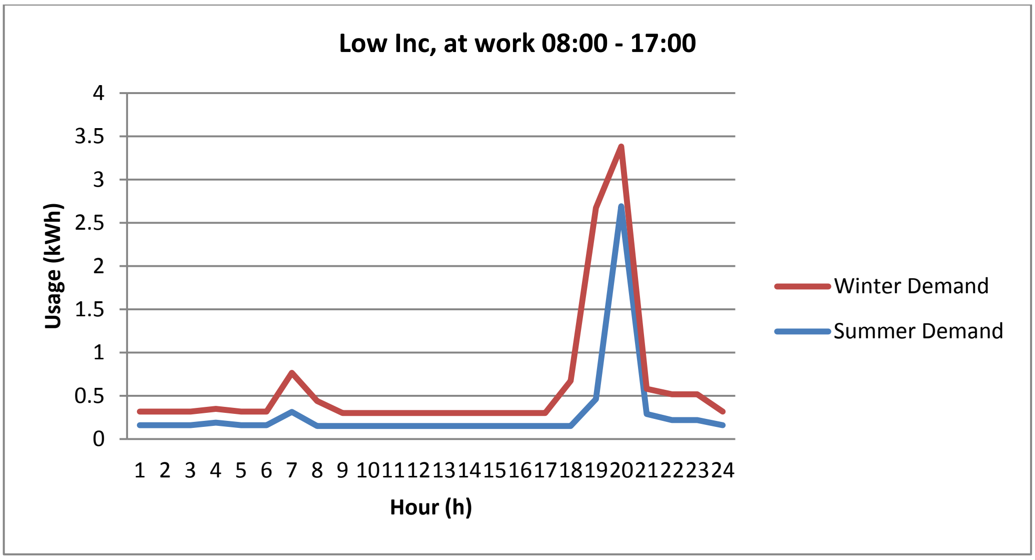

Figure 15: Low Income Energy Demand Load Profile, At Work 08:00 – 17:00

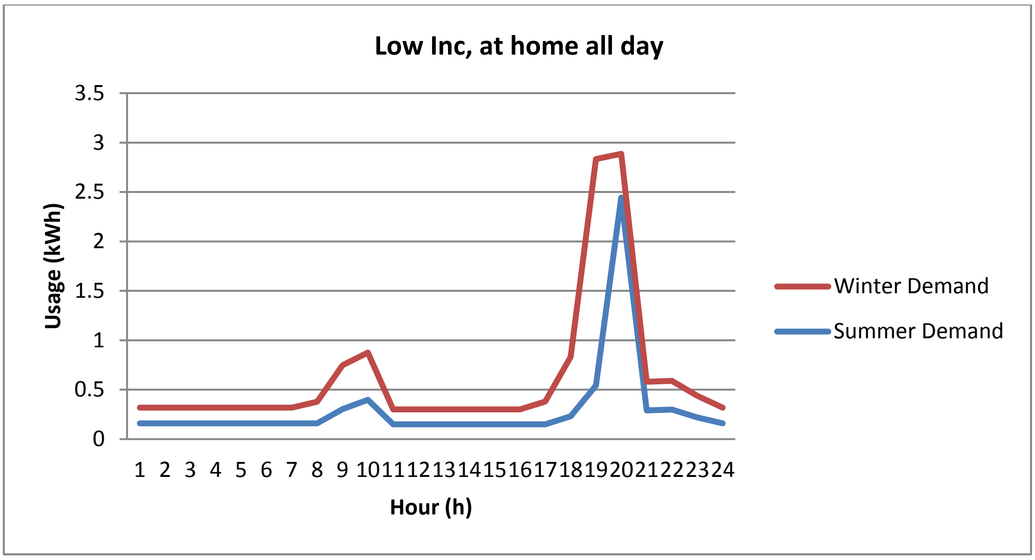

Figure 16: Low Income Energy Demand Load Profile, At Home All Day

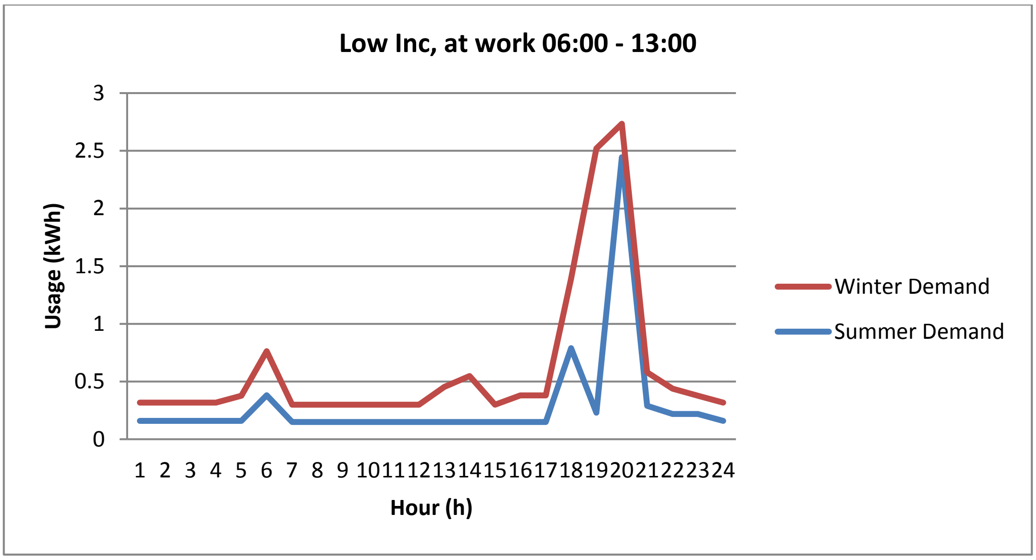

Figure 17: Low Income Energy Demand Load Profile, At Work 06:00 – 13:00

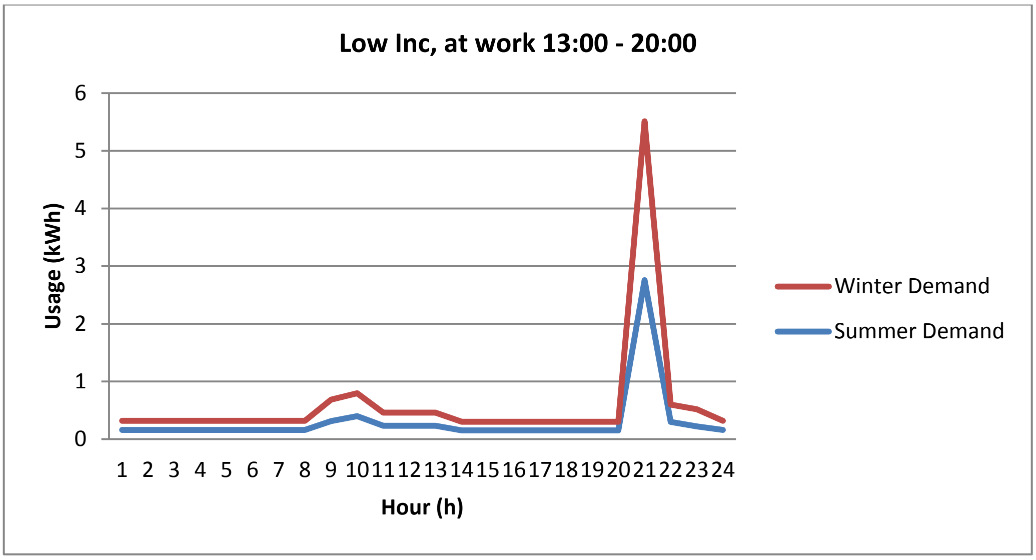

Figure 18: Low Income Energy Demand Load Profile, At Work 13:00 – 20:00

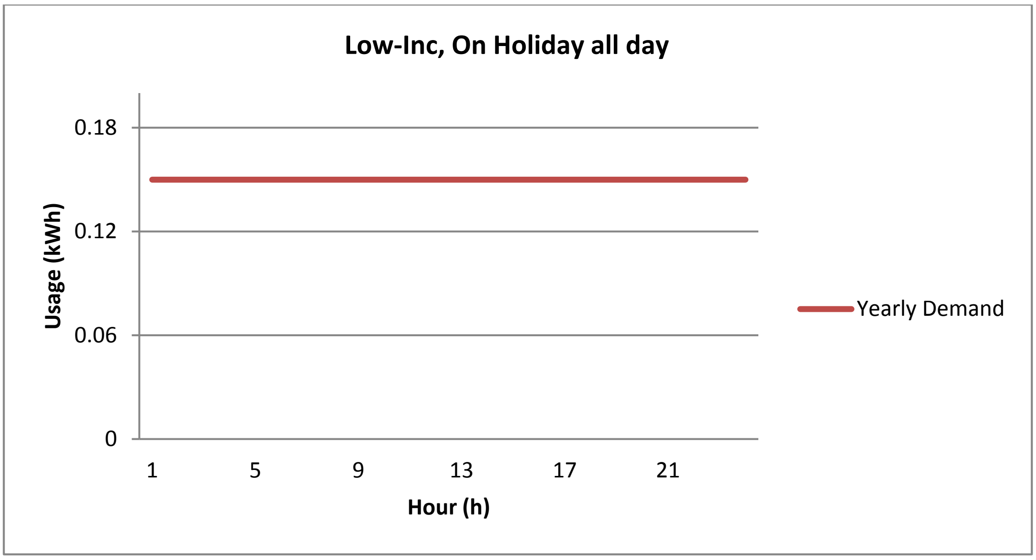

Figure 19: Low Income Energy Demand Load Profile, Away All Day

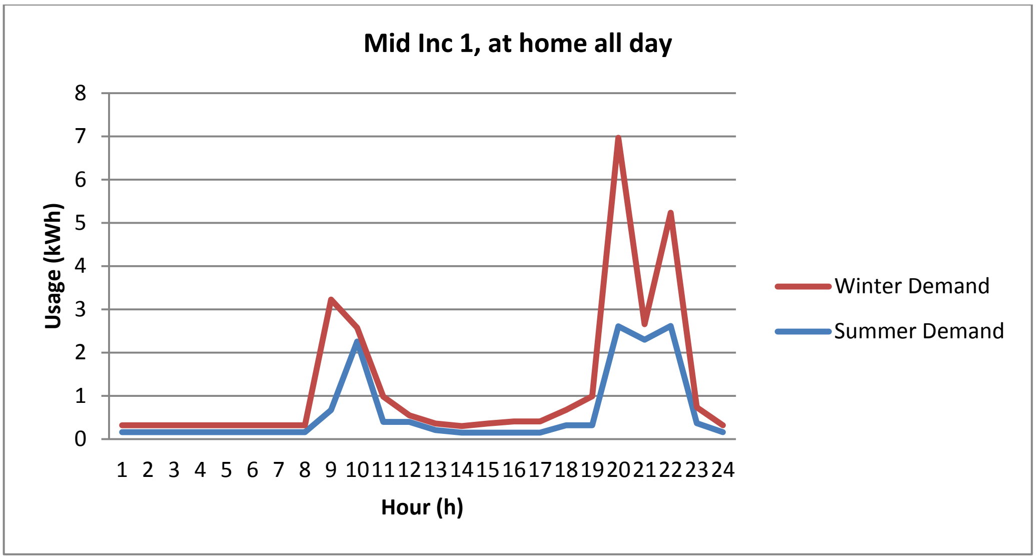

Figure 20: Middle Income 1 Energy Demand Load Profile, At Home All Day

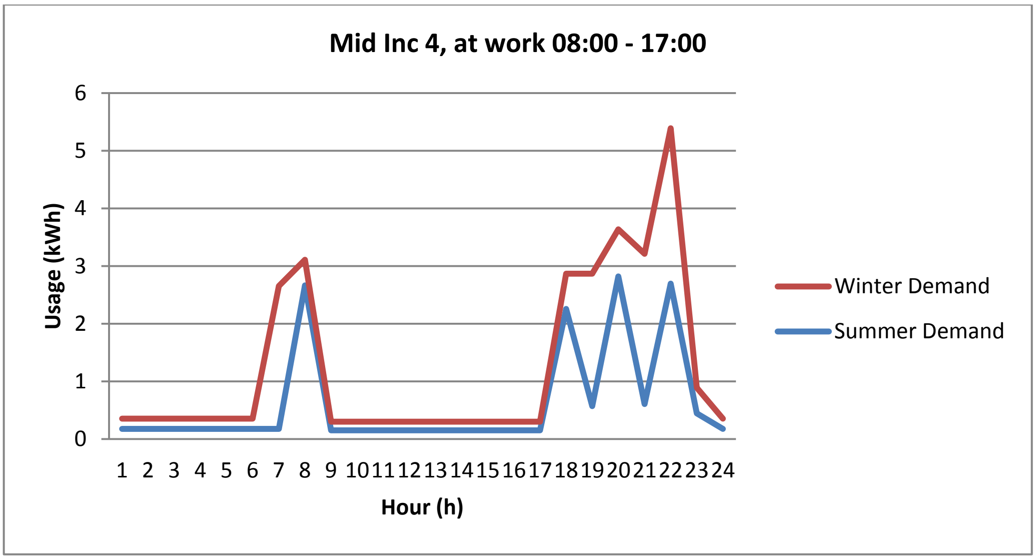

Figure 21: Middle Income 4 Energy Demand Load Profile, At Work 08:00 – 17:00

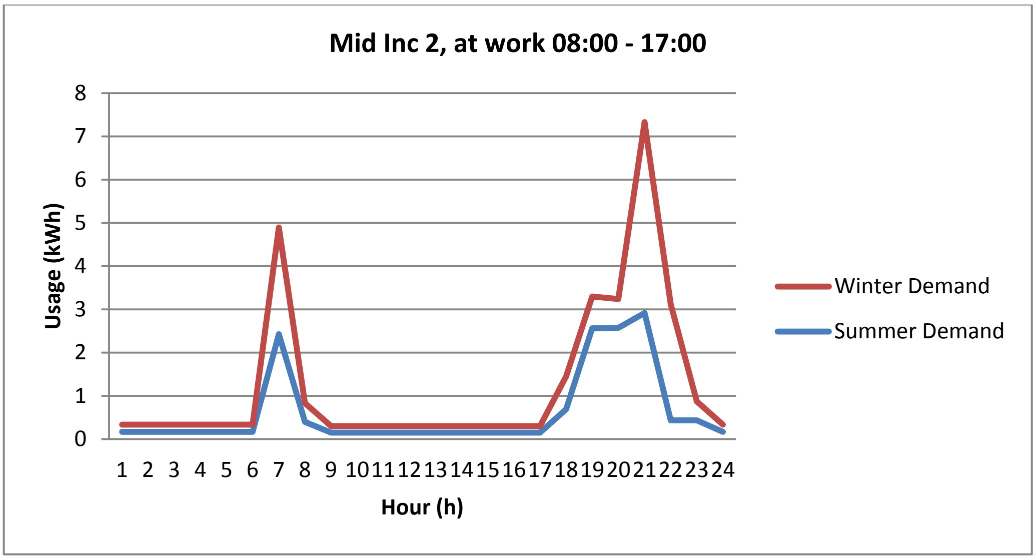

Figure 22: Middle Income 2 Energy Demand Load Profile, At Work 08:00 – 17:00

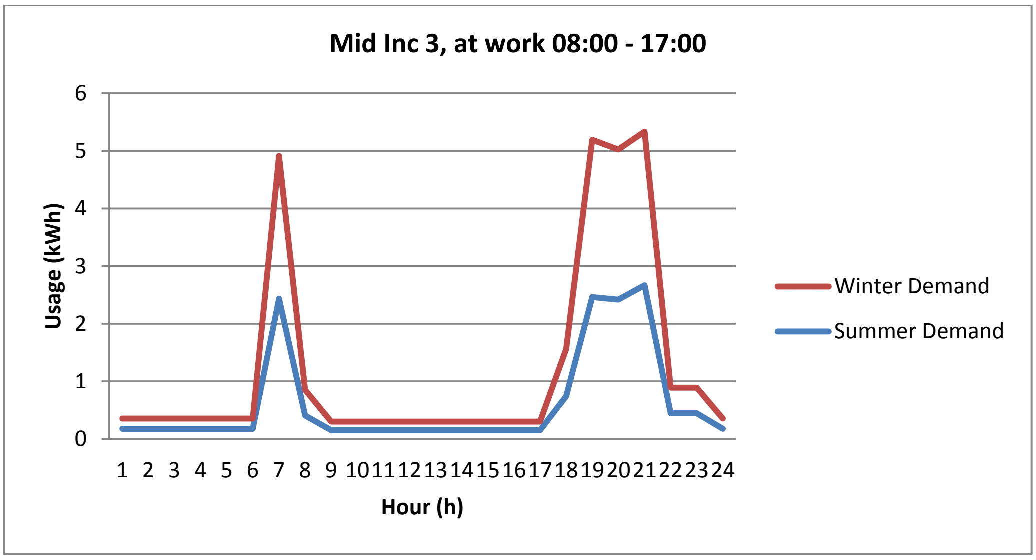

Figure 23: Middle Income 3 Energy Demand Load Profile, At Work 08:00 – 17:00

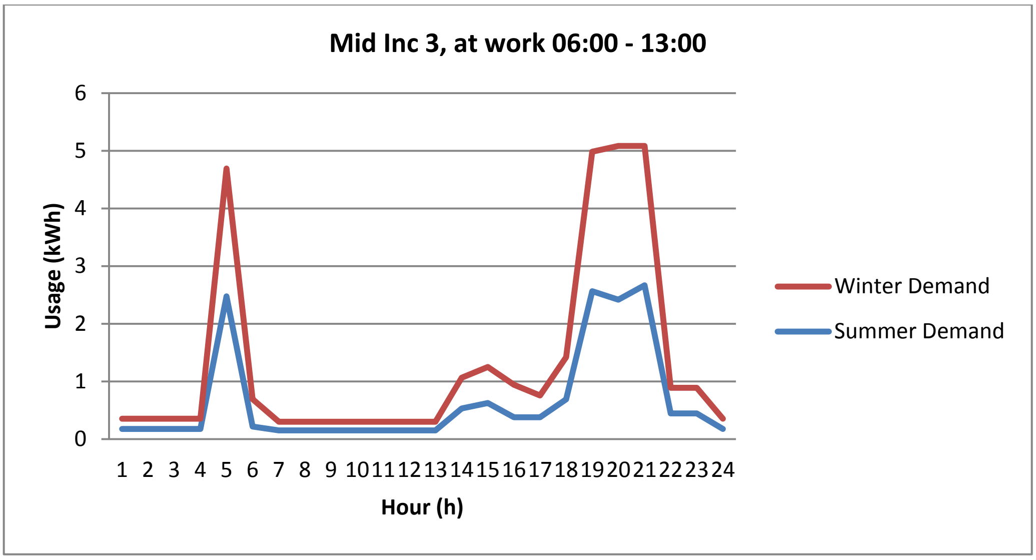

Figure 24: Middle Income 3 Energy Demand Load Profile, At Work 06:00 – 13:00

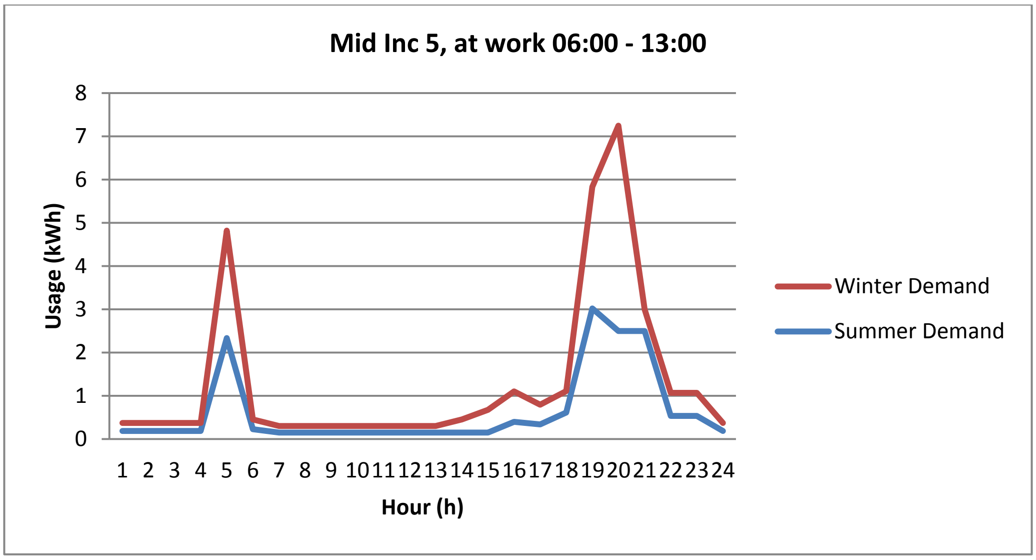

Figure 25: Middle Income 5 Energy Demand Load Profile, At Work 06:00 – 13:00

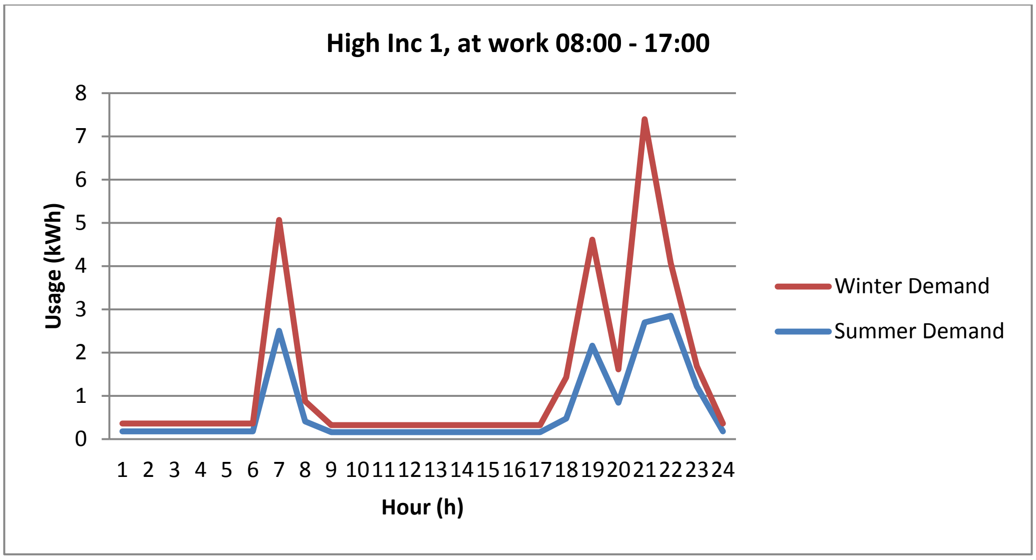

Figure 26: High Income 1 Energy Demand Load Profile, At Work 08:00 – 17:00

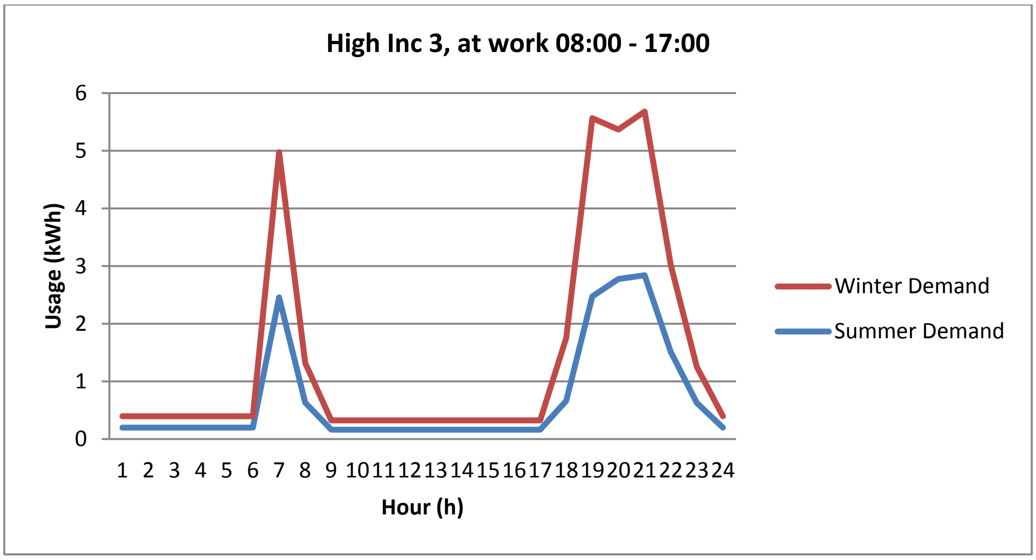

Figure 27: High Income 3 Energy Demand Load Profile, At Work 08:00 – 17:00

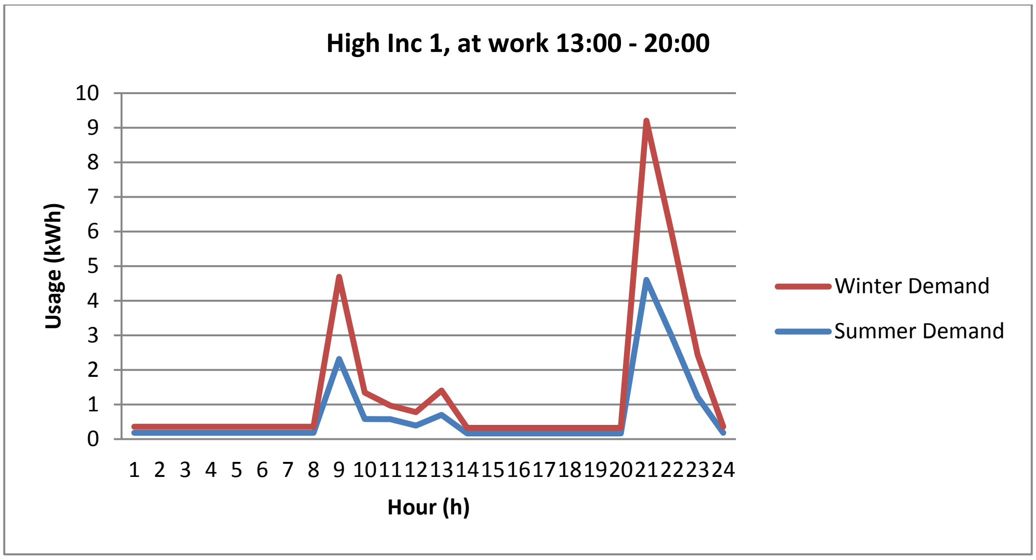

Figure 28: High Income 1 Energy Demand Load Profile, At Work 13:00 – 20:00

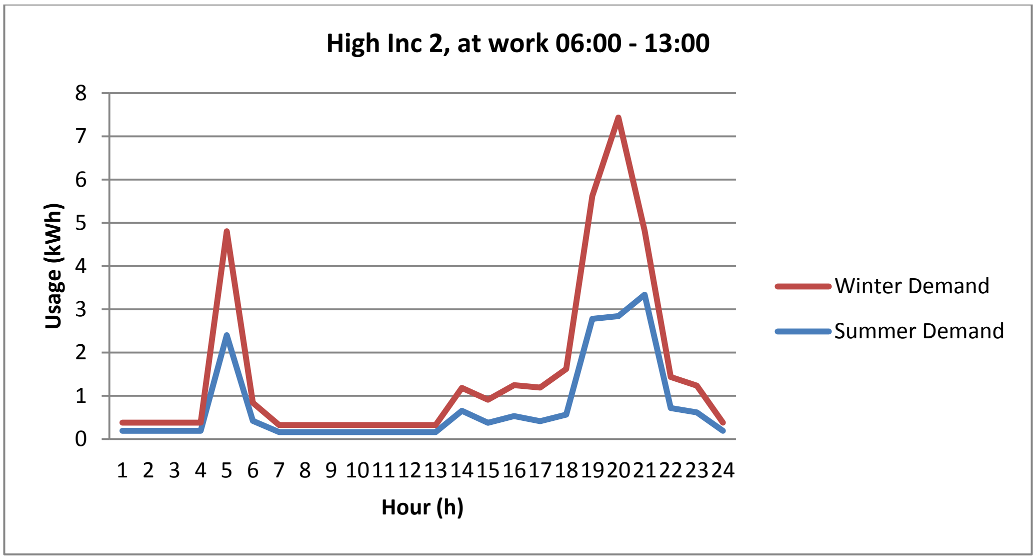

Figure 29: High Income 2 Energy Demand Load Profile, At Work 06:00 – 13:00

Appendix D – Wire Diagrams of Blocks' Electrical Layouts

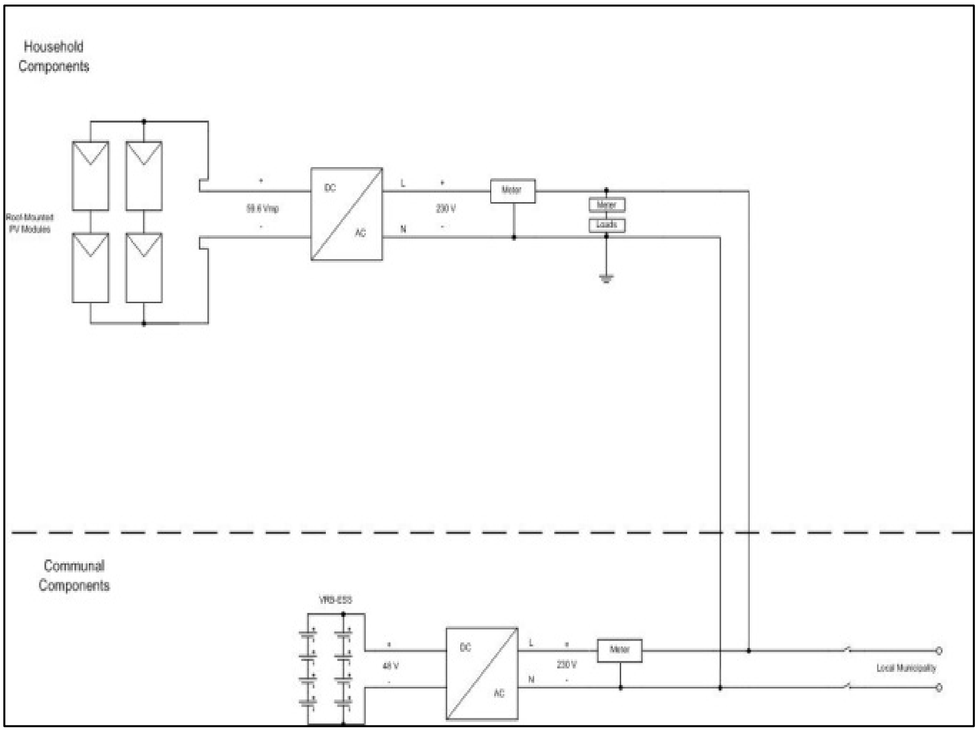

Figure 30: Low Income Block Option 1 – Electrical Wire Diagram

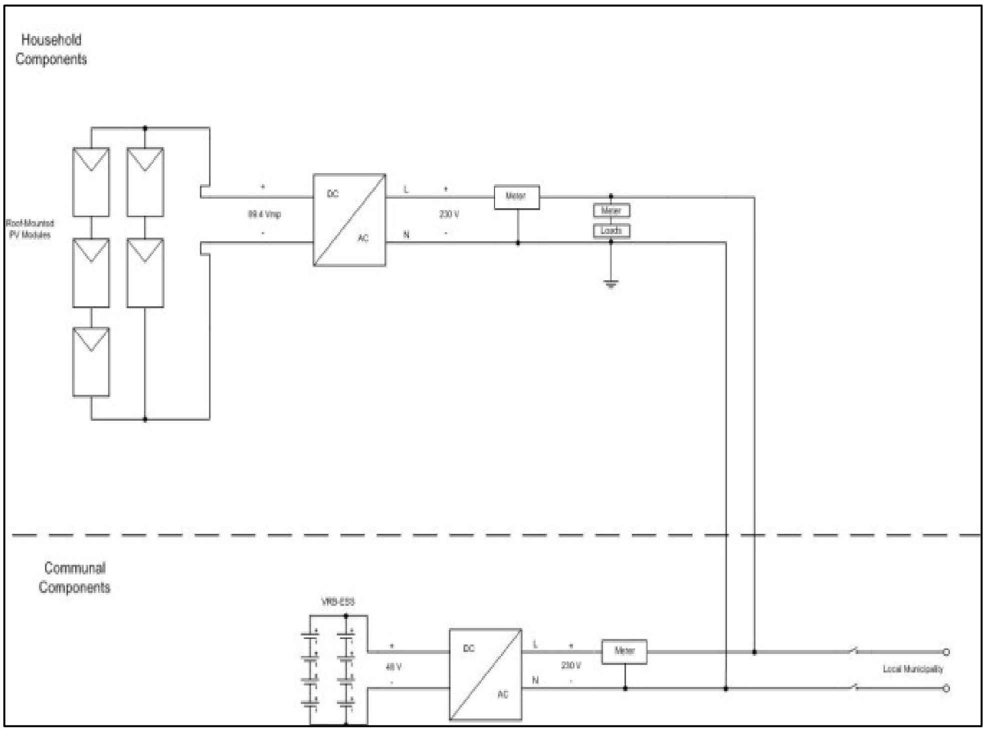

Figure 31: Low Income Block Option 2 – Electrical Wire Diagram

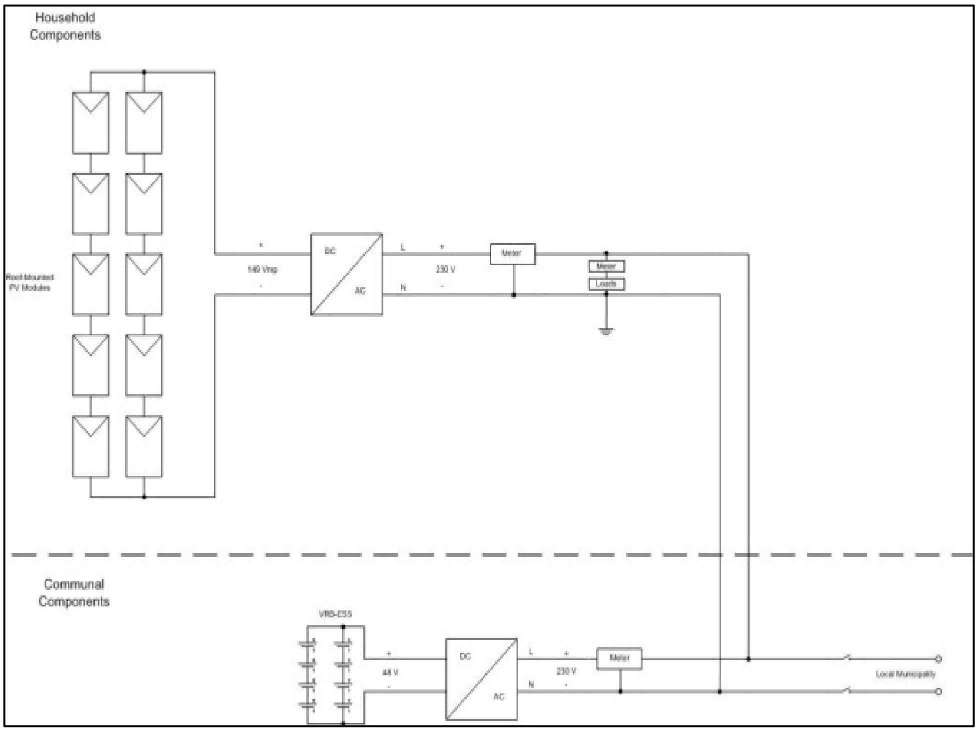

Figure 32: Middle Income Block Option 1 – Electrical Wire Diagram

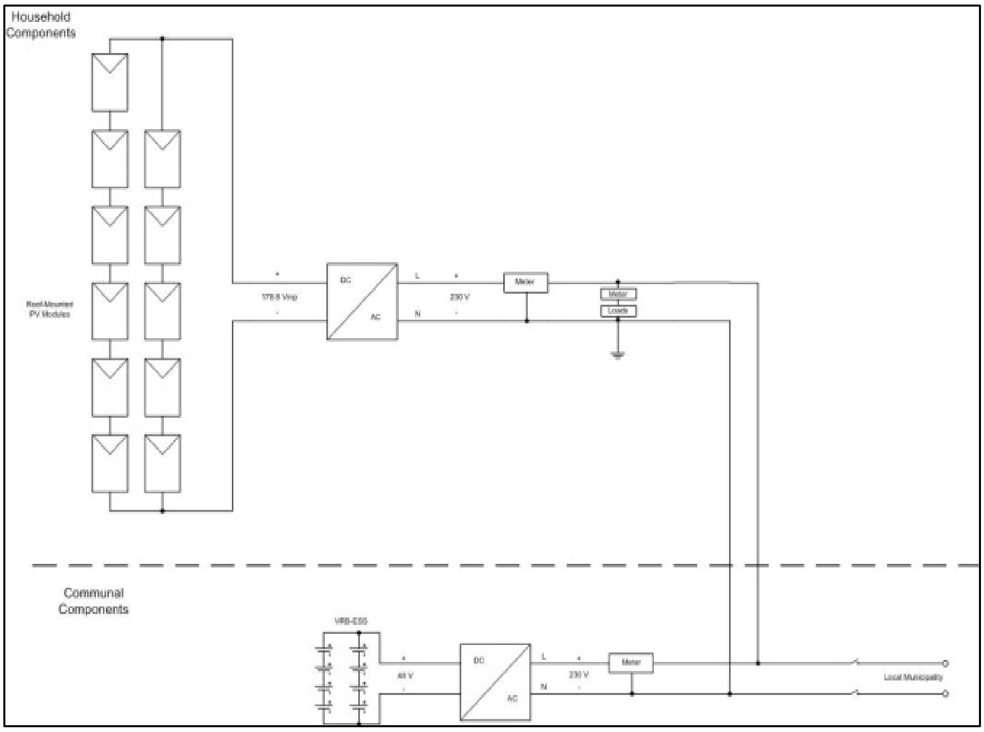

Figure 33: Middle Income Block Option 2 – Electrical Wire Diagram

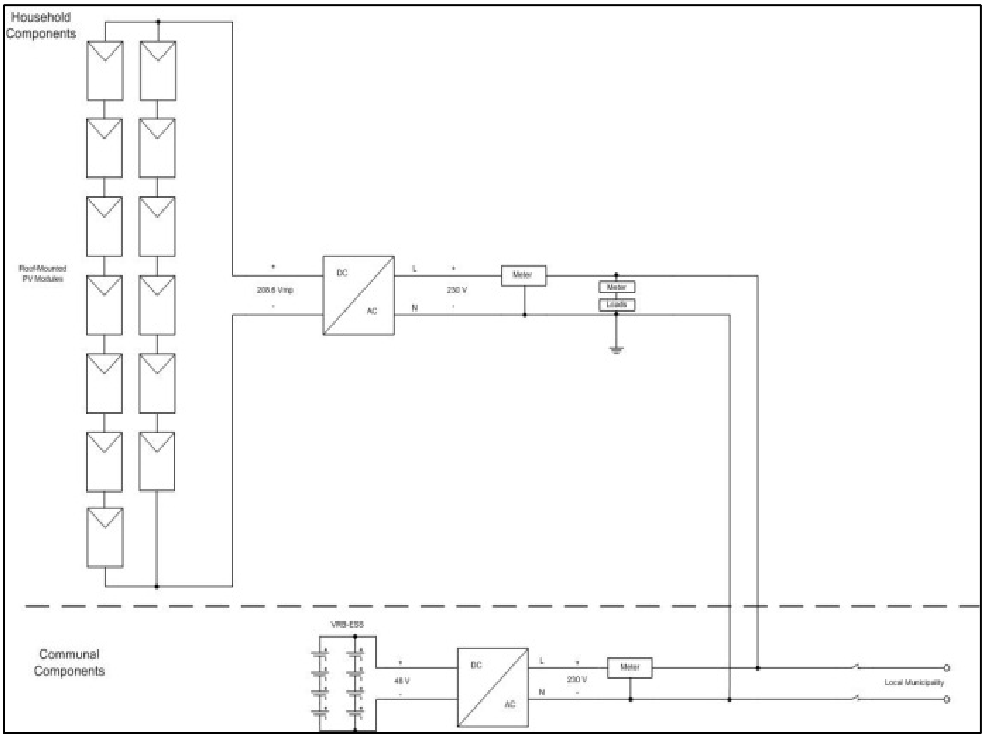

Figure 34: High Income Block Options 1 & 2 – Electrical Wire Diagram

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