

Modelling and macroeconomic analysis of a Solar PV/Diesel hybrid power plant



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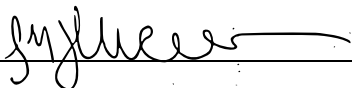
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Terms of Reference

- Review available and latest literature on global trends in renewable energy
- Review available and latest literature on PV/Diesel power plants globally
- Using a macroeconomic analysis to develop a PV/Diesel power plant model
- Discussing results of the model

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Abstract

This research thesis covers the latest research on renewable energy globally and focuses on the solar panel and biofuels market.

A full macroeconomic analysis is done on the Chinese Taipei, and this results in some parameters which then become the basis of this research. The macroeconomic parameters are then put into a tabular form and applied to India, Turkey and Australia to see how much weight the analysis can hold and if there is enough data per country on the macroeconomic parameters chosen.

This research thesis conducts a shorter, custom version of a macroeconomic analysis on a South African area, and considers the national Gross Domestic Product, pollution, length of transmission lines, weather factors such as sunlight and temperature and more. Following from this, a hybrid power system is developed under these circumstances and the information is compared with past research.

A very informative discussion is then had as to what the model means on a macroeconomic scale and how it performs technically. The technical solution at this point has no economic barriers. Economics can be a tool and not a financial hurdle in the face of technological advancement.

This research is interesting because it touches on so many countries, and covers various current renewable energy trends globally. It is detailed enough for the technical reader to get their facts whilst maintaining an easy enough structure for a non-technical person to read and realise where there are pockets of value.

Finally, based on the results, it is found that economics that often limit what can be done in engineering, can be used to define and not limit what engineers do. A few recommendations are finally made to show how this work can be taken further. One is an analysis to see how the heat generated by a power system can be re-used.

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Glossary

<i>AC</i>	Alternating current
<i>Ah</i>	Amp Hours
<i>BTOE</i>	Billion tons of oil equivalent
<i>CDM</i>	Clean development mechanism
<i>COE</i>	Cost of electricity
<i>CO₂</i>	Carbon Dioxide
<i>CPI</i>	Consumer Price Index
<i>DC</i>	Direct current
<i>DG</i>	Diesel generator
<i>DSM</i>	Demand side management
<i>EC</i>	Energy cost
<i>EIA</i>	U.S. Energy Information Administration
<i>EMEA</i>	Europe Middle East and Africa
<i>EMF</i>	Electromotive force
<i>FOB</i>	Free on Board
<i>Fossil fuel</i>	Natural deposits used as fuel, from remains of past geological times
<i>GA</i>	Genetic algorithm
<i>GDP</i>	Gross domestic product
<i>GHG</i>	Greenhouse gas
<i>GNI</i>	Gross National Income
<i>GW</i>	Gigawatt
<i>HOMER</i>	Hybrid Optimization of Multiple Energy Resources
<i>HPS</i>	Hybrid power system
<i>HRES</i>	Hybrid renewable energy system
<i>ICT</i>	Information and communications technology
<i>IEA</i>	International Energy Agency
<i>IPP</i>	Independent power producer
<i>IRP</i>	Integrated resource plan
<i>IT</i>	Information technology
<i>JPY</i>	Japanese Yen
<i>kWh</i>	Kilowatt-hours
<i>MEA</i>	Middle East and Africa
<i>MJ</i>	Mega Joule
<i>MMF</i>	Magnetomotive force
<i>mt</i>	Metric tons
<i>MTOE</i>	Million tons oil equivalent
<i>mW</i>	Milli Watts
<i>MW</i>	Megawatt
<i>MWh</i>	Megawatt hours
<i>NPV</i>	Net present value

<i>NREL</i>	National Renewable Energy Laboratory
<i>NT\$</i>	New Taiwan Dollar
<i>OECD</i>	Organization for Economic Co-operation and Development
<i>PV</i>	Photovoltaic
<i>R&D</i>	Research and development
<i>RES</i>	Renewable energy source/system
<i>RSA</i>	Republic of South Africa
<i>\$</i>	United States of America Dollar
<i>SOE</i>	State owned enterprises
<i>TNPC</i>	Total net present cost
<i>TW</i>	Terawatt
<i>TWh</i>	Terawatt hour
<i>U.S.</i>	United States of America
<i>US\$</i>	United States Dollar
<i>VAT</i>	Value-Added Tax
<i>¥</i>	Chinese Yuan

1. Introduction

1.0 Background to the study

The United Nations (UN), South Africa (RSA), Thailand, Germany, Spain and many other countries are currently looking at renewable energy. Ever since the early 20th century, there is a need not only to produce more power for the global population but also to produce power in a fashion that meets the new global environmental standards.

Majority of power today is produced from a single fossil fuel energy source, be it coal, crude oil or natural gas [73,80]. Extensive research is going into harnessing more sources and even combining the existing sources to produce energy. With the mixing of sources, comes the concept of hybrid. This is whereby more than one energy source is used, hence a hybrid power plant/hybrid power system would produce electricity from more than one fuel or energy source.

This research will look at the leading energy reports, literature and macroeconomic surveys of various countries in various continents and economic data for different countries from global organizations to inform the current macroeconomic indicators. Current macroeconomic factors such as geographical, political, social etc. will be applied to investigating the economic feasibility of a hybrid power plant. Once the region under investigation has been analysed, the outputs will be used to inform a technical software simulation of a PV/Diesel hybrid power system. The aim is to use the economic factors, which often limit what engineers can do, to instead help develop a realistic hybrid power system model. The accuracy and usefulness of the results will indicate whether or not it is worth the extra time in doing a macroeconomic analysis before the simulation of a PV/Diesel power system.

In the 21st century, a lot of work has been done in the field of fuels. This includes biofuels and even biodiesels. These fuels exhibit beneficial properties and this is useful for the advancement of renewable energy. Work has also been done on solar power. Solar panels that absorb the sun's energy have been drastically dropping in price over the years. Also, many countries are adopting their use as the source of energy is completely free. Wind power has also taken a huge leap forward and countries like South Africa (RSA) [13] now have more wind power being installed to help the power demands. Countries with mountainous regions and large coastal areas are prone to stronger winds and thus can benefit from wind power.

With such interest and even government subsidy measures in place for renewable energies, finding good mixes that suit a particular environment and climate is understandably a trending topic across the world.

1.1 Objectives of this study

1.1.1 Problems to be investigated

The focus of this thesis is on designing a PV/Diesel hybrid power plant modelled in one geographical location.

This work will model the power plant defined by certain macroeconomic parameters, such as new biodiesel prices, carbon emissions, user acceptance, the cost of importing fuel and Photovoltaic (PV)

module prices. This plant will be modelled under a load pattern already defined by the region and its inhabitants.

Problem statement: Do a macroeconomic analysis of an area and model a hybrid power plant for it. Focus on how economics affect the plant developed and compare the results of a new station with new economic inputs to current literature.

1.2 Expected outcomes

This research thesis expects to develop and use a macroeconomic approach to designing a HPS. Very little research has been found to do this, and perhaps there is good reason. This thesis expects to find that there is more accuracy and more reliability in a HPS developed through systematically doing macroeconomic research before making assumptions and technically modelling.

This research aims to show a thought process of how to come up with a macroeconomic model of a HPS. The factors that often limit realistic design of a HPS using simulation software can instead be used to positively assist in such design.

This research will be useful in RSA particularly, as it is a country that has been experiencing rolling blackouts due to power plants being overrun and their maintenance not being kept [13]. Looking at where a new power station can be placed assists government and their power supply pressures. Furthermore, using a Solar power system helps achieve the government's renewable energy targets. Within RSA, this research will surely help inform how to take a macroeconomic approach to modelling a power system. This makes it more understandable for a non-technical person, municipalities and smaller Independent Power Producers (IPPs).

1.3 Scope and Limitations

For this research thesis, the focus is on macroeconomic factors that influence a PV/Diesel power plant. One such factor is the level of reforms made in each country to accommodate renewables as in the 21st century.

A review of global renewable energy trends will be done. This will then set the pace for the review of macroeconomic parameters from general renewable energy sources. Thereafter Solar PV/Diesel will be discussed and how it is affected by macroeconomic parameters such as diesel prices. Then, drawing from the global renewable energy parameters, a detailed macroeconomic analysis will be done for India, China, Turkey and Australia. Thereafter a less detailed macroeconomic analysis will be done for RSA. This thesis will model an ideal power system using input from the macroeconomic analysis. This thesis will determine if such a method will yield a better or more realistic system configuration than any previous study.

This thesis will cover

- Review of the latest advancements in global reforms supporting renewables;
- A Solar PV/Diesel power system and the general issues that surround it;
- A macroeconomic analysis of an environment for a Hybrid Power System (HPS);
- Current trends in biodiesel;
- Use of the macroeconomic model in at least three different countries;
- Use of quick-form macroeconomic analysis with a focus on factors that affect PV/Diesel; and

- Simulation of an area already simulated before, but now with new inputs.

The scope of this thesis will not include:

- Hybrid power other than PV/Diesel;
- Power plant architecture;
- Greenhouse gas and other harmful emissions;
- Mechanical engineering processes behind Diesel power generation;
- Chemical engineering processes in the HPS;
- Controllers for the HPS;
- Power flow simulation and measurement of the HPS;
- Developing a new mathematical model for analysing a HPS;
- Programming and coding done by the author;
- Optimizing a hybrid power plant;
- Mathematical modelling of a HPS; and
- Biofuels in detail

This thesis is expected to fulfil the problem statement by considering inputs from a macroeconomic scale, such as PV module prices, solar radiation and renewable energy targets.

1.4 Plan of development

The format of this thesis is broken down as follows:

- **Literature review:** The latest literature on macroeconomic issues such as renewable energy, are discussed to give a macroeconomic analysis of our 21st century. Then the macroeconomic factors affecting the power plant are described such as renewable energy targets.
- **Macroeconomic model of HPS:** This thesis will use the macroeconomic analyses of certain regions and expand upon them for a more complete analysis by using a full table of macroeconomic parameters. Thereafter a few key parameters that can be changed are identified and reasons for their change are mentioned. Finally, the hybrid model is simulated using HOMER.
- **Modelling and Analysis of HPS:** This is already begun in the literature review, whereby the literature surrounding renewables is tabulated and filled with other latest research. This table will then be used for parameters for the region under consideration as the HPS is modelled using HOMER.
- **Discussion of results:** A side by side comparison of each scenario under the old and new environments is done. The changes in the macroeconomic environment are discussed as to if, they yielded any substantial change.
- **Conclusion:** The success or failure of this thesis to meet the objectives set out is discussed, along with avenues for further research.

2. Literature Review

2.0 Global background to energy generation

The advancement of human knowledge has brought the world far and one-thing remains; we need energy. This energy, in the form of electricity, is used for cooking, lighting, automating, traveling and mass-production.

The United Nations Environment Program (UNEP) has indicated that approximately 2 billion people in the world do not have access to grid based electricity services [2], which is a great number. In 2007, the world was consuming one thousand barrels of oil per second [35] and by 2011, the world energy consumption rose to ten Terawatts (TW) per annum [25]. This is projected to be thirty TW by the year 2050, which is sensible because to advance human development, electricity is known to be a key driver [2].

A few approaches to producing power in ways involving naturally occurring, freely available resources will be discussed in this chapter.

2.1 Global energy scenario

The biggest challenge in supplying over 1.5 billion people [2,7,8,17] without electricity access, is the economic investment required [2,91,94]. It is too expensive to erect the infrastructure for a scant number of people in mostly remote areas [2,8,11,17,27,67,93,95,99,136].

With an increasing global population and energy demand [5,20,32,33,54,67,99] there are many remote areas in developing countries that need sustainable energy [6,67,82]. The reality of most of these people is that the world has depleting fossil fuel reserves, fuel costs are rising and some countries are in economic recession [6,55,72]. Eighty percent of people in remote areas, mostly in developing countries, use wood for energy, which has led to deforestation [93, 95]. Essential commodities are reducing in supply and refuse disposal facilities are either inadequate or inefficient [6]. Supplying these people without connecting them to the grid is labelled mini-grid or microgrid. The impact of these microgrids in rural electrification is like the impact of mobile technology and wireless communication to the telecommunications industry [27]. Electricity access helps break the cycle of poverty [7] and renewable energy systems/sources (RESs) clean up the air by emitting fewer pollutants [7,10,16,17,89]. Although there are other not so positive environmental impacts, which will not be listed here, RESs overall, promote sustainable development [64,80,96,99,103].

A recent review [80] states that the concept of 'sustainable' includes reliability, environmental friendliness and cost effectiveness. Hybrid Power Systems (HPSs) and RESs seem to be the best in achieving this sustainability. This is because by diversifying the input sources of energy, there is redundancy so the reliability improves. The environmental friendliness is implied through the use of resources in the HPS that have fewer negative side effects than fossil fuels. The cost effectiveness is supported by some RESs not incurring energy input costs once constructed. For example, a Hydropower station uses running river water, or a solar powered station uses the sun's rays. This means the running costs of fuel such as coal are eliminated.

The concept of 'renewable' implies power that is virtually free of emissions [2,32,67,85]. RESs release no Carbon Dioxide (CO_2) and other harmful gases into the atmosphere [7,72,89], which helps fight global warming [2,57] and the endangering of human life [18,72].

RESs have been used in everything from small isolated communities to large grid connected communities and even HPSs [6]. They have the benefit of being inexhaustible, cost effective and practical [8,11]. A few issues hamper the extension of the grid such as rough terrain [2,17,91] and the underdevelopment of the remote regions [2,11].

Many countries classified as emerging markets [6] experience the problems associated with access to electricity in rural areas. A few include Indonesia, RSA, Mexico, Saudi Arabia, China, India and they have found that bringing in RESs and HPSs is becoming viable [2]. In 1997, it was indicated that HPSs would be needed in the future for rural and remote areas [127]. These countries and others have infrastructure that needs primary energy to be useful in applications such as transportation, storage of medicines and vaccines, telecommunication and refrigeration of food [3,95,104]. Furthermore, supplying electricity to small industries and houses can create jobs and revenue generating activities [27,71]. Water and energy are two key basics for humans [31,80] and a prerequisite for economic development [34,81]. One method of supplying this much-needed resource to remote settlements is importing electricity from a part of the grid [18,108]. However, renewable energy that is not connected to the power grid is experiencing a massive uptake [3,5,71,77] and the cost of this electricity is proven to be low [6,8,72]. For example, in 2014 a Solar PV/Biomass HPS can operate at 0.143 \$/kWh [6], a Photovoltaic (PV) system can operate at 0.238 \$/kWh [72] and an 8 kW Diesel system can cost 0.803 \$/kWh [6]. This is not to compare the electricity cost with grid tied electricity, but it is to show the cost of energy is within a reasonable ballpark.

Large industries, institutions and public enterprises funded the inception of the power industry [34]. With industrialization in the 1880s came electrification and this fully matured, years after World War II [34]. From the mid-1970s to the 2000s, there have been changes that have affected the cost of electricity (COE) [22]. These include higher interest rates, greater construction costs and greater volatility in the fuel market. Since the 1970s oil crisis, renewable energy started penetrating worldwide [36,51,89]. According to the International Energy Agency (IEA), an internationally respected reference for energy markets, in 1980 the global primary energy demand was 7.2 [73,74]. However, in more developed countries, such as the United States of America (U.S.), billions of litres of fossil fuels like diesel are used for major operations such as locomotive transport and shipping [14,15,83,96]. This resulted in the world consuming 11.4 billion tons of oil equivalent (btoe) by 2005 and in 2011, the IEA projected almost seventeen billion btoe by 2035 [106]. In the 2013 Energy journal, South Korea in Geoje Island, in 2011 installed the first prototype PV/Diesel HPS for a "Green ship" [120] and found that it is feasible for a ship under one hundred tons [120].

The problems faced with non-renewables such as crude oil, natural gas and coal have led to a lot of research on low carbon alternatives [2,85,91,97,99,103]. Some problems with fossil fuels that have led to global concerns are:

- Its depletion [2,29,54,80,98,71,156];
- Fossil fuels are the largest single source contributor to GHGs [33,16,33,54,76];
- Climate changes due to greenhouse gases (GHGs) and other pollutants [2,16,21,33,54,72,76,80,97,98,99];

- Increasing costs; The price of oil per barrel is projected to be \$133 by the year 2035 [35] and contributing factors are limited fossil fuel reserves and volatility of supply which are part of the demand-supply scenario [36,80,89,105]; and
- Fluctuating fuel prices [71,108].

Furthermore, the increase in global population will only spur on the need for more power [2,5,20,36,80,82] and aggravate the rift between countries that rely and trade on oil and its by-products [35,55,80,103], which further supports research that has a preference towards renewable energy [2,29,32,51,89,91,105,107]. One country that trades in Oil is Iran. According to its “Fourth Five-Year Economic Development Plan” [7] Iran has been successful in electrifying almost every village with over 20 households [7]. Iran has since been developing technologies to electrify the ones with less than 20 households and that are too far for new transmission lines to be invested in just for them [7].

In light of the global warming challenge, the Kyoto protocol was formed in December 1997 [2,17] and 160 nations signed the agreement to reduce carbon emissions. This reduction was to be achieved by the clean development mechanism and carbon taxes. More country specific energy policies exist to address Global warming, GHG emissions and other political issues [46,68,72,97].

There are two ways to deal with global warming. Firstly, prevent atmospheric pollution by using alternative energy technologies that do not have fossil fuels [76,80] and secondly, create technologies that actively delay global warming [18,22]. The easiest, currently pursued method is the first one. It includes energy efficiency, better fuels that use RESs and this has helped stabilise GHG emissions [18].

The past decade has seen aggressive growth in renewables [17,33,82]. Moreover, due to the sun and the wind being the most freely available natural resource, most literature focuses on using the sun and the wind’s energy. Looking at renewable energy sources which are replenished naturally and freely available [3,29,32,54,85], such as biomass, hydro, tide, geothermal solar photovoltaic (PV) and wind, power can be produced in a way that is much more environmentally friendly [6,17,38,88,89,99]. Using such resources gives economic benefits, social benefits and benefits from many government incentives [6,71]. Production costs of renewables are also on a downward trajectory [72] due to optimised construction methods and freely available fuel sources like the sun.

Furthermore, RESs have been reducing in price, making them more cost competitive [7,8,38] whilst the cost of diesel and other fuels has been increasing [105]. In some countries, oil, coal and gas are not only expensive but also politically regulated [16,80], which also supports the move away from these. The chairman of the Centre for Climate Change Economics and Policy at Leeds University [40] said, “the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP (Gross Domestic Product) each year, now and forever.” Across the globe, non-governmental organizations (NGOs) and environmental groups have begun promoting campaigns [64] such as “World environment day 2008” in efforts to raise environmental consciousness around carbon emissions, habitats and GHGs [64].

Another reason why a call to action is needed is because the IEA and the World Bank believe that, developing countries will need approximately five million Megawatts (MW) to meet predicted needs [19]. It is unquestionable that developing and already electricity-dependent countries can benefit from access [3,34]. Such energy demands, especially in rural areas, will bring huge infrastructure costs [34,67], the possible burning of more fossil fuel with its negative environmental impacts [54,67,76,85]

and more stress to any grid supplying or exporting power to these countries. Thus RESs will play an important role in lightening the burden on the grid and the demand for more fossil fuel [19,88].

Demand side management (DSM) is the process of tackling the uncertainties in load growth [22]. When this happens on a large and global scale, it now requires supply-side management to also be considered. When both of these are now considered, we have the concept of Integrated Resource Planning (IRP) [22]. With IRP, the optimal demand-side and supply-side measures are sought, in an attempt to meet the energy demands that lie within the jurisdiction of the electricity supply utility [22,40].

According to [22,67] the most relevant supply-side option to incorporate into any IRP is RESs. Since more than five years ago renewables have been forecasted as a solution against global warming and the increasing COE [22]. In order to develop any sound policy, past, present and future energy demands need to be taken into account [52]. National energy planning that takes into account energy efficiency [73] and a low environmental impact creates a more sustainable future for that nation. By the year 2050 the globe will need about twenty TW of energy from RESs to stabilize the CO_2 levels in the atmosphere [25]. Also, for universal access to energy services that can be considered modern, the IEA estimates forty percent of new generation will need to be installed globally between 2010 and 2030[27] and in 2012 there were one point three billion people in developing countries who have no access to the electricity grid [92].

The inadequacy of traditional fossil fuel and the demand for more energy makes energy security and supply concerns a reality. The U.S. Energy Information Administration's (EIA's) Annual Energy Outlook [188] stated in 2010 that in 42 years the world would run out of oil, in 60 years natural gas will be depleted and in 12 years coal will be finished.

If one looks at only the technical demands of the globe and compares them with the potential energy of all RESs, it is postulated that renewables alone could power the world [19,24]. The inability to harness all this potential is often due to economic and technical reasons [19]. This research thesis addresses this idea specifically through this macroeconomic analysis before the technical model is then developed using renewables.

Modern energy services are now a want from emerging economies. There are varying financial, climatic, political, institutional and cultural conditions across each of these countries [34]. Countries that already have power face their own unique challenges such as demand side management, because of the plethora of new devices being connected to the grid and consuming power [82]. Since the 1970's industrialization has spurred on energy needs and in the modern day, there is modernisation that spurs on the need for more energy in any country [85]. The energy situation of any country is an indication of the economic and social development [35,73,76,95] and quality of life [36].

Though RESs are not the focus of this research thesis, they open the door to the discussion of using other sources of primary energy and even combining different sources. Thus, HPSs can be conceptualised through multiple energy sources and one source in any HPS is often a renewable one. The reasons behind the popularity of RESs have been briefly discussed in a global context and now specific continents and their macroeconomic challenges concerning introducing HPSs will be discussed.

2.1.1 Macroeconomic research approaches

As a country with one of the largest populations, China is a good place to begin to draw information from on some macroeconomic challenges.

The Chinese renewable energy industry is experiencing unprecedented growth [4]. Since 2004, China has been looking at wind/solar HPSs with the purpose of feeding the grid. This endeavour calls into question many factors such as site selection, which in turn calls in energy and resource security, which in turn questions the societal, economic, environmental and meteorological aptness of any site for a HPS [4].

HPSs are large monetary investments and require technical skill. A macroeconomic look at a site will yield much needed information on the technical solution to be developed. Microeconomic will look at the individual power units and layout possibilities based on the macroeconomic outputs [4].

The macroeconomic issues around RES development were listed back in 2002, by [111] and the diagram is shown in Appendix B Figure B3. This information was used to deduce that more bottom-up support is needed to make solar PV a reality in the European Union (EU) [39]. This was also during a time when the Kyoto protocol measures were still being targeted until 2010 [39] and legislation of states was being developed. Currently, many of the policies have been put in place and the diesel and solar PV markets have since matured. The thought tree of [111] covered issues that were needed to develop RESs, but now a new set of parameters should be defined for a macroeconomic analysis.

Macroeconomic analysis is choosing the most valuable area through considering the geographical location, social and economic conditions, traffic conditions, environment, natural resources, grid connection, etc. [4].

With such contradiction problems where there are multiple variables the Matter-Element Extension method can be used [4]. Taking information from site selection parameters and weights used in a mathematical method on PV/wind HPSs [4], some factors have been found to be pertinent to PV/Diesel macro site selection. These factors and such an approach will also be the base of the macroeconomic analysis to be carried out in this thesis.

Table 2.1: Streamlined indices [4]

First Class Indicator	Second Class Index	Description
<i>Natural resources</i>	Wind speed	Speed of the wind (m/s)
	Sunshine days	Sunshine days in one year (d)
	Gross solar radiation	Accumulative value of solar radiation intensity (MJ/m ²)
<i>Economic factors</i>	GDP	The total value of goods produced and services provided in a country during one year
	Electricity demand	Total demand of electricity in a certain range (MWh)
	Construction cost	Construction cost of the hybrid plant
	Operational & maintenance cost	Operation & maintenance cost of the hybrid plant

First Class Indicator	Second Class Index	Description
<i>Traffic conditions</i>	Traffic convenience degree	The ease of getting to the power station using transportation
	Transmission line length	Electricity transmission distances (km)
<i>Environmental factors</i>	Pollution	Pollution degree during the construction period
	Energy saving/pollutant reduction	Amount of Carbon, Sulphur and other pollutants that are not produced (tons)
<i>Social factors</i>	Load residents' attitude	The attitude of the local residents to the plant
	The distance to load centre	The distance from the plant to the load centre
<i>Geographical conditions</i>	Geological/topographic condition	Geological and topographic condition of plant construction
	Land usage condition	The complexity to get the land for construction

Looking at Table 2.1, more parameters need to be added to have a fully relevant model of what to look out for on a macro level. This will be detailed in the theory development chapter. Table 2.1 above, took into account only nineteen sources [4].

A first class indicator is a topic that would cover the broader issue, which will then have other issues under it that are deemed second-class indices.

From Table 2.1, six first class indicators then inform the second-class indicators:

1. Natural resources: Resource status of the HPS sources e.g. Wind, Hydro, etc.;
2. Economic Factors: The cost of construction and operation and the state of the local economy;
3. Traffic conditions: The distance of the suppliers of equipment and the power plant itself;
4. Environmental factors: The pollution during construction and operation of the HPS and the pollution that would have otherwise come from fossil fuels;
5. Social factors: The attitudes of locals to the technology, the change in lifestyles and the social impact of the technology; and
6. Geographical conditions: The availability of topographic conditions to support the system and the system's impact to the local geology.

Factors which influence renewable energy development are RES issues are put in a thought tree [111] in Appendix B Figure B3. Therein the issues to be looked at on a macro scale are:

1. Geography of the region. Climate and weather such as rainfall and sunshine;
2. Energy policies that may exist;
3. Economic environment. Subsidies and cost of raw products such as fuel and PV modules;
4. Government issues. Does the government promote green initiatives, what are the feed-in tariffs like, are there any targets of installation capacities, is the country subject to another law such as the Kyoto protocol;
5. Technology: Is the grid capable of handling distributed generation, are there people who know how to use the technology; and
6. Public awareness.

These factors are pertinent and are similar to the factors used by [4] in their mathematical method. A study done on RSA in 2012 by [2] uses two parameters for economic feasibility modelling: The cost of diesel in the region and the climatic profile of the region. The latter is also covered in the latest 2013 research by [4].

A 2014 study [6] on using rice husks in India for a PV/Biomass HPS looked at microeconomic factors such as:

1. Replacement cost; and
2. Component salvage value.

As is done in research, some aspects require informed assumptions to be made in the absence of actual data. Reference [17] assumed the price of diesel, reference [132] assumed the inflation rate of Nigeria and in [6] the replacement cost of components was adopted from another prominent research paper in 2010. This is what [7,16,17,18] and a large number of other researchers do. As a researcher the aim is not to develop the software for modelling and so scant literature fully looks at the macroeconomic issues. Paradoxically these are eventually what decide what software inputs to give the engineers when they now do techno-economic research. This thesis will spend some time showing how certain assumptions are arrived at through macroeconomic analysis, before running a simulation.

A latest 2014 research paper made a good point that not all macroeconomic factors can be applied in all contexts. This means that a hydropower station in Saudi Arabia and a diesel power system in Saudi Arabia will affect stakeholders differently and the relative importance of something like import costs will be different in Singapore versus RSA.

The macroeconomic factors from the available research papers are:

1. Technical
 - 1.1 Grid reliability and ability to rollout fast like in China where three hundred thousand people were electrified in twenty months [149];
 - 1.2 Reduction in fuel dependence;
 - 1.3 Lack of knowledge on actual load profile results in oversized expensive systems [27,153];
 - 1.4 Different protocols for equipment communication cause commissioning problems [153] hence it is advised to use a single service provider for remote power systems;
 - 1.5 Equipment should meet some minimum standards of quality [155].
2. Financial
 - 2.1 There is an increased willingness to pay for power when there is satisfaction such as fewer blackouts [153];
 - 2.2 Financial incentives to construct HPSs [65];
 - 2.3 It is often difficult to find a price per kW that is low enough for the consumer and yet high enough for the investor to realise a return [157].
3. Social
 - 3.1 Opportunity to create community businesses and raise the standard of living;
 - 3.2 Microgrids are seen as temporary measures and this is a view that can be changed [27];
4. Environmental

4.1 Reduced noise and air pollution with a properly designed HPS [2,154].

5. Organisational

5.1 Long distances to load centres pose installation and repair challenges [65,156].

6. Sustainability

6.1 Diesel price is surging and PV components are becoming cheaper [27] however, many areas still use diesel because of its familiarity.

In [75] and [159] a top-down approach is described. Figure 2.1 shows this method visually.

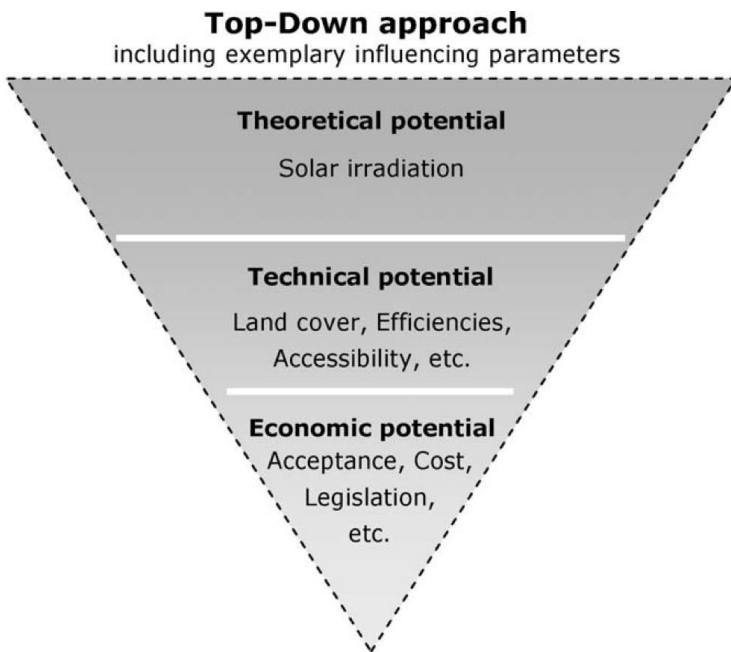


Figure 2.1: Estimating renewable energy potential from the Top-down [159].

Figure 2.1 is pragmatic. It can be applied at a country or local level. Looking at solar radiation, then the land cover, then the cost of the system, is something that allows researchers to choose their own starting point and level of detail.

A current reference [90] looked at islands and remote villages with a population under one hundred thousand people. One finding was that tourism is a key revenue driver in such areas. Furthermore, the common factors in characterising a system for each area were:

1. Population: How many people live in the area;
2. Economic activity: Does the community depend on subsistence farming?;
3. Grid: Far and not connected to the grid or already connected to the grid;
4. Load: The demand pattern and peak kW consumption; and
5. Social: What are the possible impacts of having power and night lighting?

Overall, there are six to eight parameters that can be addressed in a macroeconomic survey. The little research that exists has been addressed and the parameters have been observed. The theory development chapter will cover the design process of taking these parameters and using them in an actual design of an HPS and simulation.

2.2 Hybrid power systems

HPSs are formed when there is a combination of at least two different power sources. This could be a RES plus a low-carbon resource [2].

The benefit of PV/ Diesel system is that it addresses the erratic nature of sunlight and the high price of fuel. Other technologies such as biomass and hydropower do not have such a great investment and market sentiment. Solar power is the future of energy [5] and looking at the European, American and Asian trends, other countries will eventually adopt it.

The equivalent circuit of a PV/Diesel HPS with battery storage is shown below and this is an electrical mathematical model. The mathematical models of each component will not be covered in this research. The load Impedance, Voltage and Current flow are shown in Figure 2.2.

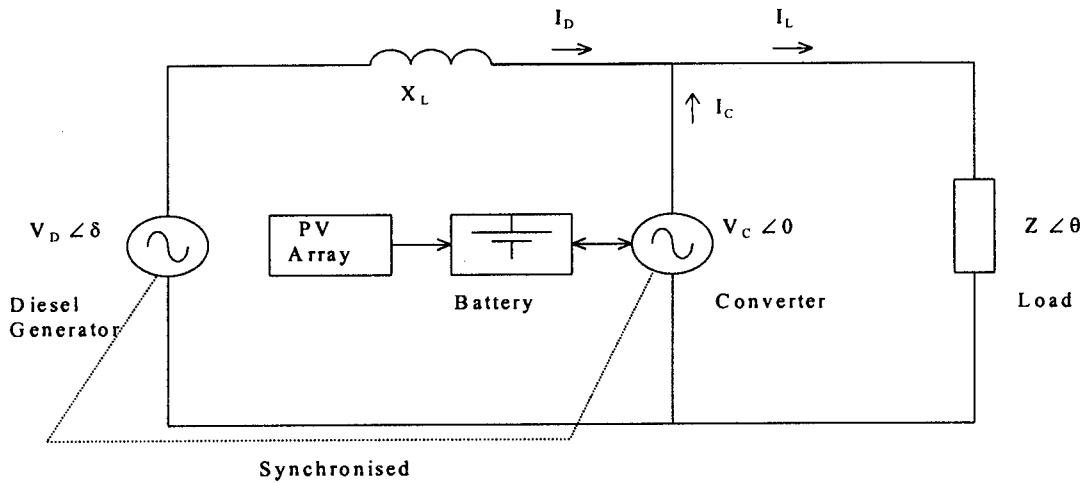


Figure 2. 2: Parallel PV/Diesel system equivalent circuit [112].

To make it easier to understand from a practical standpoint, the individual components and their configuration has been shown in a block diagram from the 2013 Energy Conversion and Management Journal [116].

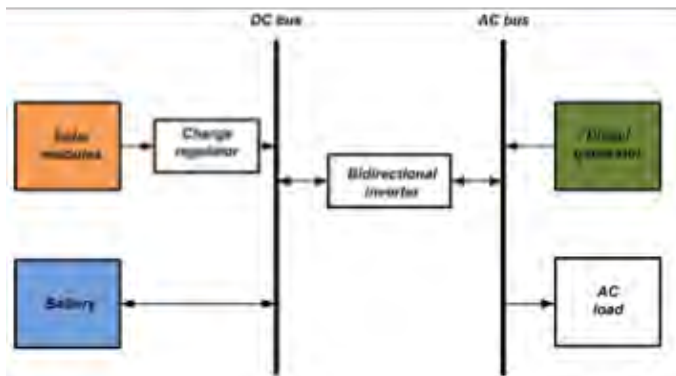


Figure 2. 3: HPS Block diagram [116].

In Figure 2.3 the solar modules are the solar PV modules. More information relating to global pricing and trends can be found in [49]. The bidirectional inverter converts the Direct Current (DC) in to Alternating Current (AC). The diesel generator uses diesel to produce power. The AC load can be interpreted as the customers and the demand side management required therein. The battery in the PV system is there to reduce the impact of power fluctuations [117,118] and ensure compliance with

relevant country grid codes, where relevant. The diesel generator also helps with this in PV/Diesel systems with battery storage. With a lot of distributed generation in a power system that is connected to the grid, local overvoltage can occur [117]. This means reverse power flow into the microgrid and this is most prone to far away, grid connected rural communities [117] where the transmission lines are of several kilometers in length.

These days it is easy to generate and store electricity [8]. A diagram of a HPS installed in Kohjig Island, in Thailand, with a size of only 1.12m² and a population of 502 houses [131] is shown in Figure 2.4.

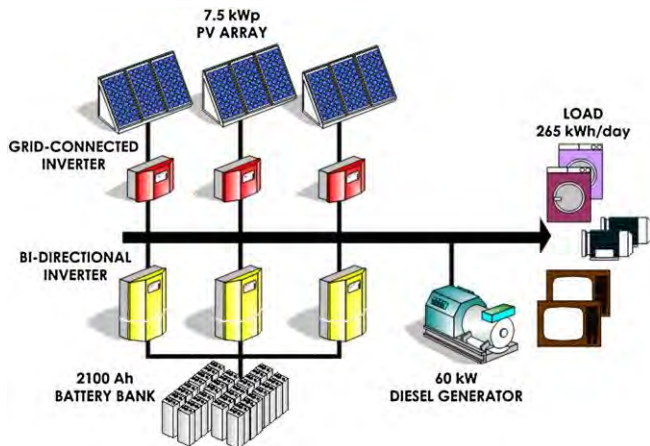


Figure 2. 4: PV/Diesel system in Kohjig Island [131].

The complexity of this system is minimal and it is used on a small island. This further shows how renewable energy generation is practical.

A practical model of a PV/Diesel system without the batteries connected is shown in Figure 2.5. The image is from a very recent experimental study in Burkina Faso in Africa [117].



Figure 2. 5: Prototype of a power system in Burkina Faso [117].

Looking at Figure 2.4 and Figure 2.5 the idea of a PV/Diesel HPS should now be clear. It consists of four main components: diesel generator, PV modules, batteries and a converter [7]. HPSs are cost effective and reliable [10,11,122]. Remote communities adopt diesel generators because they are reliable and easy to handle [11].

A solar PV system becomes feasible at an average irradiation of 3-6 kWh/m² per day [16,45], which is about 1825 kWh/m² per annum. In RSA, when one compares Bloemfontein and Nelspruit, Nelspruit

has lesser solar radiation although it is hotter in temperature [2]. This indicates that having a hotter area does not mean it is better for solar power. The use of solar power is varied across the world [93]. In Appendix A Figures A1 to A4, one can visually compare the global radiation levels of four countries. One can see where the solar potential is already very weak and probably not feasible based on the colours of the images.

With a PV/Diesel system, there are two main costs: The cost of the PV array and the diesel fuel. The diesel cost is always paid upfront and is irrecoverable. At best it can be hedged against however, that implies a financial risk and still an eventual payment for the product. The initial capital cost of a PV system in a PV/Diesel HPS accounts for 80% of the total [16]. With PV panels, there is always a point where the installation has paid itself off regardless of how much it costs upfront. The cost of energy for a PV/Diesel HPS in Saudi Arabia is 0.178 \$/kWh [45] and 0.214 \$/kWh [71] and in Malaysia it is 0.239 \$/kWh [116].

Another key input for the HPS that is covered by the macroeconomic indices Table 2.1, is the “General inflation rate” [116]. It is impacted by a country’s GDP and their national debt hence the macroeconomic survey covering GDP as an indicator is important in informing the RES.

Software takes the inflation rate and simulates a system, its parameters and gives results according to their Net Present Cost (NPC) [7,119,137]. NPC is the cash cost of all present plus future costs discounted to a present value [10,36]. NPC is given by equation (2.1) as below [7].

$$NPC = \frac{C_{ann}}{CRF_{i,Rproj}} \quad (2.1)$$

where,

C_{ann} : Total annualized cost (\$/year)

CRF : Capital recovery factor

i : Interest rate (%)

$Rproj$: Project lifetime (years)

HPSs generally exhibit lower costs of generation than using one source alone [6,71]. Diesel efficiency can be maximized and maintenance costs reduced, by the use of a HPS [11,16]. The cost of diesel can be exorbitant in rural areas [118]. Furthermore, in Saudi Arabia it has been found that the peak load can be met whilst still reducing carbon emissions by about 19% [16] through simply changing from diesel only to a HPS. In Malaysia [118] it has been found that if the price of diesel were to rise, the PV/Diesel HPS will be more economical than only running diesel, based on a 25-year projection and a 6% interest rate [118].

In 1997, a forecast was made that using controllers would be the future of HPSs [127]. In 1999, [112] did an optimization of a PV/Diesel HPS using a controller developed in 1994 by [113]. The outcome was that the battery and inverter were found to be crucial in the system cost over its lifetime [10]. Hybrid system controllers that determine the best time to turn on and off a system [113] determine when the load gets supplied by the diesel generator [112]. This helps manage the performance of the economic lead-acid batteries and PV modules.

PV modules are decreasing in price [49] and this plays positively in the design and cost effectiveness of a HPS. Installing the same HPS as another site in the world, but using today’s costs will yield a different feasibility for the same HPS. This research will do just that whilst looking at using less diesel because it

is the one component that introduces political risk, price fluctuation risk, supply issues, transportation issues, greenhouse gas emissions, maintenance issues and more.

The renewable fraction of the HPS in this thesis will be modeled in line with any local renewable energy strategies. Meaning, if the aim is to have 20% renewable energy by 2020, this research will not go below 20% for the PV array portion of the power produced in the HPS. In [121] it is stated that in order for a country to meet a renewable power generation target, the renewable energy has to be connected to the grid. This is not entirely true today; the existence of a RES and the fact it is supplying a village or user, is enough premise. Along with local renewable energy strategies, the GDP issues will be addressed in this thesis. For example, if the chosen region for the HPS is Nigeria. A few facts would be detailed:

- According to the Central Bank of Nigeria [134] in 2011, the interest rate was on average 10.5% [134] and in 2010 it was over 11% [134];
- Rebasing occurred on April 6 2014 [135], which shifted it from the 2nd largest to the largest economy in Africa;
- January 2014 information from PricewaterhouseCoopers (PwC), a leading Audit, tax and advisory firm shows that the inflation rate of Nigeria is 7.5% [133].

In 2006, the Denmark government expressed its aim to be 100% independent of Nuclear and fossil fuels [87]. This task was placed upon the Danish Association of Engineers who then designed the model for this to be achieved by 2050 [87], which included doubling solar PV from 700 MW to 1500 MW [87]. The achievements and efforts of the Danish have provided motivation for this research thesis. A country that is committed to developing engineers, RSA, can surely benefit from any energy model that this thesis will provide.

In RSA, recent research on the optimization of a HPS [3] took an objective function such as the probability that the load will encounter and insufficient supply [3] and tried reduce the system cost based on this. This yielded a few interesting results as listed below:

- Energy storage is important to ensure system stability [3] and hence the HPS modeled in this thesis will include battery storage;
- Eskom Holdings SOC Ltd supplies over 90% of the country's electricity needs [13];
- Lead acid batteries are cost effective and have been widely used [3];
- When optimizing try go for the smallest possible energy storage [3]; and
- In RSA, battery controllers are forecasted to be the most critical part of a RES [3]. This is good to know, because in other regions where there is only solar power, the Maximum Power Point Tracking module [11] becomes the most important.

This thesis will not be optimizing, as stated in the scope, but the abovementioned points from the optimization [3] will be noted when modeling.

2.2.1 Biofuels in power systems

The focus of this thesis is a PV/Diesel system, so the fuel for the diesel generator is an important aspect for the HPS model. One alternative for diesel is biofuel (biodiesel and bioethanol) and the literature surrounding this will be discussed.

In 2012, the world produced 1.86 million barrels per day (mb/d) of biofuel [101]. This trend is projected to rise by 503 thousand barrels per day (kb/d) until 2018 [101]. This means that 4% of global road transport could be supplied by biofuels in 2018; however policy support from the EU and the United States of America (U.S.) will influence this [101]. As with solar PV, Europe is the largest user of biofuel [140] and if biofuels are the next renewable energy wave, then the EU's adoption will again be the reason for other countries like China, to put more effort into policies surrounding production.

The U.S., under the "Renewable Fuel Standard 2" has a said maximum of 84 kb/d that can be produced [101]. Brazil plans to ramp up ethanol production up to 76 kb/d by 2018 [101]. Europe's production was 230 kb/d in 2012 [101] and all of Africa only produces 4 kb/d and this might rise to 16 kb/d by 2018. This is unfortunate because the African continent is neither picking up fast enough on the trend nor investing enough in it and by the time the industry matures, Africa could be left a consumer and not a producer and fall behind the RES curve.

In the EU, U.S., China, Argentina and Brazil, there are tax incentives on biodiesel retail sales, tax credits, tax exemptions and government grants [101]. The most popular incentive for adoption is mandating that a portion of the total fuel sales be from biofuels [101]. This is one aspect that RSA has chosen to catch onto and by the end of 2016 there will be a minimum percentage of all fuel being from biodiesel [139]. Fuel retailers will have to have their fuel be mixed with a minimum amount of 5% Biodiesel and if the choice is to use bioethanol, the minimum mixing into the fuel must be between 2% and 10% [139].

In Figure 2.6, the global trend of biofuel production is shown with a tapering from 2010 to 2012 at about 60 million tons oil equivalent (mtoe).

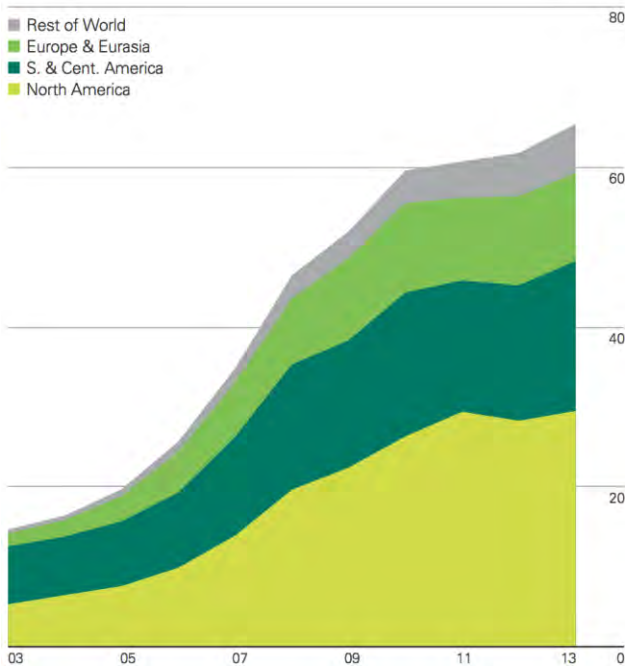


Figure 2. 6: World biofuels production trend [140].

According to British Petroleum’s (BP) “Statistical Review of World Energy” [140], Brazil and the U.S. in 2013 were the key drivers of the biofuel production rise by 6.1% and are the largest producers worldwide [140]. For an idea of each individual country, BP’s 2014 global biofuels production table can be found in Appendix B Table B1. The table in Appendix B will be used in this thesis to model the HPS, provided the region under consideration actually is a producer of biofuels.

In Southern Iraq a study was performed, funded by the U.S. Department of Energy, to try power a remote health clinic [129] using solar PV. A key finding was, the cost of electricity from diesel was four times higher than from PV [128]. Also with diesel prices rising from the 0.40 \$/L to 1.00 \$/L, the cost of producing electricity increased from \$1.33 to \$1.653 [129].

Keeping the diesel size of the generator the same and increasing the battery size will not reduce the cost of operation [128]. The load demand will determine the minimum cost [128] while the overall HPS capital cost is a function of the battery system capacity and generator size [128]. The key issue for diesel generators is variation in the load [128]. As is taught during the undergraduate degree and in [128] a machine must operate near rated capacity for greatest efficiency.

There are a few sources of biodiesel, one is Jatropha which is a natural plant with seeds called Jatropha seeds. In China, the first paper focused on Jatropha’s systematic introduction stated that Jatropha oil was first used for lighting and its milk for medicine [81]. Since the 1970’s, research surrounding it has grown and private investment has spurred further growth [81]. Now there is a need that more Jatropha forests need to be planted. Partially because research in 2006 proved that Chengdu’s buses could completely replace petroleum with biodiesel for transportation [138]. Research and investment from PetroChina and Sinopec [81] for Jatropha biodiesel technology have now, come into the following challenges since then:

- The cost of labour was not in line with the market [81];
- Project funding was mismanaged leading to great designs being poorly constructed [81]; and
- The purchase price, Three Chinese Yen per kilogram (¥/kg), is much lower than that of peanuts so farmers are not motivated to put effort into producing Jatropha seeds [81].

Jatropha biodiesel is now mentioned in China's "Five-Year" plans [81]. Also, the by-products of the biodiesel process such as glycerol are being put to use in organic fertilizers, biodegradable plastic and organic pesticides [81]. Jatropha biodiesel needs more subsidies and farmers planting to see the industry grow into a ¥18 Billion industry by 2017 [81] and cost price drop from 2012's 6000 ¥/ton [81].

With biofuels in mature industries such as locomotive transport, social factors play a big role. In American railways, diesel is still used because the operators are familiar with it and there exists solid and substantial infrastructure around it [15]. With biodiesel, as seen in China where the farms are still not fully capacitated yet, the whole value chain needs to be trusted before a switch is made. In the US, research by the Department of Defense [15] has instead gone to developing a 12MW locomotive for freight using a Diesel/Battery HPS and most other U.S. research looks at using fuel cells [15]. It is noted that the biggest reason for the U.S. not amplifying biodiesel research and implementation is the investigating of the land use impact [152].

Research continuously indicates that biodiesel reduces particulate matter, Carbon monoxide and Sulphur dioxide emissions [141,148]. Samuel Morey in 1826 developed the first internal combustion engine that can run on ethanol [148].

In 2008, B20 and B100 biodiesel managed to get a 40% reduction in CO₂ emissions from a diesel engine. The name B10 means 90% of the volume mixed is from traditional fuel, B20 means 80% is from traditional fuel and B100 means 0% is traditional fuel whilst the rest is biodiesel. In this mixture, the biodiesel portion comes from various substances, often vegetable oils, making biodiesel a RES [141]. A general list of oils is shown below:

- US: Soybean [141,144] Corn [148];
- EU: Rapeseed [141];
- Malaysia: Palm oil [141];
- China: Jatropha [81] corn [148];
- India: Karanja [141];
- Algae [144,145]; and
- Waste cooking oil [141]

Biodiesel chemically, is triglycerides of vegetable oil or animal fat undergoing transesterification with methanol or another alcohol [142, 143]. The result of this reaction is the methyl ester (biodiesel) on top [143] and glycerin at the bottom.

The resulting compound is so similar to traditional paraffinic diesel [142], that it can be used in diesel engines with little or no engine modification required [142,145]. Furthermore biodiesel is better than normal diesel in terms of the flash point, sulphur content and its biodegradable property [142,143].

In 2005, biodiesel was stated to not be able to completely replace a country's petroleum dependency [143]. However this has been disproved in 2006, where China [138] could replace an entire province's bus system with biodiesel. This has shown that the replacement depends on a country's individual consumption. For example, in the U.S. in 2005 the diesel consumed on highways, was more in terms of volume than all the potential vegetable oil and animal fat available [143]. Thus it is obvious that one cannot replace all transport fuel with biodiesel [143]. However, introducing a government subsidy

[143], as is done in the U.S., has made companies think differently and apply themselves to finding ways to increase production.

The biodiesel input will need to take into account the import cost of biodiesel or else the manufacturing cost plus the land usage cost based on available land [145] – land that is not already competing for other crops [146]. Table 2.2 below shows some information around this, but focusing on the U.S. [144].

Table 2.2: Land required for sources of biodiesel [144].

Crop	Oil yield (Liters/hectare)	Land area needed (Million hectares)
Corn	172	1540
Soybean	226	594
Canola	1190	223
Jatropha	1892	140
Oil Palm	5950	45
Coconut	2689	99
Microalgae (a)	136900	2
Microalgae (b)	58700	4.5

(a) 70% oil rich algae

(b) 30% oil rich algae

(c) for meeting 50% of the overall U.S. transport demand.

Producing algae or microalgae is more expensive than growing crops [144,145], however land in the world is limited and so research in this direction for each country is needed. A country with extensive information on the land impact and food price impact of biofuels is the US. The U.S. is a major maize exporter [148,150] and the commodity price boom of 2008, technically 2002 to 2008, has been touched upon in 2008 by [150]. Reference [150] concluded that 25% - 30% of the price rise was due to transport costs, U.S. dollar weakness and the increase in fertilizer and energy prices [150]. The remaining 70% - 75% of the price hike was due to the increase in demand of biofuels and land use reallocation [150]. In 2010, reference [151] opposed this view and reported that market specific explanations require too much coincidence [151] and there was little direct evidence of such.

At about the same time the book on biodiesel from crops [148] was released in 2014, the International Institute for Sustainable Development (IISD) released its own report [152]. According to them the entire value chain of converting land use and creating policies and physical infrastructure for biofuel makes the CO₂ benefits negligible [152].

The upside to all this information and what will drive this research to include biofuels is that world biofuels prices are projected to decrease from 2014 to 2023 [147].

2.2.2 Power system modeling techniques

In 1997, [127] indicated that more research was needed in the design and simulation of HPSs.

Below, Table 2.3 lists the simulation and modeling tools available on the market as of 2010. The Table shows what characteristics each software offers, which renewable energies each software can handle, which software is free to download.

Table 2. 3: Hybrid power system simulation tools [122].

	HOMER	HYBRID2	HOGA	HYDROGEMS + TRNSYS	HYBRIDS	INSEL	HYBRIDS	ARES	RAPSIM	SOMES	SOLSIM
Free download and use	x	x	x								
PV, Diesel, Batteries	x	x	x	x	x	x	x	x	x	x	x
Wind	x	x	x	x	x	x	x		x	x	x
Mini-Hydro	x	x	x	x							
Fuel cell; electrolyzer and hydrogen tank	x	x	x	x							
Hydrogen load	x	x	x	x							
Thermal load	x			x							
Control strategies	x	x	x								
Simulation	x	x	x	x	x	x	x	x	x	x	x
Economical Optimization	x		x	x							
Multi-Objective optimization, Genetic Algorithms			x								

Looking at Table 2.3, the only free tools are HOMER, HYBRID2 and HOGA. This is good because they are also the most developed [122]. The only tools that do economic optimization are HOMER and HOGA. Furthermore, HOGA uses Genetic Algorithms and this research would benefit from that if the focus were optimization.

HOGA was developed by the Electric Engineering Department of the University of Zaragoza in Spain. It runs simulations about as well as HOMER, by using 1-hour intervals [55,125]. HOGA, according to the latest 2014 research is now iHOGA [85].

HYBRID2 was developed by the Renewable Energy Research Laboratory at the University of Massachusetts (UMass) [126]. It can run simulations better than HOMER, down to 10-minute intervals [55,122].

Barley in [113] developed a model that included dispatch strategy back in 1996. This was a rough yet accurate framework for the beginning of computer modeling for HPSs. During this time, the framework for a piece of software called Hybrid2 was also being developed by Manwell et al. Hybrid2 did not do any optimization and used a simple generic HPS model [112]. The parameters Barley has worked on are now a backbone for the most used software - HYBRID2, HOMER and HOGA. The NREL begun developing its own software in 1993 called Hybrid Optimization of Multiple Energy Resources (HOMER).

The NREL is the primary lab for renewable energy research in the U.S. and HOMER is now licensed to HOMER Energy although originally developed under the NREL umbrella [55] according to their website [115]. Fundamentally, HOMER is capable of “simulating the long-term operation of a micro-power system” [55,119]. The optimization and other functions hinge on this.

HOMER takes in load profile, geographical resource, component cost and an optimization function [80] and outputs fuel consumption, renewable fraction and total capital cost [80, 119].

HOMER includes economic inputs and accounts for resource availability such as solar radiation [36,115,119] and clearness index [7,119]. The clearness index is a ratio of the solar radiation that hits the face of the earth, to the radiation that strikes the top of the atmosphere [7,119]. HOMER is also

user-friendly for non-technical users [115]. One advantage is that it can convert from radiation (kWh/m^2) to clearness index (0-1) [7]. This is a technical advantage because some data sources do not give information in terms of kWh/m^2 . HOMER's main functions are simulation, optimization and sensitivity analysis [118]. The simulation aspect is what this thesis will focus on and touch on the lifecycle cost, which is another HOMER output [119].

Remote villages in Malaysia [118] were investigated using HOMER software. HOMER simulates by going hour by hour throughout a year [119]. This gives an added advantage of accuracy and reliability [119] especially in wind power where a monthly average will not suffice to explain the wind pattern. HOMER can model grid connected and off-grid systems [7] which makes it versatile in analyzing any country or island when the load demands are already known.

A lot of work has been done to improve the simulation of HPSs [123,124]. A list of the most poignant research covering the optimization of PV/Diesel HPSs is in [55] and [122] and can be seen in Appendix C Figure C1.

HOMER is the most used software [7,122] and thus, will be used in this research. The NREL suggests simulation then optimization using HOMER, finally design improvements using HYBRID2 [122]. This research will not do the second and third step, but will do the simulation.

2.3 Conclusion

There are approximately 2 billion people without access to grid based electricity [2]. Electricity access brings about economic development, a better way of life and helps break the cycle of poverty [7]. Sustainable, renewable energy can be found in solar power and many places have a working knowledge of diesel power. The mixture of these two to form a hybrid power plant is thus simple and cost effective for people who have been relying only on diesel power. This mixture is also good for the environment as the sun's renewable clean energy reduces the harm to the ozone layer and after the infrastructure cost is paid, the solar PV power is for free.

In this thesis, macroeconomic analysis is seen as choosing the best place to position the PV/Diesel HPS whilst taking into account financial, geological and other factors. Other research has used mathematical methods to analyse these multivariable problems and scant research actually looks at analysing each variable from a research standpoint to come to credible assumptions.

A solar PV system becomes feasible when the area under consideration gets 3-6 kWh/m² per day [16,45], but just because an area's temperature is high, does not mean it has enough radiation for solar PV [2] and PV/Diesel HPSs can produce power at around 0.143 \$/kWh, depending on where in the world it is located and its physical size. The motivation of subsidies, drives power producers worldwide to take up RESs or convert to HPSs [65,136,150].

The use of diesel is a global concern due to the economic risk, environmental risk and political risk i.e., diesel is derived from crude oil which is controlled by global political influences regarding price and availability of supply. To combat this, there is biofuel (biodiesel and bioethanol). Biofuel is derived from a chemical process applied to organic matter and the engine performance is akin to using traditional diesel except with fewer pollutants emitted during combustion.

The U.S. and Brazil are the biggest producers of Biofuels. The latest issue surrounding biodiesel however, is the impact on land availability. The IISD has argued that there is a value chain to the actual cost of biodiesel, whereby the repurposing of land and creating physical infrastructure could be an expensive task. Other researchers argue that less land for farming causes fuel prices to rise.

This thesis will attempt to include the possibility of biodiesel in the HPS and observe the cost and environmental impacts. The simulation will be done using HOMER software. HOMER is one of the best software and only two others come close in terms of robustness. As mentioned earlier, it was conceived by the NREL, the primary lab for renewable energy research in the US.

This chapter will be the springboard for the theory development that now follows. All researchers seem to have the same list of macroeconomic factors. The table of factors, Table 2.1, will be expanded upon and applied to an area in China seeking to use a PV/Diesel HPS. This will be the development of a new macroeconomic factor list specifically for the purpose of this thesis.

3. Macroeconomic model of HPS

3.0 Countries used in the model

This chapter will discuss what goes into a macroeconomic model for a HPS. It will develop the methodology that this thesis will use and will show its usefulness in the Chinese Taipei, India, Turkey and Australia . This is useful because India is one of the BRICS nations along with RSA, whilst the other countries are more First world economies. Thus the usefulness across the board will infer that when done in the context of RSA, the macroeconomic analysis can also yield plausible results.

This section will take a list of macroeconomic factors derived by past researchers and discussed in the Literature Review in Chapter 2 and use them to analyse a Chinese country. Each parameter such as GDP, Oil Usage, Pollution, etc. will be described and the relevant country data regarding each topic with regards to Solar PV/Diesel will be explained. Finally, a table (please refer Table 3.3) displaying a summary of the results will be presented and this table will also include a few other countries such as India, Turkey and Australia. This table will be considered the “short-form” of the macroeconomic analysis because each parameter can take pages to explain. Hence important points will be referenced in this table for ease of reference on what macroeconomic factors play a role in a HPS developed for that specific country or area.

RSA will be the country of interest for the simulation of the new HPS after doing the macroeconomic analysis. The simulation however, will be detailed in Chapter 4.

3.1 Development of a macroeconomic model

By beginning with the macroeconomic approach with parameters listed in Table 2.1, the entire country of China was looked at for its viability for certain natural resources to use as input for a PV/Diesel HPS. This information can then be used to inform where to place what kind of HPS. Using data from the Chinese Central Meteorological Bureau, Figure 3.1 shows the wind and solar resource of distribution in China. The solar resource is yellow and rich solar resource is dark yellow. The wind resource is green and the richer the wind resource the darker the green. The solar and wind maps do overlap in Figure 3.1.

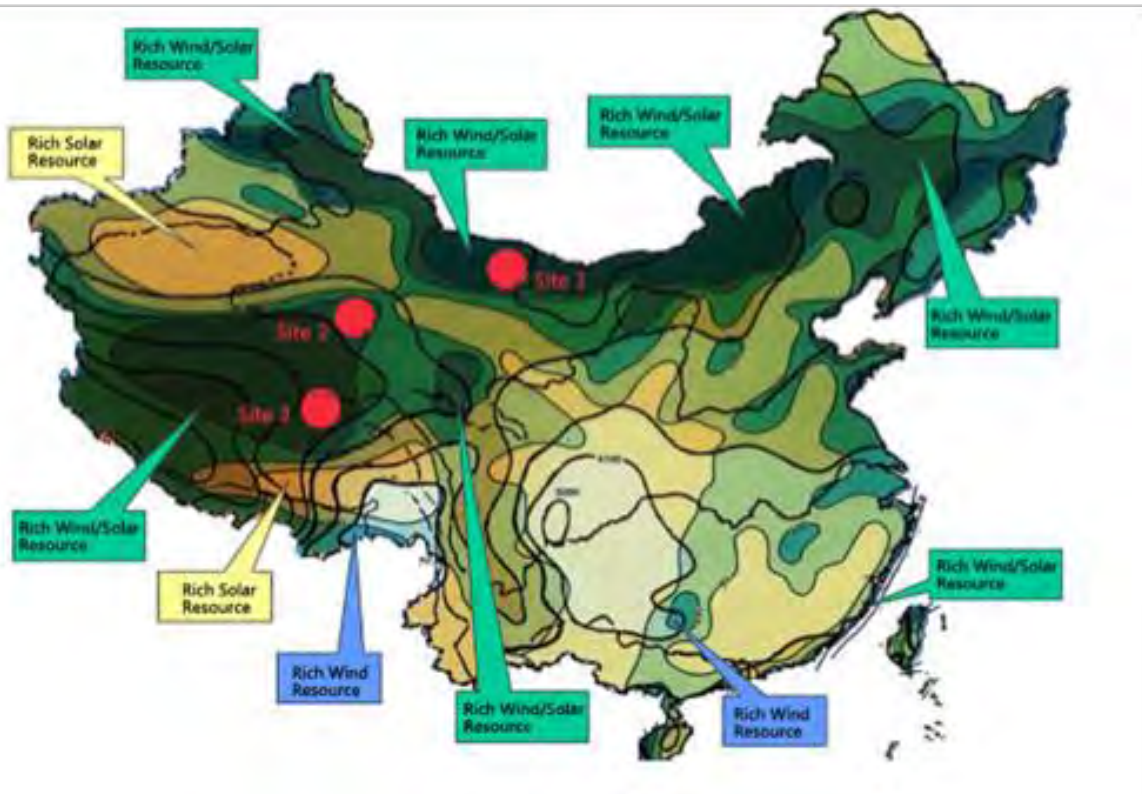


Figure 3. 1: Solar and wind energy distribution in China [4].

Out of the three sites selected in Figure 3.1 above, Site 1, which is Inner Mongolia, has the most installed wind capacity [4]. Site 2, Qinghai, has the highest installed solar capacity; however, it is far from the load centres and thus needs longer transmission lines [4]. Site 3, Eastern Tibet, is high in altitude, traffic is bad and there are high operation and construction costs.

Such factors play a role in any mathematical approach[4] or systems approach. Nevertheless, the potential in these areas has been validated by the now-installed capacities in these areas. This shows that government and investors have benefited from such data. A table of installed capacities in China is shown in Table 3.1.

Table 3. 1: Installed capacity in Chinese sites [4].

Districts	Installed Solar Capacity (MW)	Installed Wind Capacity (MW)
Site 1 (Mongolia)	230	1590
Site 2 (Qinghai)	1003	770
Site 3 (Eastern Tibet)	90	15

The installed capacity in Table 3.1 indicates an affinity for renewable energy in China. Referring to Figure 3.1, in the bottom right there is an annotation of “Rich Wind/Solar Resource.” This area is the Chinese Taipei and one region in therein is Kinmen Island.

Table 2.1 from the literature review chapter, listing macroeconomic factors, will be the basis for the indicators that will be researched relating to Kinmen Island. There will be two levels of indicators: First-class indicators and Second-class indicators. The first class indicators will cover the broader issue, whilst second class will go a little into detail. These factors are also what other renewable energy research deemed to be macroeconomic factors. As discussed in Chapter 2, the research that fully looks at the macroeconomic factors of power systems only looks at RESs as a whole through generic thought

trees [111], social acceptance [27] and triangle charts talking about theoretical, technical and economic potential [75,159].

This being the case, mathematical approaches were looked into [4,9,10,114,158,160,161,162,163,164] and one method aptly adapted macroeconomic factors into a Matter-Element Extension method [4]. This study produced the Table 2.1 presented in Chapter 2 that uses first and second class indicators.

The macroeconomic milieu of Kinmen Island will now be described using Table 2.1's factors and will discuss each parameter based on country facts. This is what is defined as a macroeconomic analysis. This thesis will not incorporate any weighting elements [165] to the factors and will use values and assumptions based on trends and facts derived from the words written in the macroeconomic analysis.

More factors will be added to second class indices to start modeling the macroeconomic milieu more accurately and factually. These indices will inform the HPS developed in this thesis.

3.1.1 Kinmen Island

First class Indicator: Natural resources, Second class index: Sunshine days

The average sunshine is 159.1 hours per month [51]. Between July and October, the average is 200 – 220 hours per month. July and August have the longest duration of sunshine hours and the highest temperatures [51]. This indicates a strong possibility of solar PV as a RES.

First class Indicator: Natural resources, Second class index: Gross solar radiation

Radiation data in many research papers (often funded by the US, such as [129]) use the NASA surface meteorology and solar energy website [130].

For this report, all solar radiation data will be from SolarGIS, a global leader in satellite information [168] and providing historical, real-time and other weather data pertinent to solar technologies worldwide [167].

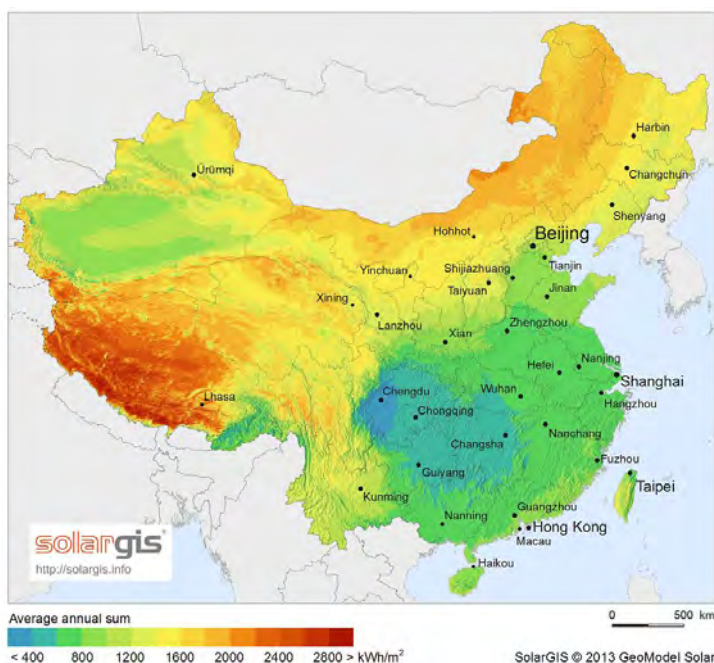


Figure 3. 2: Direct solar radiation across China (kWh/m²) [44].

The radiation map for the Chinese Taipei, which includes Kinmen Island, is seen in the bottom right of Figure 3.2. The average radiation is about 800 kWh/m². The lowest amounts of radiation are found in the southeast. Instead of radiation, one can use a clearness index; however, this thesis will use radiation. Later in this chapter, the conversion from radiation to clearness will be touched upon.

Figure 3.3 shows the global PV installations, in 2012, the cumulative installations and Watts per inhabitant [50].

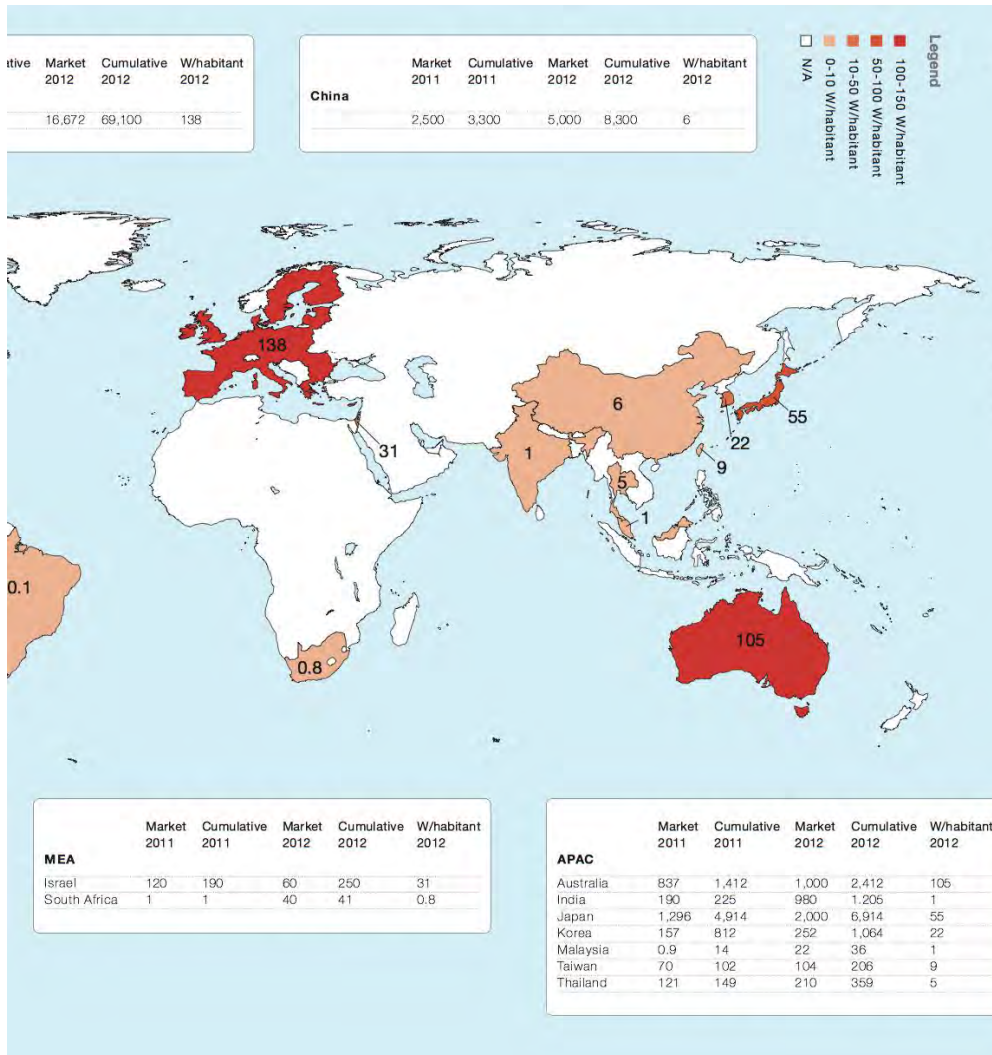


Figure 3. 3: Global PV map [50].

Figure 3.3 shows that there is a lot of PV installation per person in Australia as indicated by the red colouring at 105 W/habitant. In the Chinese Taipei, which is just off the coast of Mainland China, between Beijing and Hong Kong there is a moderate amount shown on the map by the number nine.

First class Indicator: Economic factors, Second-class index: GDP

According to the World Trade Organization (WTO) Penghu, Taiwan, Kinmen and Matsu are referred to as the Chinese Taipei [91]. It's GDP is ranked as the 19th largest exporter globally and 18th largest importer.

The Chinese Taipei imports almost all of its raw materials and exports mostly semiconductors, flat panel displays and other materials [91]. Exports comprise about 73% of GDP, which explains why the recession of 2008 caused a need for diversification of their economy. This region then rebounded with

a growth of 2.3% in 2013, however for the medium term their selling points are in information technology (IT) and manufacturing [91]. In the Chinese Taipei, 98% of the energy supply is imported and over 25% of overall imports are for fuel [91]. In 2005, there were six fuel stations and two fishing ports [64]. This was enough to sustain their economy; however, it also made their economy very susceptible to the 2008 economic recession.

The Chinese Taipei government has a few significant macroeconomic challenges. These include free-trade agreements, taxation reforms, land regulation, economic cooperation agreements.

Five percent of total tax revenue comes from trade related tax. This includes businesses tax, which makes up one third of this and then commodities and sin tax. Sin tax is tax on tobacco and alcohol products [91]. Subsidies for production in the industrial products and agricultural sectors still exist [91]. Direct tax incentives have been phased out over the past years and replaced with support for Research and Development (R&D) and innovation.

In petroleum and electricity generation, land transport and telecoms are dominated by state owned enterprises (SOEs). In all sectors apart from the aerospace sector, the privatization process that begun in 1992 has been suspended [91]. Price controls are put on telecommunications, energy services and committees exist to control and systematically stabilize prices of commodities. Some energy products require licensing and standards used locally are in line with international standards [91].

The manufacturing sector accounts for 25% of GDP and 88% of exports. The government is failing to improve product innovation and diversification [91] and so the region still is overly-reliant on the Information and Communications technology (ICT) sector [91]. Total revenue from the telecommunications sector accounts for 3% of the GDP.

The services sector is the largest and accounts for over half of the employment and 66% of GDP [91]. Financial services accounted for 6.5% of GDP in 2013. There are no notable measures to promote non-local service providers. The local labour market is well educated and there is no shortage of skills.

In 2012 there were about 7.3 million international tourists in the Chinese Taipei. This is good because they want to promote tourism [91]. The tourists however were mostly in China, Japan and Hong Kong and not Kinmen Island although it experienced tourist growth from a percentage point of view. With the opening of the “open skies regime” between the Republic of Korea, China and Japan, there are now more cross-straits flights, which positively add to tourism [91].

The government has selected ten key industries as a focus for their development policy. These are [91]:

1. Medical tourism;
2. International logistics;
3. WiMAX technology;
4. Music and digital content;
5. MICE (meetings, incentives, conferencing and exhibition) industry;
6. Fundraising for high-tech and innovation-oriented industries;
7. Urban renewal;
8. Chinese-language e-commerce;
9. International promotion of its cuisine; and
10. Recruitment of overseas students.

As of 2012, the Chinese Taipei's foreign reserves were at \$400 billion making them the sixth largest in the world [91]. The fiscal deficit in 2009 was 3.7% of GDP and has improved in 2014 to 1.4%. According to 2014 fourth quarter statistics from the World Bank [43] the GDP of China as a whole is \$9 Trillion. The Government debt of China is 14.9% [41].

In this thesis, national debt is defined as debt to GDP and not debt to GNI (Gross National Income). The World Bank uses GDP and GNI in country statistics, but their main criterion is GNI. It is the position of this research thesis that because GNI per capita changes over time and GDP statistics available are more recent than the GNI, the GDP and Government debt should be based on GDP. The Government debts are based on the latest 2012 figures [41] and the GDP figures are based on latest 2013 and 2014 figures, however due to no debt figures available for 2013 and 2014, the GDP mentioned within this research thesis will not be the same GDP used in the Government debt calculation. GDP is a yardstick measure of the structures produced, services rendered and goods produced in an economy over a certain period [26]. In the detailed calculation, net imports and exports are accounted for, but this thesis will not focus on the GDP and GNI formulae.

The preponderance of national debt statistics are derived from the World Trade Organisation Trade Policy Review of the relevant country or the World Bank's 2014 International Debt Statistics report [41]. GDP data is from the World Bank's World Development Indicators Database as of 22 September 2014 [43].

First class Indicator: Economic factors, Second class index: Electricity demand

Taiwan Power Company (Taipower) the local utility is forecasting pollution issues and supply issues. Population affects electricity demand and from 2009 it forecasted a population increase to about two hundred thousand people [64]. This

According to Taipower's "Long-Term Power Development Program" latest figures and targets for RESs in Kinmen were [159]:

- Install 513 MW in 2010;
- Install 700 - 800 MW by 2020; and
- Install 800 - 900 MW by 2025.

Kinmen Power Company has invested in constructing a new power plant [64] and upgrading the capacity of the other constructed plants. Great Kinmen has three power plants [64]. The new plant is Tashan which produces 64 600 kW and the older ones are Xiaxing which produces 22 312 kW and Chu-Kuang which gives 4 540 kW [64]. Little Kinmen has Cilin which produces 5 672 kW using 24, diesel generator sets. On Kinmen Island as a whole, the total installed capacity is 97,124 kW and in 2007, total generation capacity was 254 GWh per annum [64]. This was supplied by base power of diesel and unstable base power of wind and solar [64]. This is the plan for Kinmen Island until 2020 when RESs are to be phased in.

A general household consumes 3-4 kW at peak load. Families have on average 2.7 -4.5 persons and the average monthly consumption per four-member family is estimated at eight hundred kWh [64].

Electricity is generated by Taipower or by IPPs. A non-local investor can own an IPP however, the IPP must sell to Taipower who will then distribute to end users [91]. The price of electricity is announced

by Taipower or determined by a competitive bidding process involving the IPPs. Table 3.2 shows the latest electricity tariffs across South East Asia. These countries are chosen for this table because the climates are similar, they are all mostly islandic communities, they all rely quite heavily on tourism and it was easier to convert their various currencies in to the New Taiwan Dollar (NT\$). Countries in the table are supplied by various utilities and Taipower only covers the Chinese Taipei region. Table 3.2 gives the reader an idea of the tariffs in South East Asia and how they compare to Kinmen Island, which is a part of the Chinese Taipei. The information is from the latest World Trade Organization Trade policy review [91].

Table 3. 2: Electricity tariffs in 2013 [91].

Residential use		Industrial use	
Country/region	Average unit price (NT\$/kWh)	Country/region	Average unit price (NT\$/kWh)
Malaysia	2.5762	Republic of Korea	2.3079
Shanghai, China	2.8837	Malaysia	2.6487
Republic of Korea	2.8998	Chinese Taipei	2.8020
Chinese Taipei	3.1165	Thailand	2.8174
Thailand	3.1545	Hong Kong, China	3.2023
Shenzhen, China	3.1781	Shenzhen, China	3.7763
Hong Kong, China	4.1421	Shanghai, China	3.8303
Singapore	5.2500	Singapore	3.8960
The Philippines	6.1095	The Philippines	4.3273
Japan	7.3409	Japan	4.8729

First class Indicator: Economic factors, Second class index: Oil demand

According to the Kinmen Power Company, a government owned utility, in 2006 the oil demand was 58 072 160 litres and in 2007 the oil demand dropped down to 58 041 404 litres [64]. By the end of 2007, Taiwan Power Company, a larger government utility which had been managing Kinmen Power company assets since 2002 [171] had absorbed Kinmen Power Company and thus became the new utility [171].

Two hundred and four companies hold diesel wholesale licenses and another two hold petroleum refining licenses [109]. The main player is the Chinese Petroleum Corporation, which is also running at a loss and the government is trying to privatise this entity [91].

In the whole Chinese Taipei, there is no limit on the amount of crude oil and petroleum products one can import [91]. Private companies may set their own prices for petroleum products sold. Together with subsidies, this encourages healthy competition because energy products are monopolised by government owned companies [91] and 47% of crude oil and petroleum is imported. There are mechanisms in place to regulate the prices. These include an average import tariff of 1.5 % [91], licensing requirements and price controls. The Bureau of Energy oversees petroleum product sales, import, export and production [91].

First class Indicator: Economic factors, Second-class index: Solar PV market

Solar cells were first used in the U.S. for spaceships in the 1950's [93]. Today, even Sub-Saharan Africa has a large potential for solar power according to the Wealth report [5].

In 2009, China had 300MW of Solar PV installations [53]. China's electricity price used to be cheap, thus stifling the PV market development. However, recent advances in technology and climate change concerns have put it in the front seat again.

The PV market in China consists of five parts [53]:

- Grid, building integrated modules;
- Solar PV farms in vast land masses and deserts;
- Off-grid, telecommunications, transportation etc.;
- Off-grid PV for domestic and commercial uses;
- Off- grid in rural areas.

The most installed capacity in 2009 was in desert areas [53] followed by rural areas which promoted building integrated PV, then off-grid transportation and other industrial applications and finally the domestic use.

China produces more than 55% of the PV modules in the world [53]. PV technologies such as module, cell, silicon and wafer are the most popular. Purified polysilicon was uneconomical to make prior to 2009, so China relied on importing this from Germany, Japan and other countries [53].

The manufacturing cost of PV modules has been on a steady decrease and until 2009 thanks to issues such as reduced labour costs, reduced infrastructure costs and no customs duty (until 2010) [53]. In 2009, the demand and cost of PV modules dropped drastically, during the global financial crisis, the market cap implementation of Spain and the feed-in tariff reduction in Germany [53]. This is shown in Figure 3.4 where the cost price of a PV module sharply decreases.

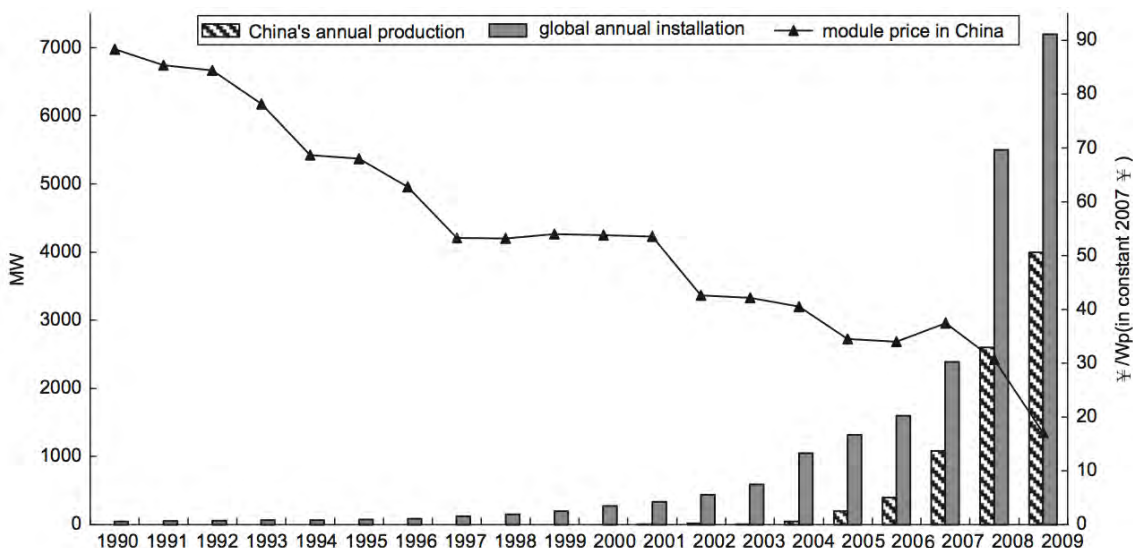


Figure 3. 4: Annual PV module production and cost in China [53].

When converting the Chinese Yuan in Figure 3.4 into U.S. Dollars, we get a 2009 price of 2.02 \$/W. The decrease in China's from 2008 to 2009 was more drastic than in any other PV module producing country. Between 2005 and 2010 the most significant producing countries were Germany, Italy, Canada, U.S. and Japan [172]. Looking at Appendix B Figure B2, the U.S. production cost dropped to 2.55 \$/W, Germany was 3.92 \$/W and Italy 2.76 \$/W [172]. The lower price in the Chinese market

meant they ended up with a greater competitive advantage. When looking at the Appendix B Figure B2, it can be seen that every country's price gap relative to China grew between 2008 and 2009 placing them farther behind. This is expected because for one, the U.S. and Europe have price margin pressures that are greater than China; where there are lower production costs.

In China, more PV modules are produced as a percentage of global output as seen in Figure 3.5. The total installed capacity is, however, greatest in Europe as seen in Figure 3.6. This is mostly because of the policies the Europeans have in place to adopt solar energy.

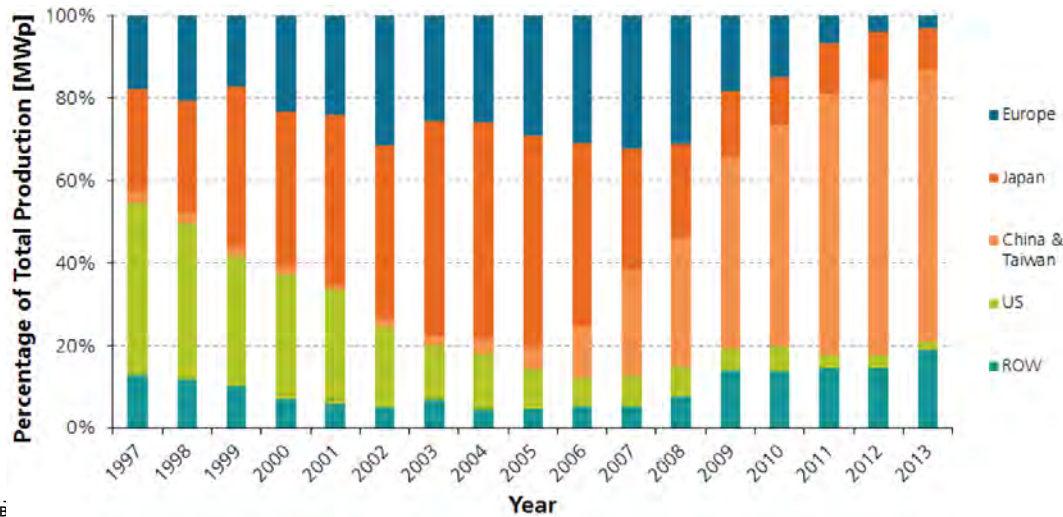


Figure 3. 5: PV module production as a percentage of global production [109].

In Figure 3.5 and Figure 3.6, ROW is the Rest of the World. In Figure 3.6, MEA is Middle East and Africa and APAC is Asia Pacific.

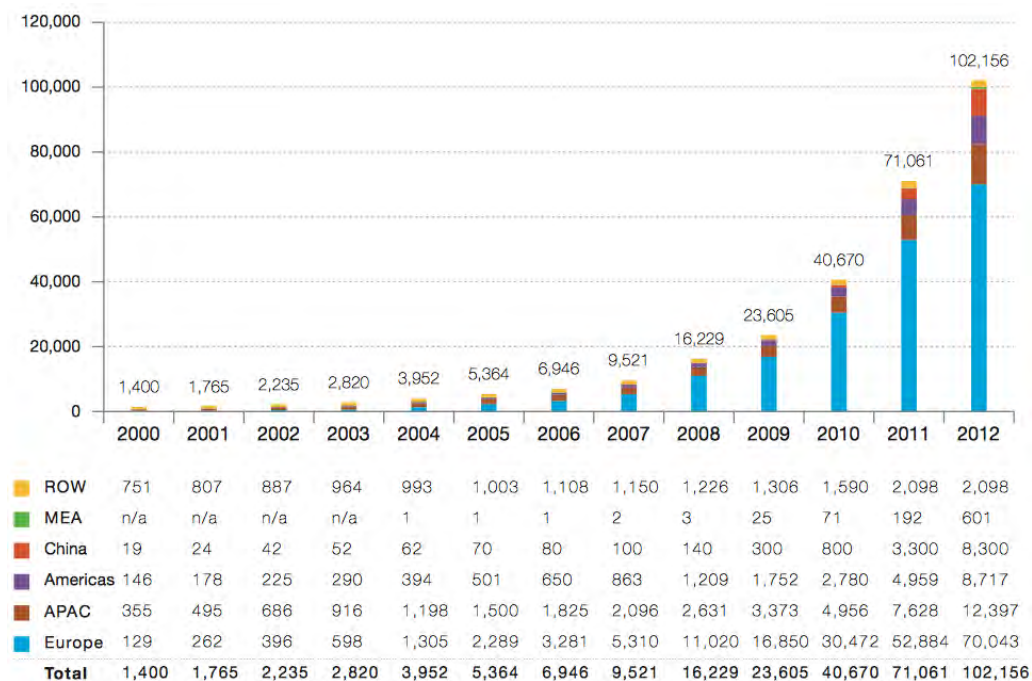


Figure 3. 6: Global cumulative installed PV capacity (MW) [50].

Figure 3.6 shows the total installed PV capacities globally. This data is from the European Photovoltaic Industry Association, one of the leading sources of information.

Public bidding forces manufacturers to be innovative and handle suppliers in a more cost-sensitive manner [53]. In China, the PV deployment works like a top-down structure. The central government sets total PV targets in policies such as the “11th Five Year Plan of Renewable Energy Development and the Medium and Long-term Renewable Energy Development Plan” [53]. Then the government starts rolling out programs such as the “Solar Roofs Program” and each program has targets to meet. Finally, the investors and manufacturers for these projects are chosen using a public bidding process. What sets the Chinese system apart is the decision-making through a linkage of departments and ministries. For example, the “Solar Roofs Program” had the investors chosen through discussion between the Ministry of Finance and the Ministry of Housing and Urban-Rural Development of China [53]. Furthermore Research and Development (R&D) support at a university level is implemented for achieving each of their “Five-Year” plans [53].

The problems identified and topics of interest for breaking current barriers include [53]:

- Getting governments to support PV manufacturing, R&D and develop sound policies for industrial development;
- The planning of PV systems in remote areas should, as far as possible, be aligned with grid transmission line planning;
- Getting international buy-in for PV applications and co-operation in manufacturing can bring more advanced technologies, manufacturing methods and policy recommendations; and
- The cost of PV needs to be subsidized by government because it is costly to manufacture in terms of accessing raw materials such as silicon [68].

First class Indicator: Economic factors, Second-class index: Construction cost

The central government has drawn up subsidies to encourage purchase of solar thermal collectors. These subsidies for offshore islands are at least double what one would receive in mainland Taiwan.

A solar energy system for a general household can cost around 1000 000 NT\$. This is half subsidised by the central government and then the remaining NT\$ 500 000 is subsidised in half again by the local government [64]. Thus, there is a clear promotion of solar energy in Kinmen Island.

In 2009, there was only one PV module manufacturer in Kinmen [64]. The spot market price for PV modules can be found online, at the largest brokerage platform for inverters and modules. With over ten years’ experience, strong market presence and monthly releases on PV price trends, they are best poised for a market price overview. The prices for PV modules are shown in Figure 3.7.



Figure 3. 7: Spot module prices in the market from the EU and surrounds €/W [49].

The prices from the pvXchange magazine [49] in Figure 3.7 reflect the latest information until 13 October 2014. From Figure 3.7, it can be seen that China’s price stagnated in September 2014 [49], though since October the price everywhere has slowly dropped in Euros per Watt produced (€/W or EUR/Wp). Germany however, declined faster recently and this due to slow sales and price adjustments from lower demand at the end of the year [49]. It makes sense that the price would drop to about 0.6 €/W as manufacturers would fear holding extra stock entering a new year and possibly the close of their financial years around February and March in 2015.

For PV module manufacturers, the most important cost-contributing elements are the feed-in tariff and the public bidding price output. Public bidding is a market-based measure used for utility-scale, to get a suitable tariff [53]. In Jiangsu in China, the feed-in tariff in 2011 was 1.4 Chinese Yuan per Kilowatt-hour (¥/kWh) for ground installations, 2.4 ¥/kWh for rooftop installations and 2.9 ¥/kWh for building integrated PV modules [53]. Other factors that manufacturers consider are current orders, manufacturing capacity and the technological competitiveness.

First class Indicator: Economic factors, Second class index: Operational & maintenance costs

According to the Taiwan Renewable Energy Development Act [173] which is used in Kinmen Island, there is a guaranteed price for electricity generated using RESs.

There is a problem of maintenance costs as there is not much skilled labour on the island. Furthermore, material supply is an issue and involves large costs for Kinmen Island [64]. Solar energy systems to be used in Kinmen can achieve a lifespan of at least twenty years [64], which would make financial sense when considering a payback period.

Electricity produced from diesel in 2009, was 7.2 NT\$/kWh [64] and this is expected to be NT\$ 14 by 2020 [64]. However, this price includes carbon taxes collected by the local government, which directly influences the price of electricity [64]. In 2013, according to the Taipower rate schedule [170] the cost of electricity was on average 3.1 NT\$/kWh.

First class Indicator: Economic factors, Second class index Strategies and policies

Kinmen's economy has phased out military rule over the last half century, and is now more tourism focused.

In 2004, the local government drafted the first strategy for sustainable development [64] called "Planning for Sustainable Development Strategies in Kinmen." This focused on economic development constraints derived from ecological constraints. Thus, there were issues such as how to develop RESs that are not centralized and more distributed and how to harness the wind and solar energy available. It went so far as to include social issues such as protecting the local language.

The central government drafted the Renewable Energy Development Bill, which provides incentives for clean, renewable energy facilities up to an installed capacity of 6.5 Million kW [64]. There are also directives such as "directions for the establishment and operation of solar power PV system subsidiary projects."

By 2020, Kinmen plans to have at least 34% of power generated, come from RESs. The energy intensity needs to be reduced by 20% relative to the 2005 figure, by 2015 and reduce by 50% relative to 2005, by 2025 [91].

The Chinese Taipei's Taipower is running at a loss [91]. The revenues from sales less the cost of generation and buying from IPPs has raised the net loss from NT\$43 billion in 2011 to NT\$62 billion in 2012, which is part due to that Taipower itself does not receive any government subsidy [91]. The government is putting measures in place to privatize Taipower.

First class Indicator: Traffic conditions, Second class index: Traffic convenience degree

Equipment manufacturers are close to the concentrated solar power, power stations. In addition, very good PV technology exists in Taiwan, so the suppliers are nearby.

First class Indicator: Traffic conditions, Second class index: Transmission line length

According to the 2012 Taipower sustainability report [59] their distribution lines in 2011 totalled 357 000 km. Covering the supply of Taiwan and the offshore islands of Mazu, Kinmen and Penghu [59]. In 2012, the total lines had increased to 364 000 km [78]. The distribution network of Taipower is shown in the power grid map of Figure 3.8 and Kinmen is at the top left [59].



Figure 3. 8: Taiwan power grid and power development map [59].

As shown in Figure 3.8, Taipower handles most of the power generation. Moreover, the transmission lines within Kinmen are of such a short distance they are neglected. The transmission costs are not a significant factor for Kinmen as a small island.

First class Indicator: Environmental factors, Second-class index: Pollution

According to Taipower, one litre of fuel oil produces 2.98 kg of CO₂. This means when Kinmen region generated 250 TWh in 2007, it used 50 Million liters of fuel oil and emitted 150 000 mt of CO₂ [64].

China from 2000 to 2010 emitted a growing amount of pollution, of ten percent [86] that is close to the GDP growth over the same period. In 2010, the CO₂ emissions were a quarter of the global total and multiple measures have been put in place since by China, such as their 12th Five year Plan [86], issued in 2011. One key output from this plan was to increase the RESs supplying loads, by 11.4 percent by 2015 [86].

First class Indicator: Environmental factors, Second class index: Energy saving/pollutant reduction

Kinmen Island is very reliant on diesel power plants and as an island, it is doing well making steps in playing a role in preventing global warming.

The promotion of green buildings is not something Kinmen is looking at, however of a larger scale they are looking at reducing current CO₂ levels. In June 2005 [64] the “National Energy Convention” was held in response to CO₂ reduction requirements set forth from the Kyoto Protocol.

Producing one kWh costs NT\$7.2, so solar power could help Taipower save money. With an installed solar capacity of 1 470 000 kWh, there would be a fuel saving of 294 000 l and carbon emissions of 876 mt and cash savings of approximately NT\$10 000 000.

Looking at the cost of diesel generation, there would be a savings of over NT\$1.5 billion if conventional diesel generators [64], which Kinmen is heavily reliant upon, were completely replaced with RESs or HPSs.

First class Indicator: Environmental factors, Second-class index: General waste

General waste includes kitchen waste, recycled items, bulk waste, industrial waste and transportation of old waste.

General waste in 2007 amounted to 18 245 kg [64]. This resulted in an average waste volume of 0.63 kg per person per month in 2007.

A stationary type biomass energy generation system can convert eighteen mt of refuse into 11 070 kWh of electricity per day [64]. Based on Kinmen’s waste amount, further investigation into using waste as a biofuel is to be done.

First class Indicator: Social issues, Second class index: Load residents attitude

The residents do not want to lose their local language in the process of adopting new technologies.

As an offshore island, Kinmen needs to maintain a low density of tourists and a high quality recreational milieu [64]. Historical culture and tourism policies are vital.

First class Indicator: Social issues, second class index: The distance to load centre

The power plants are generally close to the load centres and distance is not an issue on the island.

First class Indicator: Geographical, Second-class index: Geological/topographic condition

Kinmen Island is on the southeast coast of mainland China. It is ideal for wind and solar power.

First class Indicator: Conditions, second class index: Land usage condition

Kinmen had 198 villages as of 2009 [64] and in 2007, a population of 948 000 people.

There is limited land on the island, so setting up large-scale solar PV arrays or wind farm will not suffice, but small and medium scale wind will [64]. One option considered already is vertical axis wind turbines for wind power taking into account wind data, which is not a focus of this thesis.

Kinmen Island's local government is looking at military and public owned land for the space to setup power plants [64].

The Macroeconomic table of Kinmen Island will later be shown with the new factors derived from the high-level country review concluded above. The point of this is to use these factors in the construction of the HPS later in this thesis and construct a table for the region the HPS will model.

From Asia, four new second-class indexes that are important for a macroeconomic analysis are listed below:

- Strategies and policies;
- Oil demand;
- General waste; and
- Solar PV market.

These four factors will be a part of the table of macroeconomic factors in this thesis. This adds to the robustness of the model herein.

The macroeconomic parameters have been researched and more factors that this research thesis deems relevant have also been listed above. At this point, there are a few countries aside from Kinmen Island that will be used to tabulate the macroeconomic analysis done above. This tabulation will be another method of representing the information found and will be considered a 'quick-form' of the macroeconomic analysis because the information is summarised in a table.

The countries were chosen to show that the quick-form methodology can be applied without a need to do the extensive form applied thus far in this chapter. The countries chosen are:

- Chinese Taipei, because it has been covered by the above macroeconomic survey, with a focus on solar PV/Diesel HPSs;
- India, because it is an Asian country like the Chinese Taipei and it is one of the BRICS countries and is a developing nation that carries similarities with RSA;
- Australia, because it is a first world country and has some of the best solar radiation available. It also has one of the most advanced power grids in the world [101]; and
- Turkey because it is a country that lies in Europe and Asia. It is also a more Eastern than a Western influenced country and there is a reasonable amount of available country data on it [47,48,88].

Indices relating to an Asian country, an Oceanic country and a country that is part of Europe and Asia will now be tabulated to show their macroeconomic information.

Table 3. 3: Asia, Europe and Oceania macroeconomic indices.

First Class Indicator	Second Class Index	Chinese Taipei	India	Turkey	Australia
Natural resources	Sunshine days	The average sunshine is 159.1 hours per month [51]. Between July and October, the average is 200 – 220 hours per month. July and August have the longest duration of hours and the highest temperatures [51].	Average is between 2300 h and 3200 h per year [70].	Average is over seven hours per day [88].	Average is 5h to 9h per day. The lowest parts of the country get fewer hours [66].
	Gross solar radiation (kWh/m²)	The average is 800 kWh/m ² , (please see Appendix A Figure A1.)	The average is 1500 kWh/m ² , (please see Appendix A Figure A2.)	Across North Turkey, like Istanbul, Average is 1311 kWh/m ² [48], but the rest is 1800 kWh/m ² , (please see Appendix A Figure A3.)	The major coastal cities from Melbourne to Brisbane have the lowest at about kWh/m ² . The preponderance of Australia is strong at 2700 kWh/m ² , (please see Appendix A Figure A4.)
Economic factors	GDP (Million USD)	\$9 240 270M [43] with a fiscal debt of 14.9% [41].	\$ 1 876 797 M [43] with a government debt of 68.5% [41].	\$ 820 207 M [43] with a government debt of 37.6% [41].	\$ 1 560 597 M [43] with a government debt of about 105% [41].
	Electricity demand	254 452 584 kWh per annum [64]. There are RES plans to install 700-800MW by 2020 because currently diesel generators supply most of the load.	The Northeast region of India consumes very little energy. Some states consume only 163kWh/per person per annum [6]. In 2012, there was 210 GW of capacity and in 2014 the	The demand in 2014 was 260TWh and capacity in 2012 was 55 GW [101].	The demand in 2014 was 260 TWh [101] and capacity in 2012 was over 62 GW [101]. Australia has one of the most advanced power networks in the world [101]. The price of electricity is one

First Class Indicator	Second Class Index	Chinese Taipei	India	Turkey	Australia
Economic factors	Electricity demand		demand across India was 1200 TWh [101]. Ineffective load management led to blackouts in 2012 [101].		of the lowest in the world [21]. RESs total about seven percent of primary energy [65]
	Oil demand (litres)	58 041 404 l in 2007 [64]. Companies may set their own price for petroleum products.	Crude oil supplies 19% of power in Tamil Nadu [110]. More than 18 000 village communities still rely on kerosene [70]. In 2012, fossil fuels made up 80% of generation power source [101]	The market is dominated by Natural gas at 44% and coal is 28% [101]. Increasing standards of living and population and strong tourist growth spurs on more oil consumption [88].	Coal supplies 70% of power with Natural gas taking 19% [101].
	Solar PV market	China produces more than 55% of the PV modules in the world [53]. In 2012, China had 8300 MW of PV [50]. Kinmen has 1 470 000 kWh of solar capacity.	Installed PV capacity of 1.3 GW [50], with 980 MW having come in 2012. The capital cost of a PV module is 1200 \$/kW and replacement cost is 720\$/kW [6].	600MW of Large-scale PV licenses were on auction in 2013 [101]. Chinese and European PV panel manufacturers have opened shop in Turkey. The cost of a PV panel is between 4200 and 1200 \$/kW [19].	The only solar is focused on residential areas and not large scale PV [101]. The installed capacity in 2013 was 3.2 GW [101] and the output from one state, Victoria was 550 GWh in 2012 [63]. A PV panel in 2012 had a price of between \$1482/kW and \$1871/kW.
	Construction cost	A solar energy system for a general household in costs NT\$ 1000 000. This is government subsidised by NT\$ 750 000. A PV module costs 0.5 €/W.	Regulated prices make RESs unfeasible in many areas of India. This is because the transmission cost and increased cost for industrial users subsidizing others like agriculture [101] makes the overall generation cost high,	The Industrial Development Bank of Turkey offers low interest loans to RES players.	The cost of extending the grid has increased the price consumers pay per kW [101]. The cost of a solar PV plant in 2012 was between 200 and 320 \$/MWh.

First Class Indicator	Second Class Index	Chinese Taipei	India	Turkey	Australia
Economic factors			so the traditional, abundant, fossil fuel is still used.		
	Op. & maint. cost	RESs suffer from maintenance costs due to no skilled labour on the island and material costs onto the island [64]. Diesel is already used so that is no big issue.	Biodiesel in India costs on average 0.58 \$/l [69].	The cost of solar energy in 2009 was 0.13 \$/kWh [47]. Wind and Hydro are cheaper than this to produce in Turkey [47].	Current fuel and carbon costs increase the price consumers pay per kW [101].
	Strategies and policies	By 2020, Kinmen plans to have at least 34% of power generated, come from RESs [91]. The Renewable Energy Development Bill provides incentives for clean, renewable energy facilities up to an installed capacity of six point five million kW [64].	By 2022, India plans to have 20GW of grid connected solar power [101] and 10GW by 2017. Mismatched policy making and implementation is hampering the renewable energy market [101].	There is no need for a license to supply solar power under 1MW. Above that, the grid remains tight and not all capacity can simply be added on [101]. The electricity market law was established in 2001. However, currently, lack of proper lending facilities hampers industrial scale growth [88]. The biggest barrier for foreigners is the laws. In Turkey, it can take a... ...year to invest due to paperwork [88]. On interesting they do is, they refer investors to the World Bank and then guarantee them backing of 30% - 40% of funds required [88].	The 2012 Clean Energy Future Plan aims to cut GHG emissions by 5% by 2020 [101] and have RESs of 20% by 2020 [65]. The Clean Energy Finance Corporation, established in 2013 is going to help with future wind and PV projects. Australia allows states and regions to develop their own plans and policies on renewable energy [65]. A few barriers in Queensland for RESs are power... ...purchase agreements, inadequate financial incentives, not enough network capacity and complex zoning and planning procedures [65].

First Class Indicator	Second Class Index	Chinese Taipei	India	Turkey	Australia
Traffic conditions	Traffic convenience degree	In 2009, there was only one PV module manufacturer in Kinmen [64].	In 2008, 119570 villages were not electrified and about 18 000 were in areas too far to be economical for grid extension [128].	Turkey is technically part of three continents and the EU [23,58]. There is ample access to resources. In 2006 it was importing 90% of natural gas from Iran and Russia [47].	Grid constraints may hamper the adoption of PV power [101].
	Transmission line length	The transmission costs are not a significant factor for Kinmen as a small island. Taipower in 2012 cites 364 000 km of distribution lines [78].	The North Eastern parts of India are not feasible for grid extension [6]. India experiences high power distribution losses [101].	Total investment required for transmission lines in 2010 was \$45 Million. This is too much for public funds only and so it is Hobson's-choice to find private investors [88].	Australia has the longest transmission line network in the world [57]
Environmental factors	Pollution	One litre of fuel oil produces 2.98 kg of CO ₂ . This means Kinmen region in total, in 2007, when it generated 250 000 000 kWh it used 50 000 000 l of fuel oil and emitted 150 000 mt of CO ₂ [64].	Tamil Nadu is ranked 14 th largest CO ₂ emitter globally [110]. Tamil Nadu relies on coal for 68% of power [110]	In 2008, Turkey emitted about 300 Mt of CO ₂ .	The Clean Energy Act in 2011, introduced carbon pricing [21] which provides 23 AUD/t [101]. Queensland, the second largest state in Australia [65] has the highest CO ₂ emissions per capita. Australia as a whole emits over 190 Mt of Carbon a year [57].
	Energy saving/pollutant reduction	Saving of NT\$1.8 billion if all diesel fuel in Kinmen was replaced with a RES. An installed solar capacity of 1 470 000 kWh, there would be a fuel saving of 294 000 l and carbon	No data.	Being environmentally conscious is a recent trend, but firms are positively adopting the methods [88]. Turkey does not have a national energy strategy document and has not had one ever [48].	A Carbon credit price of 23 \$/t was introduced in 2012 [21].

First Class Indicator	Second Class Index	Chinese Taipei	India	Turkey	Australia
Environmental factors		emissions of 876 mt.			
	General waste	Average waste volume of 0.63 kg per person per month in 2007. And total bulk waste of 18 245 kg.	In parts of India like the Tripura state, rice husk is found in abundance and this is used for biomass power [6].	No data.	No data.
Social factors	Load residents attitude	The residents do not want to lose their local language in the process of adopting new technologies. Historical culture and tourism policies are vital.	No data.	The residents are very open to adopting new technology.	This is a well-educated workforce and they are willing to explore the RES possibility.
	The distance to load centre	The power plants are generally close to the load centres.	Many villages are far from the power plants and it is difficult for them to get power.	No data.	The transmission lines can reach the loads. However with the potential of RESs being mostly in remote areas from the load centre [57], there will be a need to revisit the transmission grid layout.
Geographical Conditions	Geological/topographic condition	Kinmen Island is on the southeast coast of mainland China. It is ideal for wind and solar power.	India has high solar regions and high wind regions like Tamil Nadu. It also has high coal reserve regions and lots of land space available.	Turkey is best suited for Solar and Wind power [88].	Queensland is a very sunny state, with about 100 MW installed capacity by 2010 [65]. The area accommodates 167 MW of Hydropower, 65 MW of Biomass and 12 MW of Wind and is looking closely at a tidal wave power plant [65]. 64% of the Australian

First Class Indicator	Second Class Index	Chinese Taipei	India	Turkey	Australia
Geographical Conditions					population resides on the coast [57]. The top part of Australia is more tropical and hot and as you go to the south it gets cool [57].
	Land usage condition	Kinmen had 198 villages as of 2009 [64] and in 2007, a population of 948 000 people. Land is limited, local government is looking at military and public owned land for the space to setup power plants [64].	The North-Ease part of India is a region known for growing rice. 91.7% of agricultural land is dedicated to food grains [6].	Turkey is suited for Hydropower and in 2009, most of the projects funded by the Turkish Industry and Development Bank were hydropower [88].	New South Wales, Queensland and Victoria still use coal and in South Australia a shift towards wind power is taking place [21].

Table 3.3 can be considered a 'quick-form' macroeconomic analysis. The process of delving into each parameter can be undergone by a researcher, however this is not always feasible. By observing how the in-depth macroeconomic analysis was done above, on issues that have a relation to a PV/Diesel HPS, the quick-form can be effectively used.

The macroeconomic model that will be shown in the next chapter will look like Table 3.3. There will be one country, RSA and two columns: One for the macroeconomic factor values and information from a past research paper and the second column for inputs from this thesis's macroeconomic analysis. The second column depicts the macroeconomic parameters described and referenced. Thus there will be a juxtaposition of the input variables. This will make for ease of reference when the results are also juxtaposed, so one can see more precisely the differences in the level of input.

The software inputs for the simulation are mostly microeconomic inputs. Such as equipment replacement cost, site layout [69], derating factor of each PV panel [72] and more. Thus, the software inputs will be fewer than the number of macroeconomic inputs covered. This is fine, because one day in the future the software might incorporate these factors. Furthermore, if the macroeconomic analysis were not done independently before simulation, then the analysis would basically now be a 'simulation based analysis', which is not the aim of this research.

The variables in this research thesis will be linguistic parameters and not converted to weights as in other studies involving multiple variables [165]. This is because there is no added benefit with regards to the software inputs and the PV/Diesel system. Meaning the GDP of a country can be found, the electricity consumption pattern of an area can be found and these are immediately used in the simulation and they directly relate to a HPS. If actual country data is unavailable, which is highly unlikely as seen in the macroeconomic analysis of Kinmen Island, then assumptions will be made based on past research papers.

3.2 Conclusion

The EU adopts solar PV technology the most, China manufactures the most and RSA invests the most as a portion of its GDP. The EU's largest barrier for PV power is the permits to produce power [39]. In Germany there are municipal challenges, the Netherlands has environmental permits that are a hurdle and very active societal groups that protest [39]. In Spain, the social development plan is scrutinized, along with the environmental impact assessment [39].

Energy system modelling is gaining importance in Africa and across the world [166]. In developing (low to middle-income) countries, the government debt levels are lower than the more developed countries. Debt is not always a bad thing and because of the low government debt levels, a lot of the available funds from other countries are not used to enable funding mechanisms. Thus financing for projects is a sticking point, even in Alaska [102], Turkey, Australia and in Chinese Taipei. Without adequate financing or price mechanisms, even big firms will not take the risk of developing infrastructure [102].

Many countries have the minimum required kWh/m² to capture a useful amount of solar power but government policies play a big role. If policies are not in place or effectively implemented, then the PV/Diesel or other RES is difficult to implement. The cost of operation is often higher in rural areas because of infrastructure costs whereas in places where there is already urbanisation, this is easier.

Countries separate the ideas of residential solar PV and desert installations. This is due to the MW output and eventual possible uses of the two methods of solar power. But a good finding is that the public perception toward solar power is much more welcoming than that of nuclear power.

This section has focused on a few countries to set the scene at a high level. RSA will now be used to do a macroeconomic model. These same factors will be used to estimate pricing for the PV modules, diesel costs and estimate the limitations on the amount of diesel that can be used. An existing model of a PV/Diesel HPS will be remodelled through using the quick-form of the macroeconomic analysis in the next chapter.

4. Modelling and analysis of HPS

4.0 Location of the HPS and essential chapter information

An already-simulated HPS in Stellenbosch, RSA [2] will be re-designed using parameters informed by a macroeconomic analysis. The oil input will be looked at in terms of a biodiesel input where possible and where legislation may lend itself to such. This is one aspect that was not covered by past researchers [2].

This thesis will then run a simulation and plot the results to see the impact of a macroeconomic analysis on the hybrid power plant. This is to see what impact the macroeconomic analysis would have had and if the extra effort is worth the time.

This method is in line with the research aims: to show that economics, which usually limits engineers, can be positively used to actually be a basis for the technical design.

4.1 Macroeconomic analysis of Stellenbosch house, RSA

A recent research paper simulated a PV/Diesel system in Stellenbosch [2] and it was based upon a Masters-level thesis by the same author [169] simulating only a PV/Battery system. There is no other currently available research on PV/Diesel for RSA, however the benefit of a macroeconomic analysis in this regard can still be realised when comparing with the PV/Battery system.

The research in [2,169] focused on a household in Stellenbosch that would be a typical urban house in that area. The house as had some loads connected to the Eskom grid such as the stove, geyser and oven [169] and the rest was powered by the PV system [169]:

- 2kW washing machine
- 2kW kettle;
- 1.8kW vacuum cleaner;
- 1.7kW dishwasher;
- 1.5kW electric toaster;
- 480W incandescent light bulbs;
- 300W refrigerator;
- 100W television;
- 50W personal computer;
- 22W Compact fluorescent light bulbs;

The resulting load pattern is shown in Figure 4.1.

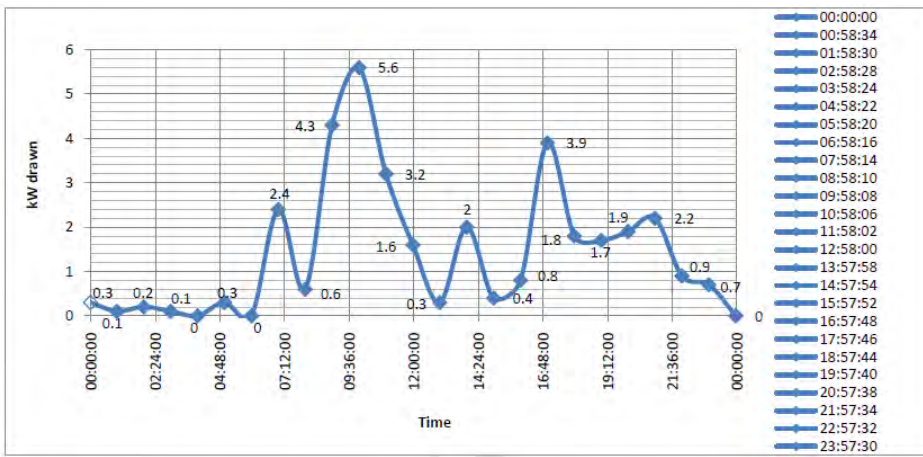


Figure 4. 1: Stellenbosch residential load pattern over 24 hours.

This research thesis will compare input from previously simulated systems [2,169] with a newly developed HPS, focusing more on the macroeconomic inputs.

In this chapter, where N/A is written, it implies that there was no consideration of that factor by past research, or that factor has no available information that would be useful. The quick-form macroeconomic analysis is applied below.

Table 4. 1: Macroeconomic analysis of Stellenbosch, RSA.

First Class Indicator	Second Class Index	Previously simulated	Newly simulated
Natural resources	Sunshine days	An annual average temperature of 17.53°C [169].	327.29 days in a year with an annual average temperature of 18.01°C [174].
	Gross solar radiation (kWh/m ²)	5.33 kWh/m ² per day [169].	5.08 kWh/m ² per day [115].
Economic factors	GDP (Million USD)	N/A	\$350 630M [43] with a government debt of 46.1% [41]. The local inflation is 5.3% [180] and the Prime lending rate is 9.25% [180] (please see Appendix B Figure B4.) The GDP is only expected to grow by 3.2% on average until 2018 [101]. All items collect Value-Added Tax (VAT) which is 14% [180] atop any item cost. Only few items are excluded such as milk, bread, and fresh produce. The Rand/Dollar exchange rate median of the 52 week range from February 2013 was 11R/\$ according to Bloomberg [183].

First Class Indicator	Second Class Index	Previously simulated	Newly simulated
Economic factors	Oil demand (litres)	Diesel price assumed at 0.7\$/l.	RSA in 2013 used 5.7 million barrels per day and 1.224 btoe [140]. There is a minimum blending of 5% biodiesel with traditional diesel [139]. The capital cost of biodiesel is lower than bioethanol [152].
	Solar PV market	N/A	By 2030 there should be 7.4 - 10 GW of installed PV capacity [179] (please see Appendix C Figure C2.) RSA has the most installed PV in Africa [50]. There was 0.8 W/habitant in 2012 [50]. There are only five countries with a greater PV attractiveness and investment attractiveness greater than RSA (please see Appendix B Figure B5.) The datasheet for the battery [182], taking into account the temperatures of the area, will have it operating at 100% or more throughout the year. The past research [2] assumed 200W panels, whereas the same price panels today can be found for 250W hence 250W panels were used.
	Construction cost	Component prices for the HPS were from MLT drives, a local distributor [175]. The number of days of autonomy was assumed to be 2-3 [169].	According to the number of no-sunshine days in Stellenbosch [174] 3-5 days autonomy is needed. A PV panel costs about R 28 910 per kW [179]. Average cost of electricity from IPPs is 88c/kWh [13]. On 31 March 2014, Eskom had purchased a total of 3.67 TWh of electricity from these producers [13].
	Op. & maint. Cost	Most component costs were assumed to be zero because of their small value relative to the capital cost [169].	PV crystalline costs 208 R/MWh per annum [179] to maintain. A PV fixed tilt panel is projected to drop in cost to R8 029 per kW by 2030 [179]. The average inverter price reduced between...

First Class Indicator	Second Class Index	Previously simulated	Newly simulated
Economic factors		With the diesel system [2] the cost was \$21 per year.	2011 and 2013 by 54% [181]. A 50% overall reduction over the next 15 years is a reasonable estimate.
	Strategies and policies	N/A	Biodiesel has a 40% fuel levy tax exemption [177]. The National Development plan in 2012 [178] cited a minimum of 20 GW of clean energy was needed by 2030, and the Integrated resource plan update in 2013 [179]. There is a \$113 M Investec fund for RES projects [101].
Traffic conditions	Traffic convenience degree	N/A	There is ample infrastructure in Stellenbosch to facilitate movement of materials.
	Transmission line length	N/A	RSA has 29 924km of transmission lines [13] and 46 093km of distribution lines [13]. The difference is the voltage capacity.
Environmental factors	Pollution	N/A	Eskom, the local power utility emits approx. 233 Mt of CO ₂ per annum [13]. Over 90% of the power in RSA is from coal fires power stations [13].
	Energy saving/pollutant reduction	The simulation looked at taking a household off the grid, and there was no benchmark for pollutant reduction or a focus on this.	68% of electricity is from coal fired power plants [2]. From 2015 the new atmospheric standards will regulate emissions [184].
	General waste	N/A	N/A
Social factors	Load residents attitude	N/A	Residents are frustrated with the current load shedding [13] and want reliable power.

First Class Indicator	Second Class Index	Previously simulated	Newly simulated
Social factors	The distance to load centre	Diesel price of 0.9 \$/l.	There is a local power station not far off, called Koeberg. There are power lines sufficiently close to each residential load in Stellenbosch. Biodiesel can be manufactured on site or nearby. If this were replaced with diesel however, then the coastal price of diesel will have to be paid which as of 4 February 2015 was R8.9549 per liter [185]. This is considerably cheaper than biodiesel [140].
Geographical Conditions	Geological/topographic condition	N/A	A mediterranean climate, with many valleys [175]. There is a lot of fauna and flora in the area and an average temperature of approximately 17.5°C [169].
	Land usage condition	N/A	Most land in Stellenbosch is for wine farms [175] and other agricultural uses. There is a University, a hospital, medium and high density residential, sporting facilities, industrial and business parks [176]. In RSA only 14% of total land is arable [177] however there is often a crop surplus from farmers [177].

The macroeconomic analysis resulted in inputs to the simulation that can be found as follows:

- Appendix D: Simulation inputs summary;
- Appendix E: Components chosen; and
- Appendix F: Screenshots from simulation.

The simulation in this section will be compared to [2] and [169]. A Solar PV/Diesel HPS was modelled in [2] however, the author also did the longer, Masters dissertation in [169]. The dissertation was a PV/Battery only HPS but the location, load pattern, inflation rate and other factors were used for [2].

In [2] there is a simulation of a PV/Diesel HPS in South Africa to determine if it was feasible to supply the load seen in Figure 4.1. The simulation in [2] used the six various climatic zones of RSA and came up with a NPC for each zone. The results are shown in Figure 4.2.

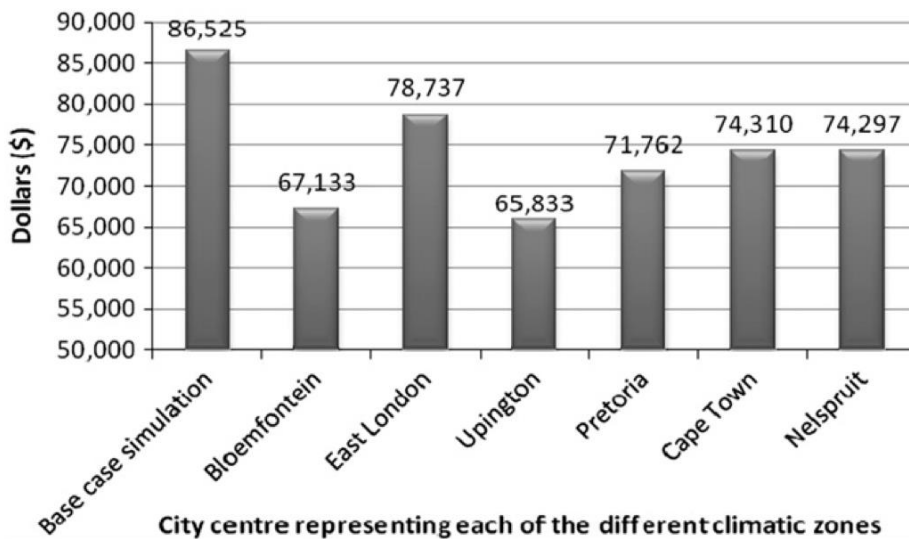


Figure 4. 2: NPC with diesel price of 0.9 \$/l [2].

It was found that Upington, an inland region was the most feasible [2] and not Cape Town which is home to Stellenbosch. Upington had a NPC of R594 480.

Reference [2] used an exchange rate data of 2011. [2] used diesel cost of 0.9 \$/l and one of 0.7 \$/l and an exchange rate of 8 R/\$. If the quick-form macroeconomic analysis were to be applied in retrospect for the month of April 2011 the cost of diesel inland (reef) was actually R9.48451 [186], closer to the coasts (coastal) was R9.28051 [186] and the exchange rate was 6.8 R/\$ [187]. So firstly at 0.7 \$/l and 8 R/\$, the cost per liter is implied to be 5.6 R/l which is too far off from [186]. At 0.9 \$/l the cost per liter is R7.20. So the diesel cost in \$/l of 0.9 \$/l [2] is too low and it would mean that either the exchange rate had to be 10.53 R/\$ or the fuel price had to be different as well. Either way the point is the NPC of Upington at R526 664 is an underestimate. In [2] the aim of the two diesel prices was to show the impact that diesel prices have on a HPS and this was well expressed. It should be understood that a macroeconomic analysis was not the focus of [2] and their price assumptions sufficed to effectively prove the point.

However, let one assume that the assumptions made in [2] were a real case. Then, although the technical configuration accounting for solar radiation and the batteries chosen was properly done, the design would face higher, more realistic costs when put into a real-world scenario. This is exactly where this research thesis fits in. It has done a macroeconomic analysis already in Table 4.1 and this will inform more realistic fuel prices, interest rates and exchange rates and thus yield a more economically viable HPS for the RSA context.

This research thesis will draw data from [2] but where [2] falls short or more background information is needed, [169] will be cited.

This research thesis aims to see if there is merit financially, technically or otherwise in doing a macroeconomic analysis before designing the HPS. It is expected that there is benefit because, economic factors often limit what can be technically achieved, however if that were to be reversed and the macroeconomic factors were used to design a power system, there should be benefit. The design of the HPS within this section will be similar to [2] meaning the load and area will be exactly the same, but component sizes will be within a very close range to what was done in 2011 in [2]. The main difference between [2] and this research thesis is the number of assumptions made and how they were made.

To avoid assumptions regarding the software, the workings behind HOMER will now be discussed. HOMER is designed to optimise a given power system for the lowest cost in today's terms (NPC). If any single PV/Diesel system is given, as in this research thesis, it will optimise based on:

- Dispatch strategy [119]: Various ways of running the diesel generator e.g. 2 hours a day or 5 hours a day or 24 hours a day. This is part of a process called cycle charging (please see Appendix D Table D9);
- Maximum annual capacity shortage [119]: Various amounts of load that is left unmet by the end of the year e.g. Having 0% of the load unmet, or having no more than 1% of the load unmet by the end of the year (please see Appendix D Table D10);
- Operating reserve [119]: How much extra power should there always be? e.g. always have 2% of the annual peak demand available, or always have an extra 5% of the highest peak load that occurs in the year (please see Appendix D Table D10). The peak load is automatically derived from the user's input of load pattern; and
- Renewable output [119]: How much should the PV panels be used e.g. If they are used 90% of the time, then the renewable output is 90%, but if the diesel generator is used half the time throughout the year, then the renewable fraction drops to 50%. However there was benefit in this simulation from using biodiesel that the renewable fraction thus remained very high (please see Appendix D Table D5).

If multiple component ranges are given for a single PV/Diesel HPS, as in this research thesis, the software will perform a sensitivity analysis using the abovementioned points along with:

- PV Panel permutations e.g. using 1 panel then using 3 panels up to using 9 panels (please see Appendix D Table D3);
- Diesel generator permutations e.g. using a 5kW or 6kW (please see Appendix D Table D4);
- Battery permutations e.g. using batteries in increments of six, up to 30 total batteries (please see Appendix D Table D6); and
- Converter permutations e.g. three sizes of converters, being 6kW, 8kW and 12kW, each with a different capital cost (please see Appendix D Table D7).

The user will input the component prices for each different component in the range. The user can also specify one price then the software will simulate an extrapolation of that price using various sizes e.g. give the price of one battery then tell the software to try using one, two or three batteries. The user could also specify prices for three different batteries and the software will incorporate that into the sensitivity analysis. For this research thesis, the major components used and their market costs can be found in Appendix E Table E1.

Once all combinations and permutations have been done, they are ranked according to the cheapest system setup and operation mode down to the most expensive setup and operation mode. The NPC translates directly to a cheaper cost of electricity (COE) which is measured in R/kWh.

The format of the results discussion will be such that the focus is placed on the macroeconomic factors and the role they played. The results achieved will be juxtaposed with the results [2] achieved and success within this research thesis will be if the system comes out as the cheaper system or is within a tolerance of 5% of the Stellenbosch HPS system in [2]. It should be noted that, [2] and this research thesis will be serving the same load, just four and a half years apart. To the ordinary technical person, it will be a revelation to see how macroeconomic factors play a role. One cannot just add inflation to all costs and assume that will be the real future cost of the system. There are demand and supply forces that will throw all mathematics out the window, and there are underlying currency fluctuations that will affect international trade and component prices, and that has nothing to do with input costs, it is a political matter and a matter of investor sentiment. These will be shown as to how they work and the usefulness or not of the macroeconomic analysis will be seen.

4.2 Simulation results

The HPS simulation took 220 seconds to complete and the results are shown herein.

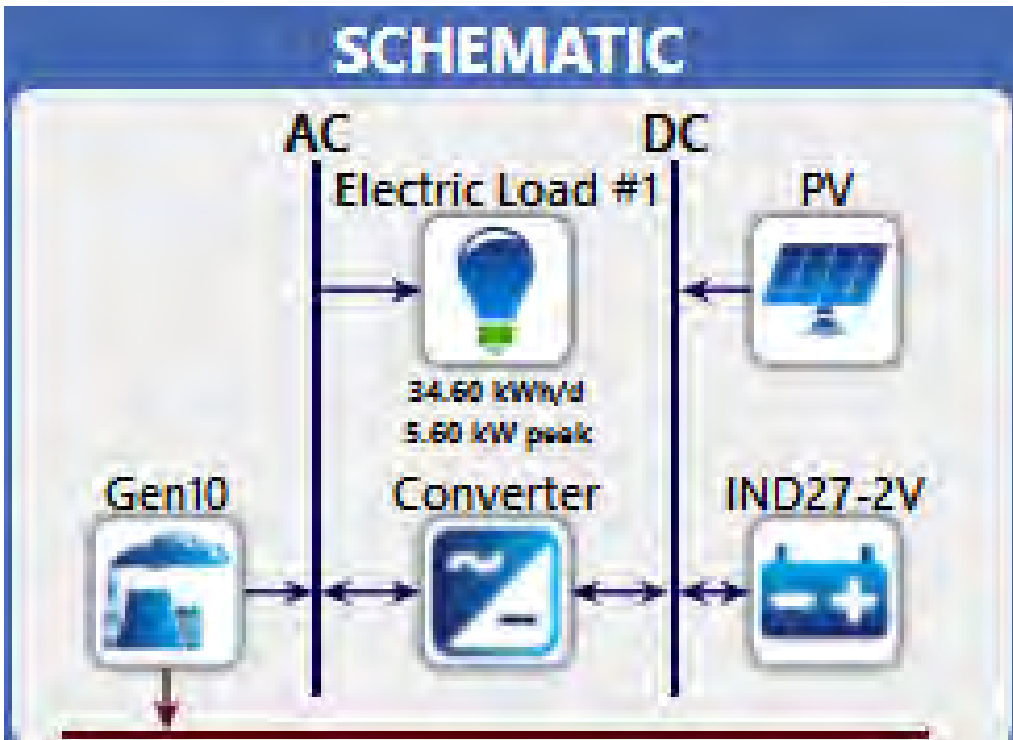


Figure 4. 3: Solar PV/Diesel HPS schematic diagram.

Figure 4.3 shows the schematic layout of the HPS. Gen10 is the diesel generator that runs on biodiesel, the converter connects the DC and AC buses for power flow in either direction. The electric load is the household load that is the same as [2] and is shown in Figure 4.1. The PV is the solar panel which represents any size solar panel, depending on the user’s input. The IND2702V is the Trojan 2V battery which represents a string of batteries.

Sensitivity Cases: Left Click on sensitivity case to see optimization cases.												
Architecture				Cost				System			Gen10	
PV (kW)	Gen10 (kW)	IND27-2V (qty)	Converter (kW)	COE (R/kWh)	NPC (R)	Operating Cost (R)	Fuel Cost (R)	Ren Frac (%)	Unmet Load (kWh/yr)	Fuel (L)	Hours	
9.0	5	12	8	R 2,961	R 599,750	R 15,472	R 7,991	77.8	0.00024801	725	636	

Optimization Cases: Left Double Click on simulation to examine details.												
Architecture				Cost				System			Gen10	
PV (kW)	Gen10 (kW)	IND27-2V (qty)	Converter (kW)	COE (R/kWh)	NPC (R)	Operating Cost (R)	Fuel Cost (R)	Ren Frac (%)	Unmet Load (kWh/yr)	Fuel (L)	Hours	
9.0	5	12	8	R 2,961	R 599,750	R 15,472	R 7,991	77.8	0.00024801	725	636	
9.0	5	18	8	R 2,998	R 607,340	R 12,594	R 5,941	82.5	0.00024855	539	397	
9.0	5	12	12	R 3,035	R 614,915	R 15,644	R 7,991	77.8	0.00024801	725	636	
9.0	5	18	12	R 3,073	R 622,505	R 12,766	R 5,941	82.5	0.00024855	539	397	
9.0	6	18	8	R 3,090	R 625,971	R 12,726	R 5,999	82.3	0.00025046	544	337	
8.0	5	12	8	R 3,112	R 630,344	R 18,111	R 9,960	72.4	0.00025257	903	796	
9.0	6	12	8	R 3,118	R 631,681	R 16,433	R 8,708	76.4	0.00024062	789	610	
9.0	6	18	12	R 3,165	R 641,136	R 12,897	R 5,999	82.3	0.00025046	544	337	
8.0	5	12	12	R 3,186	R 645,509	R 18,283	R 9,960	72.4	0.00025257	903	796	

Figure 4. 4: Best case system setup result and next best configurations.

Figure 4.4 shows the best case from the sensitivity analysis in the first table. The second table shows the first nine permutations and their result in terms of COE and NPC. The variations for the sensitivity analysis herein are not the focus of this thesis, so this will not be described.

The first three columns of either table show the number of system components used or the power from each component. The first column is the output of the PV panels, then the size of the diesel generator, then the number of batteries used, then the size of the converter used. For explanations on the rest of the columns please look below to Figure 4.6.

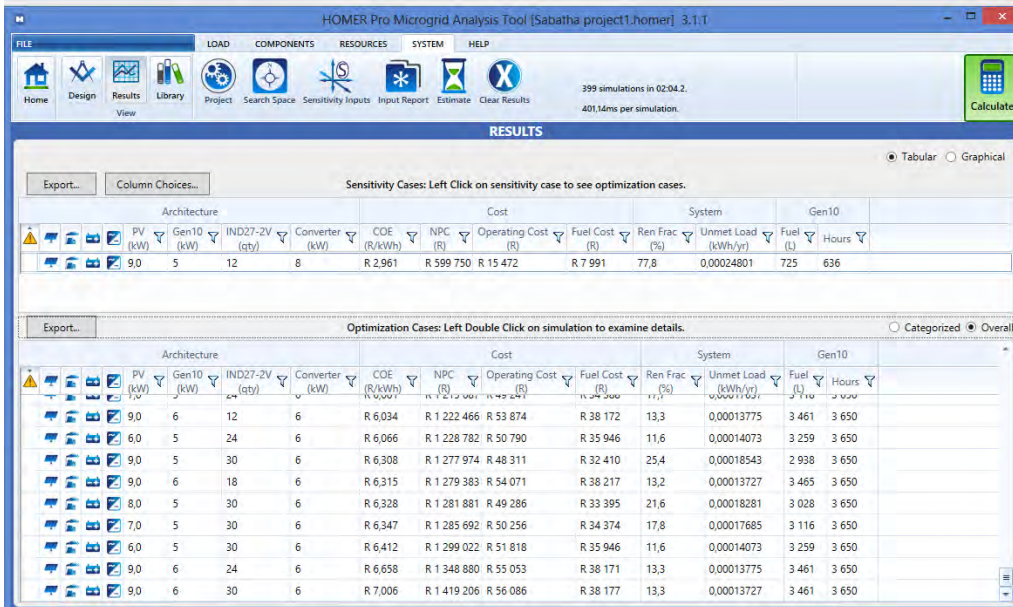


Figure 4. 5: Best case system setup result and worst case configurations.

Architecture				Cost			System		Gen10		
PV (kW)	Gen10 (kW)	IND27-2V (qty)	Converter (kW)	COE (R/kWh)	NPC (R)	Operating Cost (R)	Fuel Cost (R)	Ren Frac (%)	Unmet Load (kWh/yr)	Fuel (L)	Hours
9,0	5	12	8	R 2,961	R 599 750	R 15 472	R 7 991	77,8	0,00024801	725	636

Figure 4. 6: Best case system setup.

In Figure 4.6 under the “Cost” heading, ‘COE’ is the cost of energy that the HPS configuration would yield. The NPC is the most important output. This is how much the system would cost today if all costs for the next 25 years were monetised in today's terms.

The RenFrac column shows how much of the HPS is from a renewable source over the lifetime of the system. It was easy to get a high value for this because the HPS was using biodiesel and PV panels which are both renewable sources of energy. The only non-renewable was the battery.

The Gen10 column is the diesel generator. The Fuel column is how much total fuel is used over the lifetime of the system, and the Hours column shows how many total running hours the diesel generator accumulates over a year. In all outputs shown by the results above, there is no indication of the running costs of each component because HOMER does not show this to the user.

Architecture						Cost			Gen10	
PV (kW)	Gen10 (kW)	IND27-2V (qty)	Converter (kW)	COE (R/kWh)	NPC (R)	O&M (R)	Fuel (L)	Hours		
9,0	5	12	8	R 2,961	R 599 750	R 3 291	725	636		

Figure 4. 7: Best case system setup including operation and maintenance costs.

Architecture				Cost			
PV (kW)	Gen10 (kW)	IND27-2V (qty)	Converter (kW)	COE (R/kWh)	NPC (R)	Operating Cost (R)	Fuel Cost (R)
9,0	6	30	6	R 7,006	R 1 419 206	R 56 086	R 38 177

Figure 4. 8: Worst case system setup.

Architecture				Cost				System		Gen10	
PV (kW)	Gen10 (kW)	IND27-2V (qty)	Converter (kW)	COE (R/kWh)	NPC (R)	Operating Cost (R)	Fuel Cost (R)	Ren Frac (%)	Unmet Load (kWh/yr)	Fuel (L)	Hours
9,0	6	30	6	R 7,006	R 1 419 206	R 56 086	R 38 177	13,3	0,00013727	3 461	3 650

Figure 4. 9: Worst case system setup including operation and maintenance costs.

4.3 Discussion of results

The solar radiation availability of 5.08 kWh/m² as per the macroeconomic analysis in Table 4.1 made the area of Stellenbosch in RSA a viable candidate for solar power. Furthermore, the planned introduction of biodiesel into RSA regulation made the biodiesel option a viable candidate instead of diesel.

4.3.1 System component discussion

The resulting HPS from the simulation of this research thesis is shown in Figure 4.3. The constraint for the system was the lowest NPC. The electric load was the same as [2,169] and more compensation was made for the seasonal variation in load pattern for a consumer in RSA. The peak load of 5.6kW meant that this is the maximum draw and any solar panel, battery bank or diesel generator needs to be able to handle this.

Figure 4.5 represents the best scenarios with least NPC, and Figure 4.6 shows the best scenario in detail. Figure 4.7 represents the scenarios that were the most expensive and Figure 4.8 shows the most expensive scenario in detail. There were a total of 399 simulations run for the sensitivity analysis, based on the combinations of PV panels, batteries, etc. as explained in Section 4.1 above.

The most expensive system configuration used a 6kW generator, 9kW of PV panels, 30 batteries and a 6kW inverter. This had a cost of 7 R/kW and a NPC of R1 419 206 and a renewable fraction of 13.3%. This system is very expensive and it would not make financial sense to try use this system.

In the most cost effective system, there is 9kW of PV panels. This is made up of a total of 36, 250W PV panels and a 5kW generator. The inverter was 8kW and the battery bank comprised of 12 batteries. The resulting NPC was R599 750. This was made of a cost of energy at 2.96 R/kW and an operating cost of R15 472. The fuel input costs across the 25 year lifetime were R7 991. The renewable fraction of the system was 77.8% which is high, and the unmet load was less than half of one Watt which means all load was supplied. The generator used 725 l of fuel and ran for 636 h.

The quick-form macroeconomic analysis of Table 4.1 had a great influence on the HPS inputs (please see Appendix D). The resulting outputs of the system in [2] which was done a while ago and focused on architecture and technical design, will be paralleled with this research thesis that took into account macroeconomic factors before the technical factors. The three to four year time between [2] and this research thesis has changed one non-macroeconomic item that affected the results of this research thesis: HOMER software has become more user friendly, with increased functionality and is able to manage larger amounts of data.

A table comparing the previously simulated literature case of Stellenbosch [2] with this research thesis' results is shown in Table 4.2.

Table 4. 2: Comparison of HPS outputs.

Variable	Previously simulated [2]	Newly simulated	Difference and reason	Impact of change
<i>Net Present Cost</i>	R594 480	R599 750	0.879% difference. This was one of the two expected outcomes. Either the simulated system is cheaper or it is very close to [2].	The macroeconomic analysis affected the component choice (please see Appendix E Table E1) and system constraints (please see Appendix D Table D8) in a positive way. The new system is almost as cheap as four and a half years ago when the exchange rate was 7R/\$ [187], almost half what it is now, 11 R/\$ [183].
<i>Load pattern</i>	5.6 kW peak.	5.6 kW peak.	None. It was assumed in the IRP 2010 of RSA [179] that by 2015, 40% of all households will fall into the living standard measure that can afford solar PV on their rooftops. This was a good reason to stick with the load pattern of [2] because urban area dwellers in Stellenbosch are well-off so this load pattern is justified.	N/A
<i>Interest rate</i>	6%	9.25%	This simulation's interest rate was higher because that is the real value.	In HOMER, all components rise in price using the same inflation rate, which is good for simplification. This research thesis finds that this is very inaccurate for long term planning because all governments have a target range for inflation. Perhaps HOMER could take into account the inflation range, and not value, as per each country's annual budget report.

Variable	Previously simulated [2]	Newly simulated	Difference and reason	Impact of change
<i>Renewable energy fraction</i>	62.5%	77.8%	This simulation provided over 10% more renewable energy. This is because of the use of biodiesel as opposed to diesel. And this simulation used more solar power in terms of kW from panels, to supply the load.	Renewable energy targets are met in both simulations. This simulation just has more that could be gained from selling Carbon credits. It also emits fewer pollutants.
<i>Diesel consumption</i>	1 922 l/yr	636 l/yr	This simulation uses no diesel, only biodiesel. The diesel consumption in this simulation was two thirds less than in [2]. The reason is because	There are no harmful emissions from the HPS. This has yielded a good question: What happens if the PV panel cost and the biodiesel cost are on downward curves? Does that mean the optimisation would be thrown off? Probably not, because there would be an error if the final cost were to reach zero. But again this is impossible because of inflation and VAT. Furthermore finding a good feedstock for biodiesel is a global concern, and although it is a proven technology, as said in the Literature review, not all farmers are getting sufficient return to justify an investment into selling crops for specifically such a purpose.
<i>Strategies and policies</i>	Government subsidies and feed-in tariffs are needed to promote growth.	There are laws around biodiesel adoption, and solar geyser adoption.	More law came into effect since 2011 and more standards were developed. More private investors are also willing to fund renewable energy projects.	The country, RSA, is proving to be the most advanced in Africa. The uptake is not as fast as Europe but there are inroads being made to remain technologically relevant. This 'Strategies

Variable	Previously simulated [2]	Newly simulated	Difference and reason	Impact of change
<i>Strategies and policies</i>				and policies' factor has spill-over into the social aspect of 'Residents attitude', because now people are more willing to have solar on their own roofs because the government is making it seem like a safe technology. There is a phasing in of policies around locally produced biodiesel in RSA and this is still to be adopted by industry, through them procuring biodiesel to remain compliant.
<i>Solar Panels</i>	2kW from an unknown number of panels.	9kW from individual 250W panels.	In 2011, the IRP [179] had just come out. Panels costed over R20 000 per kW, and in 2015 they cost under R15 000 per kW. So the minimisation of panels required was helpful.	Today bigger Solar PV systems can be built using the same amount of money.

The PV panel sizes that were considered were 1 to 9kW. A 1kW panel is not commercially available and sizes available in RSA range from 10W to 300W. So, the 1kW requirement was met by joining four 250W panels. This was still relatively affordable and the cost per panel in 2014 is less than when the local resource plan estimate from 2010 [179].

The 5kW generator is highly variable in cost. The 5.5kW generator was cheaper in 2011 [2] than a 5kW generator in today's Rand terms. This is mostly due to the load shedding that has been happening in RSA which has led to suppliers inflating their generator prices. This situation has worsened since the end of 2014 because 2 power stations that should have been completed by Eskom in 2013 and 2014, have not been completed. Thus a 5kW diesel generator can cost anything from R12 999 to R16 999 depending on location, because of a higher rate of blackouts in a particular area.

The battery used was made by Trojan, a prominent battery maker for deep cycle batteries. They are popular for having a large share of the electric golf cart market. They provide 2V, 4V and 6V batteries, however for consistency with past research [2,169] only one battery was considered. The considered battery had 2V, 1520 Ah and the variability optimized by the simulation was the number of batteries used. The number of batteries was 6, 12, 18 24, 30. One string of batteries comprised of 6 batteries.

It was difficult to find biodiesel factors to change within the software. For example, the energy output of 11 MJ/kg present could not be changed. Biodiesel has about 10% less heat released than diesel when combusted [1] and has a lower Calorific value compared to traditional diesel. These could not be inputted as variables.

The most cost effective system used a 9kW panel and yielded a cost of 2.96 R/kW. By only changing to use an 8kW panel the cost became R3.11 and the renewable fraction dropped from 77.8% to 72.4%. This is a large drop in renewables and the biodiesel use rose from 725 l to 903 l. This affects the macroeconomics because more is spent on importing the environmentally friendly fuel.

4.3.2 Economic discussion

HOMER factors out inflation from the calculations by requiring the interest rate and the inflation rate [119]. This way the real interest is achieved and applied to each component in the same manner. For the results the lending rate was 9.25% and the inflation rate was 5.3% resulting in a real interest rate of 3.95%.

The real interest rate is marginally greater than the projected GDP growth of RSA until 2018 [10]. It should be considered that the costs of the components in the simulation are inclusive of VAT which is a 14% surcharge in RSA. For a larger corporate with a certain minimum turnover they can claim back VAT, meaning they can claim from the local Tax Revenue Service the 14% surcharge that was added. So in a reality for a company and not an individual, the NPC of the HPS will be even less than R599 750.

The R/\$ exchange rate has deteriorated since December 2011. It was 8R/\$ and in 2015 it was at 11.58R/\$. This simulation was optimistic by assuming the latest annual average, which yielded 11R/\$, but this is still very high. There should be a comparison of imports from various countries with certain raw materials such as biodiesel, because of the currency risk that is within foreign trade.

4.4 Conclusion

The software was very useful in running the simulations. It has evolved and become a lot more user friendly since 2011. The macroeconomic analysis definitely helped in reducing the number of assumptions made within the simulation.

The macroeconomic analysis has been very useful in informing the overall results. Multiple facets of the analysis helped interpret the results and size the HPS correctly.

By factoring out inflation, and using the real interest rate [119] the costing of the system was much more accurate. The aim of RSA to have 25% renewable energy generation in their energy mix [184] has been achieved by the system optimising and getting over 70%.

The Literature review covered bioethanol and biodiesel. Once the quick-form analysis was done, it was clear the biodiesel is the better option to model. The choice of only using biodiesel was clear because the capital cost and running cost of biodiesel is lower than bioethanol. Also, in RSA, the bioethanol mix can be as low as 2% with diesel, whereas biodiesel is going to be mandatory 5% [139].

5. Conclusions

5.0 Concluding remarks

In order to dovetail all the work done within this research thesis, the aims set out at the start will be highlighted, and the success or failure therein.

This research was successful technically because the HPS could supply the same load as past research. It was also successful socially and politically because all the national resource plan targets were met within the design. Also financially because the NPC is extremely close to the past research's NPC. When comparing the results against past research [2] in 2011 they achieved a NPC of R594 480 with a diesel cost of 0.9\$/l at an exchange rate of 8R/\$. This is slightly lower than the simulations presented in this research thesis in 2015, which yield a NPC of R599 750 with a diesel cost of 1\$/l at an exchange rate of 11R/\$. The results are within 0.879% accuracy of each other therefore it is evident that taking into account all the macroeconomic factors is financially useful in designing a HPS.

This research thesis has successfully developed and used a macroeconomic approach to designing a HPS. There is certainly more accuracy and financial benefit through systematically doing macroeconomic research before making assumptions and technically modelling.

The factors that often limit realistic designing of a HPS have instead been positively used in the design. This research has shown usefulness in RSA, a country experiencing blackouts, and in Turkey, Chinese Taipei, Australia and India.

5.1 Recommendations for further research

Further extensions of this research can consider:

- Recycling of wasted heat by doing an exergy analysis of the HPS;
- Macroeconomic plus a microeconomic analysis;
- More countries and areas around the world;
- Using this in industry to help find where planned blackouts can be mitigated in South Africa, and which spots are possibly economically feasible for a Solar PV/Diesel HPS; and
- The simulation can take into account transportation costs, because the distance to load centre is a macroeconomic input but has no place within HOMER software.

6. References

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7. Appendices

7.1 Appendix A: Global solar radiation maps

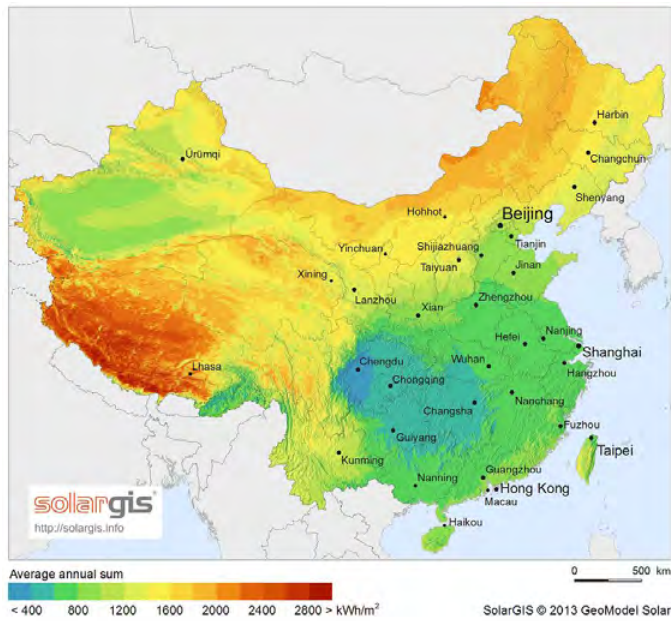


Figure A 1: China annual average solar radiation [44].

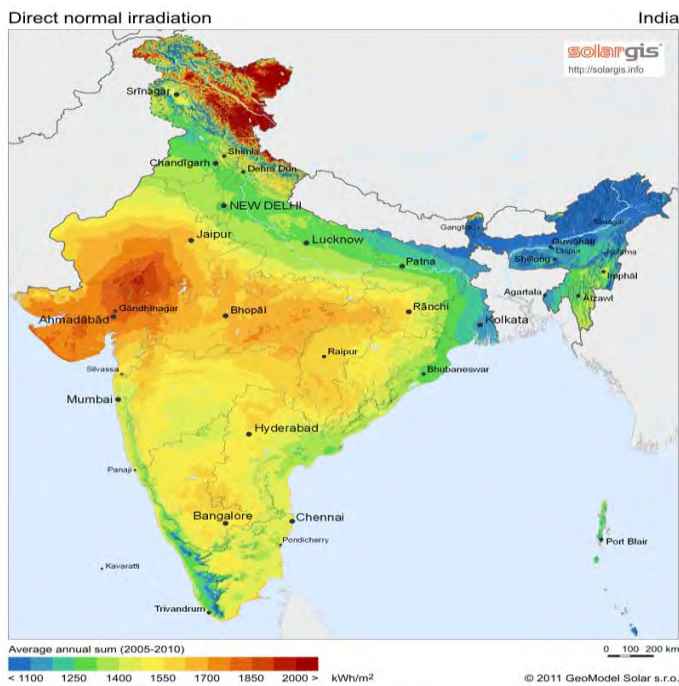


Figure A 2: India annual average solar radiation [44].

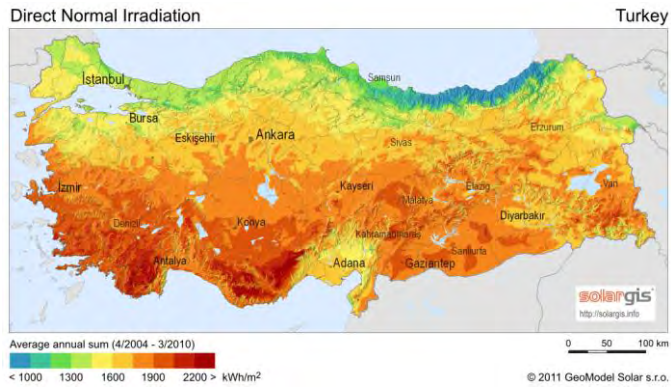


Figure A 3: Turkey annual average solar radiation [44].

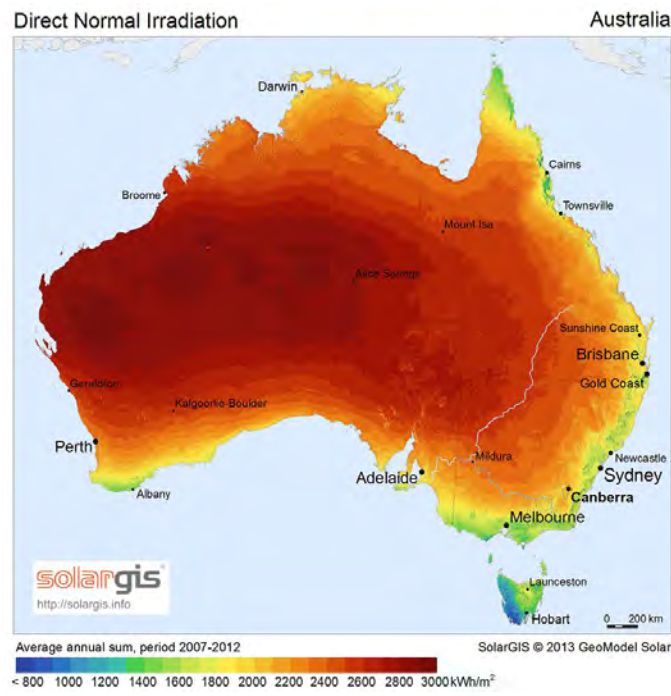


Figure A 4: Australia annual average solar radiation [44].

7.2 Appendix B: Economic Indicators

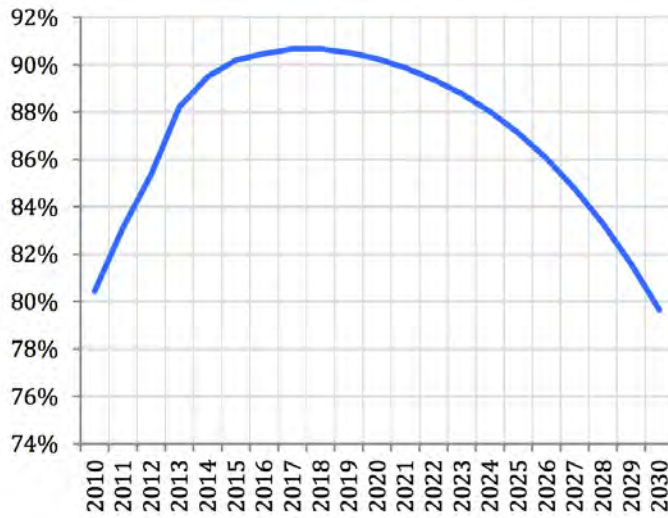


Figure B 1: EU27 Government gross debt as a percentage of GDP [23].

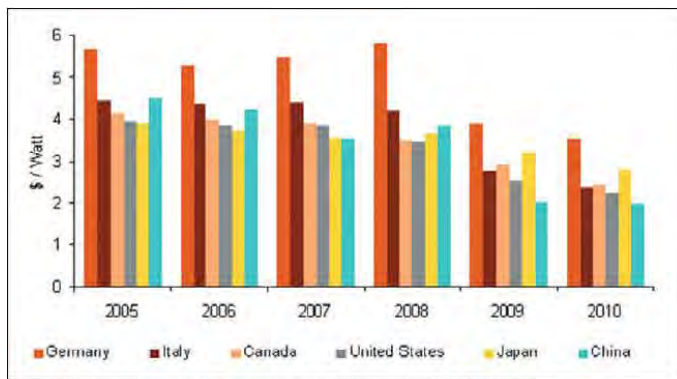


Figure 5. Solar crystalline module average price, by country, 2005-10, US\$ / Watt (Source: GlobalData)

Country Name	2005	2006	2007	2008	2009
Germany	5.65	5.28	5.47	5.81	3.92
Italy	4.47	4.38	4.42	4.21	2.76
Canada	4.18	4.00	3.90	3.50	2.90
United States	3.98	3.85	3.85	3.45	2.55
Japan	3.92	3.72	3.54	3.65	3.20
China	4.52	4.25	3.82	3.85	2.02

Table 5. Solar crystalline module average price, by country, 2005-10, US\$ / Watt (Source: GlobalData)

Figure B 2: Average solar module price [172].

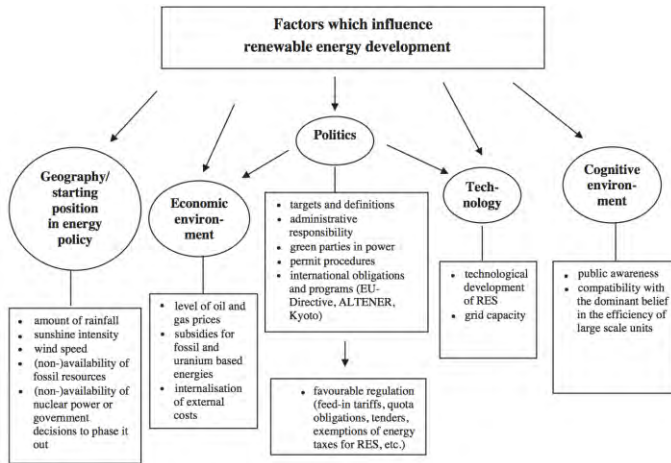


Figure B 3: EU Factors around renewable energy development [111].



Figure B 4: Consumer Price Index (CPI) representing inflation percentage [180].



* Following countries are not shown on the mapping due to poor availability of data: Chad, Côte d'Ivoire, Congo Democratic Republic, Cuba, Iraq, Madagascar, Mali, Myanmar, Somalia, Sudan, Uganda.

Figure B 5: Attractiveness of countries near the equator [50].

Table B 1: Biofuels production worldwide in 2013 [140].

Thousand tonnes of equivalent	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Change 2013 over 2012	Share of total
US	5226	6374	7478	9746	13456	19149	21697	25568	28518	27270	28440	4.6%	43.5%
Canada	113	114	133	160	461	501	721	746	875	998	1011	1.6%	1.5%
Mexico	-	-	-	-	4	4	4	13	12	14	53	276.9%	0.1%
Total North America	5339	6488	7612	9906	13922	19654	22422	26327	29405	28282	29505	4.6%	45.1%
Argentina	9	9	9	29	272	632	1048	1656	2219	2293	1684	-17.3%	2.9%
Brazil	7066	7154	7635	9729	11323	14033	13962	15575	13197	13547	10763	-16.6%	24.2%
Colombia	-	-	14	131	141	143	295	428	536	616	634	3.3%	1.0%
Other S. & Cent. America	151	148	235	515	610	767	606	314	457	458	467	-	0.7%
Total S. & Cent. America	7277	7311	8033	9435	12347	16955	15911	17973	16426	16994	16767	-11.2%	28.7%
Austria	26	48	70	105	220	253	354	375	370	370	376	2.5%	0.6%
Belgium	-	-	1	21	140	278	473	538	611	476	660	39.0%	1.0%
Finland	-	1	6	11	51	96	267	363	363	363	363	0.3%	0.6%
France	366	387	439	665	1121	2012	2312	2269	1899	2071	1936	-6.2%	3.0%
Germany	613	890	1526	2488	3181	2720	2728	2898	2825	2898	2615	-9.2%	4.0%
Italy	232	272	340	585	443	617	796	670	456	292	292	0.3%	0.4%
Netherlands	-	6	3	22	80	77	241	385	627	1256	1182	-5.6%	1.8%
Poland	28	6	109	144	96	278	393	421	398	631	664	5.6%	1.0%
Portugal	-	-	1	70	153	145	202	275	293	338	200	-38.3%	0.3%
Spain	173	210	282	251	352	359	958	1267	809	586	674	15.4%	1.0%
Sweden	32	43	48	81	139	171	238	214	212	244	271	11.3%	0.4%
United Kingdom	9	9	39	219	359	276	180	304	253	269	440	50.5%	0.7%
Other Europe & Eurasia	138	165	293	395	491	931	1175	1231	1241	1320	1295	-1.6%	2.0%
Total Europe & Eurasia	1619	2037	3157	5096	6626	8223	10280	11200	10319	11133	10968	-1.0%	16.6%
Total Middle East	-	-	-	-	-	-	-	4	4	4	4	-	-
Total Africa	6	6	6	6	6	11	15	30	23	23	23	-	-
Australia	-	4	20	54	70	111	174	238	336	409	416	1.8%	0.6%
China	396	493	622	846	901	1096	1124	1441	1597	1729	1680	-2.8%	2.6%
India	84	89	114	134	136	155	174	155	192	227	321	42.2%	0.5%
Indonesia	-	-	9	44	216	528	464	718	1104	1388	1608	16.2%	2.5%
South Korea	2	4	9	39	74	141	343	491	308	272	302	11.4%	0.5%
Thailand	-	3	32	80	136	494	616	661	721	964	1251	26.2%	1.5%
Other Asia Pacific	-	-	10	106	196	385	422	317	267	387	482	27.6%	0.8%
Total Asia Pacific	481	604	834	1304	1732	2910	3220	4021	4525	5406	6071	12.6%	9.3%
Total World	14492	16446	19791	25678	34832	46443	51948	59995	66894	61763	65346	6.1%	100.0%
of which: OECD	6960	8522	10779	15021	20780	27899	32097	37946	40014	39737	40813	3.0%	62.5%
Non-OECD	7722	7924	8922	10657	14052	18553	19051	21609	20670	22015	24533	11.7%	37.5%
European Union	1619	2028	3133	5007	6748	8077	10096	11051	10173	10925	10747	-1.4%	16.4%
Former Soviet Union	-	11	22	29	90	190	210	162	196	184	193	5.4%	0.3%

*: less than 0.05%.
 Notes: Consumption of fuel ethanol and biodiesel is included in oil consumption tables. Source: Includes data from F.O. Licht, US Energy Information Administration.
 Growth rates are adjusted for leap years.

7.3 Appendix C: Power system

	PV-Diesel-Batteries	PV-Wind-Batteries	PV-Wind-Diesel-Batteries	Wind-Diesel-Batteries	Optimization of components	Optimization of control strategy
Borowy and Salameh, 1996		x			x	
Chedid and Saliba, 1996			x		x	
Kaher et al., 1997	x				x	x
Morgan et al., 1997	x				x	
Seeling-Hochmuth, 1997			x		x	x
El-Hefnawi, 1998	x				x	
Pratagopoulos et al., 1998		x			x	
Kellogg et al., 1998		x			x	
Ehadiy and Shahid, 1999					x	
Dufo-López and Bernal-Agustín, 2005	x			x	x	x
Koutroulis et al., 2006		x			x	
Shahid and Elhadidy, 2006	x				HOMER	
Ashok, 2007		x	x		x	
Yang et al., 2007, 2008		x			x	
Dial et al., 2008		x			x	
Dalton et al., 2008			x		HOMER	
Himri et al., 2008				x	HOMER	
Shahid and El-Amin, 2008	x			No batteries	HOMER	

Figure C 1: Major publications on hybrid power systems until 2009 [122].

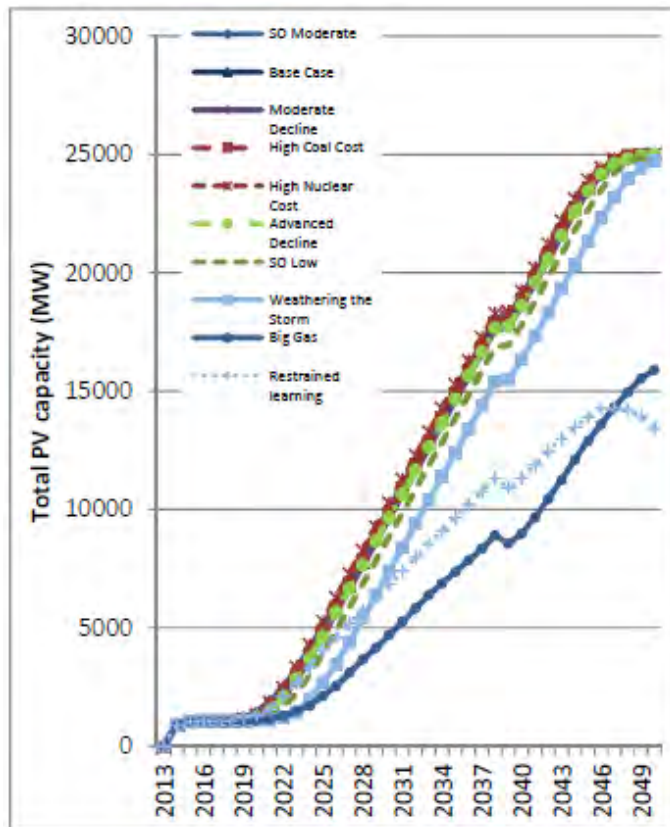


Figure C 2: Total PV capacity projections in RSA [179].

7.4 Appendix D: Simulation input summary

Table D 1: Project location

Location	Blaauwklippen Road, South Africa
Latitude	33 degrees 58,72 minutes South
Longitude	18 degrees 51,65 minutes East
Time zone	Africa/Johannesburg

Table D 2: Load

Data source	Synthetic
Daily noise	0%
Hourly noise	0%
Scaled annual average	34,600 kWh/d
Scaled peak load	5,6000 kW
Load factor	0,2574

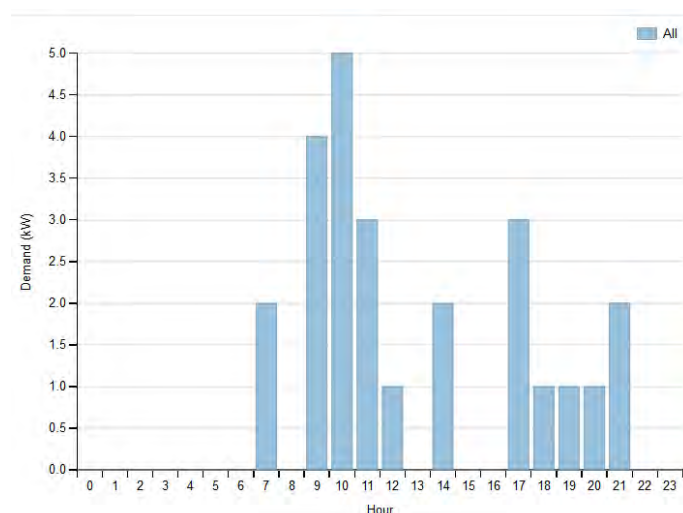


Figure D 1: Hourly load pattern [169]

Table D 3: Generic flat plate crystalline PV modules

Size (kW)	Capital (R)	Replacement (R)
1,00	R 11 728,00	R 5 864,00
Sizes to consider	0,1,2,3,4,5,6,7,8,9	
Lifetime	25 yrs	
Derating factor	80%	
Tracking system	No Tracking	
Slope	29,9°	
Azimuth	180,0°	
Ground reflectance	20,0%	

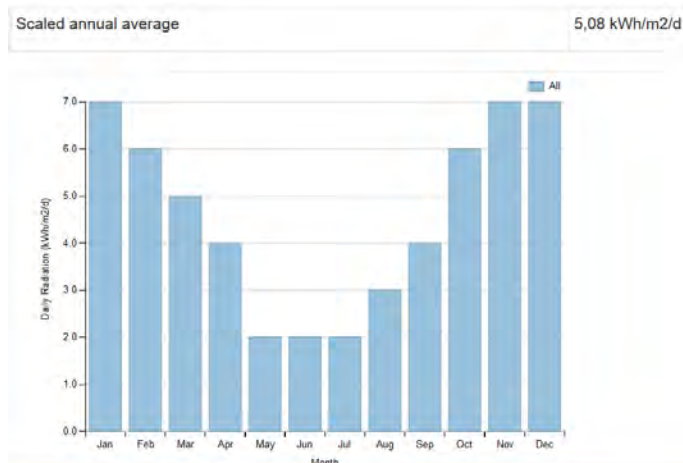


Figure D 2: Solar resource

Table D 4: Diesel generator

Size (kW)	Capital (R)	Replacement (R)
1,00	R 16 530,00	R 0,00
Sizes to consider in kW	5,6	
Lifetime	15 000 hrs	
Min. load ratio	30%	
Heat recovery ratio	10%	
Fuel used	Biodiesel	
Fuel curve intercept	0,0800 L/hr/kW	
Fuel curve slope	0,2000 L/hr/kW	

Table D 5: Fuel Biodiesel

Price	R 11,03/L
Lower heating value	11,0 MJ/kg
Density	880,00 kg/m ³
Carbon content	0,0%
Sulfur content	0,0%

Table D 6: Battery Trojan

Quantity	Capital (R)	Replacement (R)
1	R 8 958,95	R 4 479,48
Quantities to consider (one string quantity has six batteries)	1,2,3,4,5	
Voltage	2 V	
Nominal capacity	1 520 Ah	
Lifetime throughput	[5050] kWh	

Table D 7: Converter

Size (kW)	Capital (R)	
6,00	R 46 028,00	
8,00	R 55 841,00	
12,00	R 68 257,00	
Sizes to consider	0,6,8,12 kW	
Lifetime	15 yrs	
Inverter can parallel with AC generator	Yes	

Table D 8: Economics

Annual real interest rate rounded down	9%
Project lifetime	25 yr
Capacity shortage penalty	R0/kWh
System fixed capital cost	0
System fixed O&M cost	0

Table D 9: System control

Check load following	No
Check cycle charging	Yes
Setpoint state of charge	80
Allow systems with multiple generators	Yes
Allow multiple generators to operate simultaneously	Yes
Allow systems with generator capacity less than peak load	Yes

Table D 10: Constraints

Maximum annual capacity shortage	2 %
Minimum renewable fraction	10
Operating reserve as percentage of hourly load	0
Operating reserve as percentage of peak load	10
Operating reserve as percentage of solar power output	25
Operating reserve as percentage of wind power output	50

7.5 Appendix E: Components chosen

Table E 1: Components chosen

Component	Maufacturer	Cost (R)	Available at (www)
Inverter 6kW	Sunny tripower	46 028	http://www.sustainable.co.za/quickshop/index/view/path/sma-sunny-tripower-6000tl-solar-inverter.html
Inverter 8kW	Sunny tripower	55 841	http://www.sustainable.co.za/sma-sunny-tripower-8000tl-solar-inverter.html
Inverter 10kW	Sunny tripower	68 257	http://www.sustainable.co.za/sma-sunny-tripower-10000tl-solar-inverter.html
Lead acid battery 2V, 1520Ah	Trojan	8 958.95	http://www.cleanenergybrands.com/shoppingcart/products/Trojan-IND27%252d2V-2V-1520AH-%2820HR%29--Flooded-Lead-Acid-Battery.html
PV Panel 250W	Solaire	2 932	http://www.sustainable.co.za/solaire-sd610-250w-solar-panel.html
Diesel Generator 5kVA	Bundupower	16 530	http://www.bundupower.co.za/bp5s.php

7.6 Appendix F: Screenshots from simulation

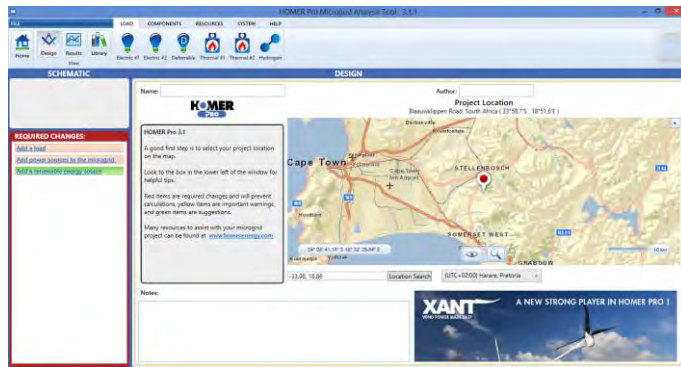


Figure F 1: Location of HPS



Figure F 2: Solar GHI of HPS

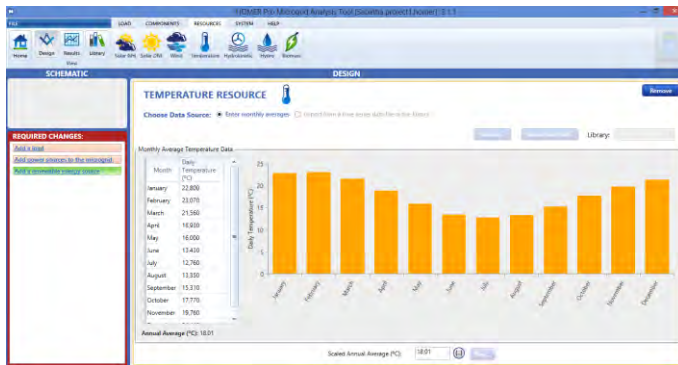


Figure F 3: Ambient temperature



Figure F 4: Load pattern

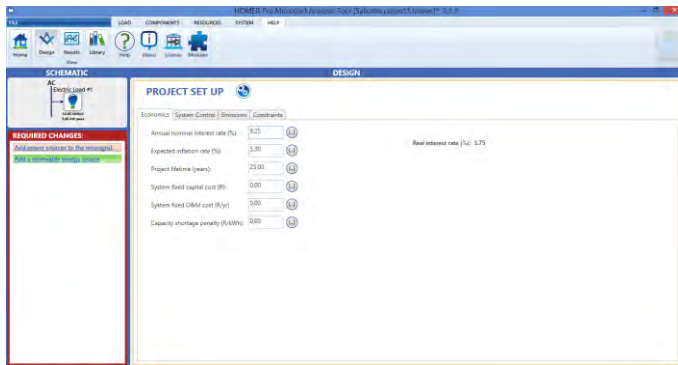


Figure F 5: Economic inputs

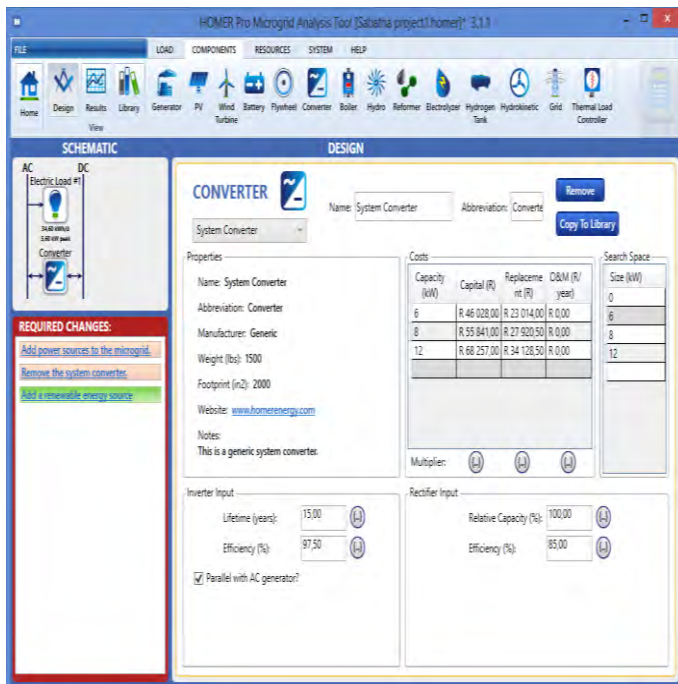


Figure F 6: Converter input

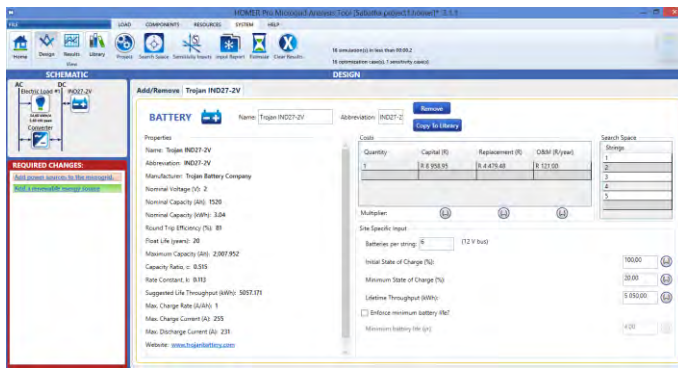


Figure F 7: Battery input

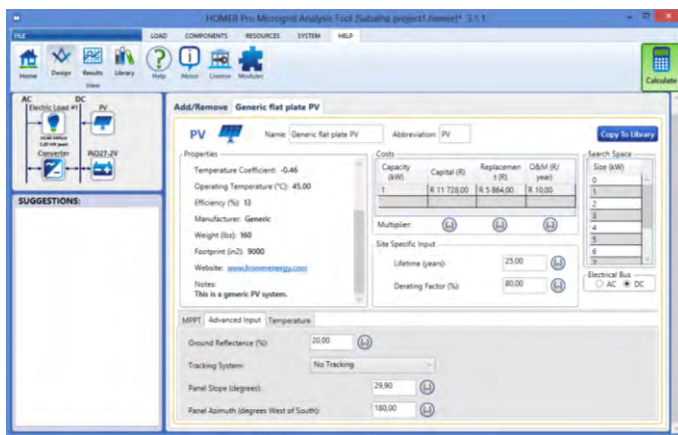


Figure F 8: PV panel input

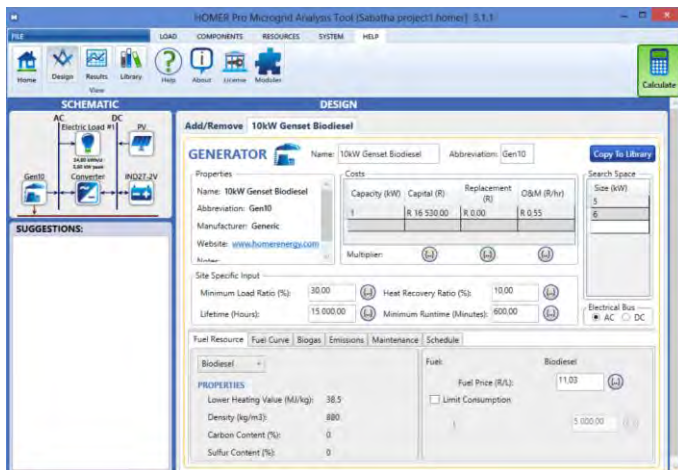


Figure F 9: Diesel generator input

8. EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791). Students must include a copy of the completed form with the final year project when it is submitted for examination.

Name of Principal Researcher/Student: Sabatha Mthwecu **Department:** ELECTRICAL ENGINEERING

If a Student: YES **Degree:** MSc. Elec. Eng. **Supervisor:** Dr S Chowdhury

If a Research Contract indicate source of funding/sponsorship: _____

Research Project Title: Modelling and macroeconomic analysis of a Solar PV/Diesel hybrid power plant

Overview of ethics issues in your research project:

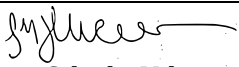
Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	<input checked="" type="checkbox"/>
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	<input checked="" type="checkbox"/>
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	<input checked="" type="checkbox"/>
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	<input checked="" type="checkbox"/>

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	 Sabatha Mthwecu	12 February 2015

This application is approved by:

Supervisor (if applicable):	Dr S Chowdhury	
------------------------------------	-----------------------	--

HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate	Janine Buxey	12 February 2015
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of		

ADDENDUM 1: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at <http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf>) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc.) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 2: To be completed if you answered YES to Question 3:

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 3: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: