Development, characterisation and verification of an integrated design tool for a power source of a soya business unit.

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Dissertation submitted in fulfilment of the requirements for the degree *Master of Engineering* at the Potchefstroom Campus of the North-West University

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November 2007

Executive summary

Selecting a suitable power source, during the design process, for a stand-alone soya business unit is challenging and complex. Especially with the aim of optimizing electrical and thermal energy, as well as minimizing the life cycle cost. During the design and development of a soya business unit it was realized that a design tool is needed to assist with the decision making process when selecting a power source. Waste heat can be recovered from either or both the exhaust gas and cooling system of the power source and can be utilized in the soya process.

Research of available literature revealed no design tool to assist with the decision making process of the stand-alone business unit and consequently lead to this study. This dissertation presents different possible power sources that could be utilized in supplying energy to the business unit, as well as design tools available. Advantages and disadvantages of the different power sources are discussed. The shortfalls of a number of the available design tools are also discussed.

A diesel generator set was selected as the preferred power source for the business unit. Criteria for this selection included the price per kWh_e generated, the ease of maintenance, the availability of the diesel generators in rural areas and the availability of diesel as a fuel. The diesel engine was characterized through experimental work for a more in depth understanding of the energy profile of the engine at part load conditions. These results were used as guidelines in the development of the design tool.

The design tool was developed with the aim of being user friendly and versatile. The time intervals of the required load of the business unit are flexible. Different types of power sources and fuels can be used within the design tool. User defined heat exchangers are utilized to calculate the possible heat recovery from the power source.

The design tool matches the available energy of different power sources at part load conditions with the required load profile of the soya business unit. It then eliminates power sources that would not be able to deliver the minimum required energy. The running cost is calculated for each of the remaining power sources and the power source with the minimum annualized cost, which includes capital cost, maintenance cost and fuel cost, is suggested.

The design tool was verified against a base load condition of the soya business unit and the suggested power source showed a saving of 31,4% in electrical energy, an increased overall efficiency of 24,9% and a saving in annualized cost of 27,3%. The design tool can be used to optimize specific components and design options within a combined heat and power system. Sensitivity analysis can be performed with the design tool to determine various influences on the designed system.

Key words:

Design tool, Combined heat and power systems (CHP), Energy optimization, Heat recovery, Life cycle cost (LCC), Heat to power ratio (HPR), Diesel characterization.

Acknowledgement

I would like to thank and praise my Heavenly Father for all the opportunities that He has given me throughout my life, and the ability to write this dissertation.

An endeavour such as this, is usually associated with sacrifices from loved-ones, colleagues and friends. Therefore I would like to thank my wife, Christel, and my sons, Wian and Marco, for their continued, unwavering support throughout this undertaking. Words can never express my gratitude to you.

To Professor L J Grobler, my supervisor, thank you for your guidance and assistance, I really appreciate it.

Professor K Vorster, thank you for your input at such short notice.

Lastly, I would like to thank two of my colleagues, Mr D Louwrens, and Mr C E Chapman, who tragically died earlier this year, who not only supported me, but also granted me the time which I needed to conclude this project. Thank you.

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Acronyms and nomenclatures

ρ_1	Density of air
Δp	Differential pressure
AC	Alternating current
AF	Annuity factor
AFC	Alkaline fuel cell
C	Discharge coefficient of the long radius nozzle
CCHP	Combined cooling, heating and power
CHP	Combined heat and power system
Cos θ	Power factor
C_p	Specific heat capacity at constant pressure
$CV_{f,LHV}$	Lower calorific value of fuel
D	Pipe diameter of the long radius nozzle
d	Throat diameter of the long radius nozzle
DC	Direct current
DITR	Australian Commonwealth Department of Industry, Tourism and Resources
HPR	Heat to power ratio
ICE	Internal combustion engine
IEA	International Energy Agency
I_L	Line current
Jun	Liquid extracted from the pulverisation of soya beans in water
k	Isentropic exponent
γ	Isentropic exponent
kWh_e	kilowatt-hour electrical
kWh_{th}	kilowatt-hour thermal
LCC	Life cycle cost
MCFC	Molten carbon fuel cell
m_f	Mass flow rate of the fuel
MUPV	Modified uniform present value
NASA	National Aeronautics and Space Administration
NPV	Net present value
Okora	Fibres of the pulverised soy beans
PAFC	Phosphoric acid fuel cell
P_{air}	Pressure of air
P_e	Electrical power

PEMFC	Proton exchange membrane fuel cell
P_{th}	Thermal energy
PV	Photovoltaic
Q_{in}	Energy supplied to the generator
q_m	Mass flow rate of air
R_{air}	Gas constant
Re_D	Reynolds number
r_p	Pressure ratio
r_v	Compression ratio
SOFC	Solid oxide fuel cell
SPV	Single present value
T_{air}	Air temperature
UPV	Uniform present value
V_L	Line voltage
β	Diameter ratio $\left(\frac{d}{D}\right)$
ε	Expansion factor of air
μ	Viscosity of air
μ_0	Viscosity of air at 20 °C
t	Time in years from the base date

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CHAPTER 1: INTRODUCTION

1.1 General introduction

The saying "If someone asks you for food and you give him a fish, he is fed for a day, but if you teach him how to fish, he is fed for life" is paramount to every developing country in the world.

In all developing countries there is a great need to empower people to provide, not only for themselves, but also for others. This is the key to economical growth and prosperity of any community or country.

In 2001 the Tshwane Nutrition Project started the development of a small business unit to provide opportunities for entrepreneurs and in the process contribute to the reduction in unemployment, as well as malnutrition in the low-income group. These business units include equipment for soya bean processing, a small bakery and a point of sale. Processed soya beans are used to produce products such as bread, pizzas, biscuits and milk, to name a few. The aim of the Tshwane Nutrition Project is to supply a self-sustainable business unit to the entrepreneur who could operate the business unit in densely populated areas such as townships, as well as in remote rural areas.

The soya bean (*Glycine max*) [1] is harvested and converted into products for animal feed, human consumption and for producing bio-fuels. The soya bean is high in minerals and vitamins, which makes it suitable for human consumption. The conversion of the soya bean involves the hydration of the beans, the cooking of the beans, the pulverizing of the beans in water and finally, the separation of the liquid from the fibres. The fibres, called okora, are used for flour and meat replacement products. The liquid, called jun, is used for milk and dairy products.

The business unit requires various forms of energy, such as mechanical power, as well as thermal and electrical energy. All the required energy can be obtained by the conversion of electrical energy. Electrical power can be supplied from the electrical grid to the business unit when it is utilized within towns and townships. However, this is not viable for the business unit in a remote area of the country, due to the lack of grid electricity and the cost involved to connect remote areas. 79 % of the energy supply of

South Africa was contributed by coal [2]. The abundant coal reserves in South Africa contributed to low electricity prices and reliance on grid electricity to supply most of the electricity.

Various other means are available for supplying the necessary energy for the different processes in the unit when grid electricity is not available. Wood, sunpower, manpower, animal power and combustible liquids, like fossil fuels and bio-fuels, can supply heat or work. The soya bean itself is used to produce bio-fuels and can be utilized as a power source. Some of these methods are not viable options if large amounts of energy are needed. Electricity is then required to supply energy to the business unit. Alternative methods can be utilized to generate electricity by means of photovoltaic (PV) cells, wind turbines, gas turbines or internal combustion engines (ICE). Hydrogen fuel cells can be considered as a possible energy source, but it is still under development and the available units are not economically viable.

Throughout the world energy sources include fossil fuels (oil, coal, natural gas), nuclear fuel, geothermal energy, solar radiation, hydropower, biomass (crops, wood, municipal solid waste), wind and the ocean [3]. All these are possible energy sources, but the ultimate solution lies in the availability of the energy source in a particular area, as well as the technology available to utilize these power sources. The technology available does not only include the hardware, but the knowledge of operating and maintaining the technology.

The challenge of the soya business unit is that it will be used in rural areas and therefore, the design of these units cannot be based on utilization of grid electricity. The technology that must be used for the power source for the business unit must be easy to install, easy to maintain, the prime energy source and support services must be available in rural areas.

Determining the correct size of a power source for the soya business unit is very easy, if one assumes that all energy will be supplied in the form of electricity which is generated by a generator. The electricity supplied from the power source must be greater or equal to the electrical and thermal load required by the business unit. However, the overall efficiencies are low and range between 29 % and 42 % [4].

The ultimate objective is to select the best-suited power source with the minimum life-cycle cost (LCC). Fuller *et al.* [5] studied life-cycle costs which involve the following costs: initial investment cost, operation and maintenance cost, energy cost, capital replacement cost, residual values and financing cost. The life-cycle cost must be a minimum if a sound business decision is made on any project.

The optimal design will have to minimize the life-cycle cost by maximizing the utilization of the thermal energy that could be recovered from the rejected thermal energy of the power source. The heat recovery will increase the overall efficiency of the business unit and therefore, reduce the running cost of the unit. The reduced running cost will reduce the life-cycle cost. By reducing the thermal load which is supplied by electricity, a smaller power source will be needed. This will reduce the initial capital cost of the prime mover, as well as the running cost, but the overall capital cost might be higher due to the additional equipment needed for the heat recovery.

The process of converting soya beans into various products requires low quality thermal energy of up to 95℃ and electricity. Heat can be supplied by using electricity and heaters but the possibility of recovering the heat from the power source with heat exchangers makes it a much better option. Combined heat and power (CHP) systems have been used for more than a century, and are used worldwide to recover heat from power sources and to utilize this recovered heat to heat various systems and processes. The efficiency of a CHP system can be increased by 80 to 90 % depending on the electrical and thermal load of the process and the technology which is used [6].

Design tools or software are listed in the directory of the United States Department of Energy [7]. A total of 343 design tools are listed. This list provides, amongst others, a description of the tools and information such as the requirements, inputs and outputs, strengths and weaknesses. These tools contain databases, spreadsheets, component and system analyses and whole building energy performance simulation programs. However, the value of the list is limited to assist in making a decision on stand-alone systems such as the soya business unit. No design tool could be found that deals with off grid, stand alone situations with part load conditions of a power source. Due to the use of the soya business unit in remote areas, it is essential that part load conditions are considered, because excess electricity or heat which is generated by a power source cannot be sold or used anywhere else.

This has prompted this investigation which aims to develop a design tool to assist in determining the optimum size of a power source to supply the soya business unit with all the energy which is needed. The design tool should consider the life-cycle cost as one of the parameters to make a final decision. Characterisation of the power source at different load conditions, understanding (CHP) systems and understanding the parameters needed to make financial decisions, are important to determine the required parameters when designing a tool to assist with the decision-making process.

1.2 Problem statement

Various power sources or prime movers can be utilized to deliver electrical power to independent small scale business units. If the demand of the business unit is for both electrical and thermal energy, the overall efficiency of the power source can be increased by recovering waste heat from the power source and to utilize it for the thermal needs of the business unit. Internal combustion engine (ICE) generators are the preferred prime movers when it comes to the supply of mid-range electrical energy to rural areas. Internal combustion engines can use different fuels such as diesel, bio-fuels or gas as primary power sources.

Internal combustion engines lend themselves perfectly to waste heat recovery from the exhaust gas and the cooling system. In rural areas these power sources would be expected to deliver at least all the energy which is needed at peak load demands. However, it would not operate at peak loads all the time and it would be expected to function under part load conditions as well.

Selecting a power source to deliver all the energy required in terms of electrical power is not very difficult. Selecting a power source to deliver sufficient electrical power, as well as sufficient thermal power, by making use of heat recovery to minimize life-cycle cost, is not that simple. Various parameters must be considered, such as part load conditions of the power source, possible heat recovery from heat exchangers at different loading conditions, and the direct running cost of the power source at different loads.

There is no available design tool to assist with the process to select a power source for a business unit. This design tool should be able to determine the lowest overall cost of operation of the business unit to maximize the profit of the entrepreneur who will manage the unit.

1.3 Purpose statement

The purpose of this study is to develop a design tool to assist with the decision making process when selecting a power source for a stand-alone business unit, which requires both electrical and thermal energy, with the objective to minimize life-cycle cost of the business unit.

1.4 Delimitations

The span of this project and the number of possible factors influencing this study are endless. During the development of the design tool the following will not be considered:

- The cost of emitting exhaust gases into the atmosphere. The environment is very important and the increase in the efficiency of a power source leads to the decrease in exhaust gas and this will be part of the study, but no consideration will be given beyond this. It is assumed that all power sources will comply with legislation.
- Heat exchanger designs or options. Heat exchangers are used worldwide with expert software available to calculate the heat that could be recovered from systems, and therefore, no consideration will be given to the design of the heat exchangers or the type of heat exchanger which is used.
- Design tools which are available on the market at a fee. The soya business unit will utilize small-scale power sources and any cost incurred to obtain software to assist with the decision-making process will have a great effect on the capital needed to complete the project. Capital cost includes all cost necessary until start-up of the power source.
- Steam turbines will not be discussed due to the complexity of operation and the money and time involved just to start the system. Steam turbines will not be a viable option especially when the business unit is operating during day time hours only. A base fuel like wood, oil, gas or coal, is needed to produce steam

and the availability of these base fuels in large quantities is a problem in rural areas.

1.5 Dissertation outlay

The remainder of this dissertation is divided into a literature study, characterisation of a diesel generator set, the development of a design tool, the set-up of base conditions and the verification of the design tool.

Chapter 2 gives an introduction to possible power sources that can be utilized for the soya business unit. Information concerning internal combustion engines are discussed, as well as electricity generation and heat recovery. Financial models which are used to evaluate power systems will be discussed. Finally, free software tools which can assist a user to make an informed decision will be discussed, as well as the shortcomings of these tools.

Chapter 3 deals with the experimental set-up and measurements taken of a Cummins diesel generator set which will be used on one of the business units. The findings of the experimental work are discussed and related to the literature available. These findings will be used as a basis for the development of the design tool.

Chapter 4 discusses the methodology which was used to develop the design tool, as well as the criteria used for the design tool. This chapter describes the assumptions which were made during the process.

Chapter 5 defines a base condition for the soya bean business unit and the energy requirements and finally evaluates the design tool against these base conditions. The influence of different parameters on the final decision-making process is evaluated with sensitivity studies.

Finally, in Chapter 6 the conclusions are drawn, recommendations are given and future work is discussed. The user interaction needed for the design model is discussed in the appendices.

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CHAPTER 2: LITERATURE STUDY

2.1 Introduction

In all developing countries there is a great need to empower people to provide, not only for themselves, but also for others. This is the key to economical growth and prosperity of any community or country.

The Tshwane Nutrition Project started the development of small soya business unit to provide opportunities for entrepreneurs to produce and sell soya products, especially to the low-income group of the population. The aim of the project is to supply a self-sustainable business that could be operated in densely populated areas such as townships, as well as in remote rural areas.

The design criteria for these soya business units were cost effectiveness and self-sustainability. Various processes can be utilized for the production of the soya products and all these processes will influence the electrical and thermal loads which are needed. A final decision on the power source will be influenced by the electrical and thermal load which is needed for these processes. Influencing the final decision on the power source utilized, will be the type of resources which are available, as well as the available technologies to utilize these resources.

2.2 The soya bean

Soya beans (*Glycine max*) was cultivated in China before 3 000 B.C [1]. The first written records are dated 2 200 B.C, advising farmers on their soya crops. Today soya beans are planted throughout the world for use as food for humans and animals and for making biofuel for use in energy generation systems.

Soya beans' nutritional value is 130 kJ per 100 g [2]. The soya bean protein quality is comparable to that of meat and eggs. The vegetable oil is cholesterol-free with poly-unsaturated fat and a low level of saturated fatty acids. The soya bean contains calcium, iron, magnesium, phosphorus, potassium, sodium, zinc and vitamins A, B6, B12, C and K. The oil and protein content of the soya bean accounts for 60 % of the dry weight, of which 40 % is protein and 20 % is oil. The remainder of the weight of the soya bean is 35 % carbohydrate and 5 % ash. Deshpande and Bal [3] determined the specific heat of soya beans as between 1,926 and 2,912 kJ/kg.K with a moisture content of between 8,1 % and 25 % at a mean dry bulb temperature of 315 K.

The optimum growing temperatures of the soya beans are between 20℃ and 30℃. The plant reaches maturity after about 80 days to 120 days. In 2005 a total of 214,3 million metric tons were produced in the United States, Brazil, Argentina, China, India, Paraguay, Canada, Bolivia and Italy. In the 2002 – 2003 growing season about half of the world's vegetable oil production was from soya bean oil, a total of 30,6 million metric tons.

The main products from soya beans, except when oil is extracted, are fibre which is called okara, and a white fibreless soya liquid called jun. The okora and jun are extracted from the raw bean through a process of hydration of the bean, cooking the beans to release or neutralize specific enzymes which make the bean indigestible for humans, rinsing the beans, pulverization and mixing with water and separation of the solids from the liquids. The okora is used as animal feed or converted to products for human consumption. The okora is converted to meat replacement products, or as flour for the use in food such as breads, pizzas and cookies. The jun is converted to soya milk, yoghurt, ice-cream, cream cheese and flavoured drinks.

Throughout the production of these soya products heat is required in low heat quality for the soaking and cooking, and high heat quality for the baking. Electricity is used for all mechanical work such as mixing, blending and separation, as well as for heaters for the oven and water. The auxiliary equipment such as lights, freezers and air conditioners use electricity.

2.3 Power sources

Deciding on which technology to use in supplying electricity to stand-alone systems can be a daunting task, if all power sources are considered. This report will give introductory information about other possible power sources which are available, and the information which was used to make a final decision.

Power sources are defined as any source that could supply electricity to the soya business unit. These sources are photovoltaic cells, wind turbines, steam turbines, gas turbines, which include microturbines, fuel cells and reciprocating engines. Reciprocating engines can be divided into external combustion engines, like the Stirling engine, and internal combustion engines, like the spark-ignition engines and the compression ignition engines.

Careful consideration should be given to the selection of a suitable power source for the soya business unit. The main factors to consider are the price of the equipment, maintenance cost, skills needed for maintenance, as well as the availability and reliability of the power source or fuel source. The soya business unit will be used in remote areas, therefore, a sustainable, low cost, easy to maintain and operate, and a reliable power source is needed.

2.3.1 Electrical supply

Generating electricity is traditionally done by generating steam from a power source and using the steam in a steam turbine to drive a generator which generates the electricity. The energy is traditionally provided by burning coal, oil, wood or gas, or by using a nuclear reaction. Hydro-electrical systems use water to drive a turbine which drives the generator that produces the electricity.

The primary energy supply in South Africa is shown in Figure 1 [4, 5]. From 1992 until 2002, the utilization of energy increased by 18 %, which equates to an increase of 1,8 % per year. It is evident from Figure 1 that the variety of energy sources which are utilized to supply electricity in South Africa is limited. Most of the crude oil used is for transportation. This is due to the low cost of electricity in South Africa.

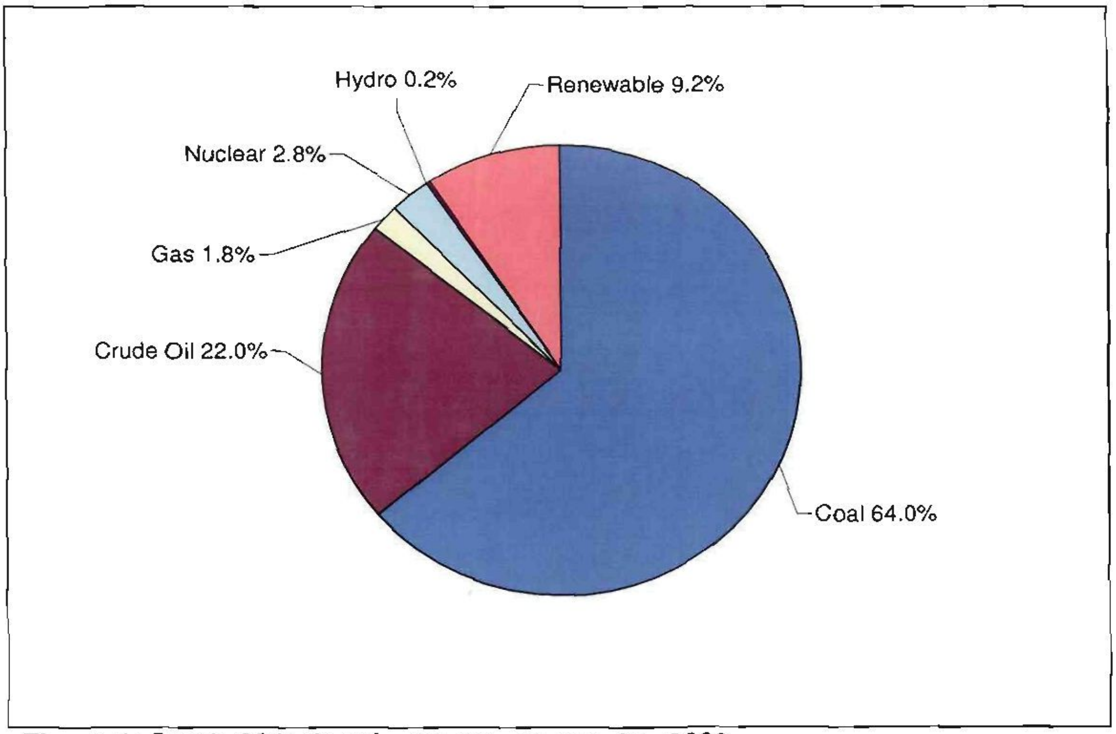

Figure 1: South Africa's primary energy supply - 2002

Source: Digest of South African energy statistics – 2005 [4]

Eskom produces 90 % of South Africa's electricity. Electricity is transmitted through a network of high voltage overhead power lines at distances of approximately 30 000km. The transmission voltages range between 132 kV and 765 kV. The average cost for the 765kV lines is R 1 million per kilometre.

Figure 2 shows the products which were produced from petroleum in South Africa during 2002. This indicates that 93,2 % of these products are primarily used for transportation. According to statistics published by the International Energy Agency (IEA) [6] in 2006, South Africa is one of the countries with the lowest price for electricity at US$ 0,0605 per kWh_e.

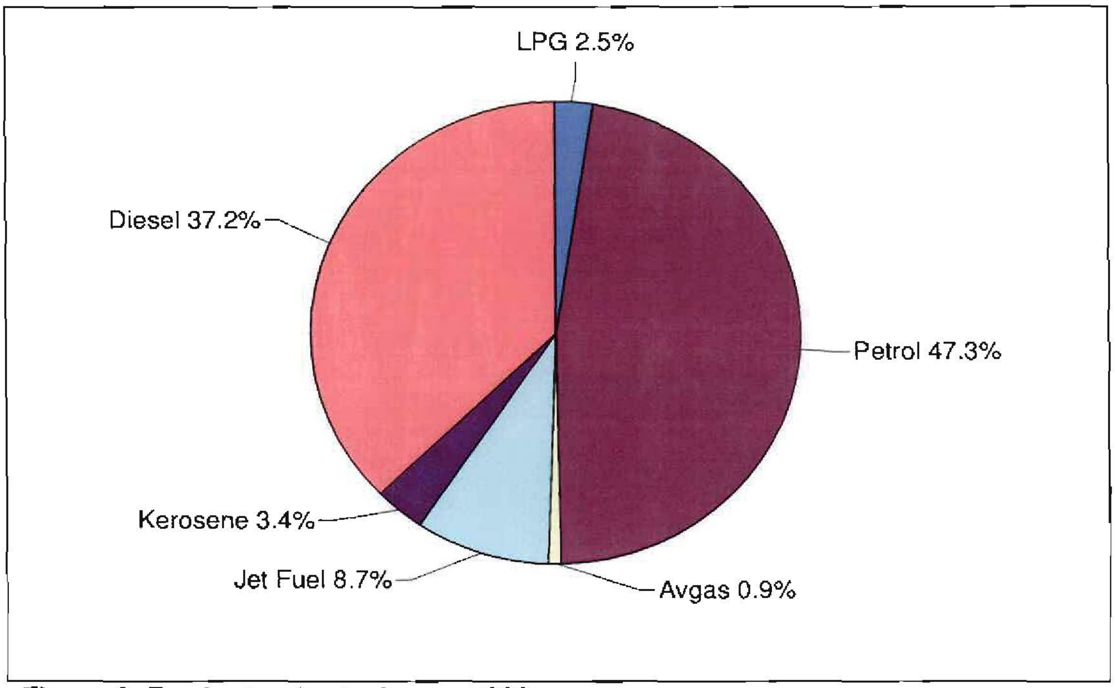

Figure 2: Products of petroleum - 2002

Source: Digest of South African energy statistics – 2005 [4]

This listed price amounts to 43,6 cents per kWh_e at an R/US$ exchange rate of 7,21 (13 August 2007). The price of electricity which is generated by a diesel generator amounts to 216 cents per kWh_e. This was calculated by using information supplied by Alterdyne [7], a supplier of diesel generators, and with a diesel price of R 7,00 per litre and an electrical thermal efficiency of 32 % for a diesel generator set. Even with a theoretical electrical thermal efficiency of 100 %, the price of generated electricity will be 69 cents per kWh_e.

To summarize; the price of grid electricity is five times cheaper than electricity which is produced by a diesel generator. Even with an impossible efficiency of 100 % for the generated electricity, the price is still twice as cheap for the grid electricity.

The relative prices of energy in South Africa are shown in Figure 3 [4]. In 2002 the price of Brent crude oil was US$ 25,00 per barrel at a R/US$ exchange rate of 10,52. Currently the Brent crude oil price is US$ 71,68 at a R/US$ exchange rate of 7,21 on 13 August 2007. This amounts to an increase of 14,5 % per year, which is higher than the price increase of electricity, which is approximately 5 % per year [8]. Therefore, the main consideration for power supply in South Africa is still the price, and grid electricity is the most cost-effective power source, due to the relative low price.

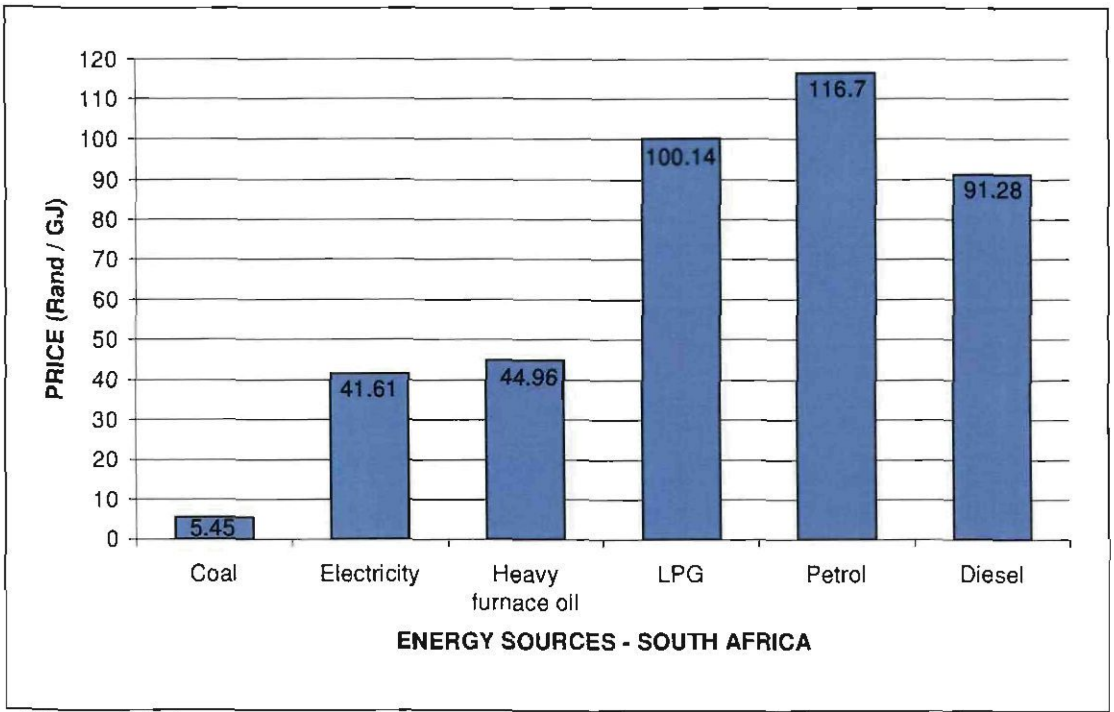

Figure 3: Price of energy sources - 2002

Source: Digest of South African energy statistics – 2005 [4]

2.3.2 Photovoltaic cells

In the 1950s Photovoltaic (PV) technology was developed for man-made satellites with zero operation emission [9]. The development of the photovoltaic cell is driven by the demand for reliable cost-effective electrical power in remote areas [10]. Photovoltaic cells are the least cost-effective option for many applications and are used in remote areas for small cottages, telecommunications, charging of batteries and water pumping, but are gaining ground.

Photovoltaic modules are used in integrated systems with additional equipment which is needed for effective utilization thereof. Additional equipment which is needed includes batteries for energy supply during night conditions or during overcast days, inverters to convert the direct current (DC) to alternating current (AC), controller units to manage the storage and utilization of energy, as well as structural support for the mounting of the photovoltaic modules.

In off-grid applications batteries are needed and battery selection becomes a critical issue. The most common batteries available are lead-calcium, lead-antimony batteries and in some instances Nickel-cadmium batteries are used. Due to the available cyclic solar radiation, the batteries need to go through many charge and discharge cycles without any damage. Lead-calcium batteries are only suitable for "shallow" cycles where only 20 % discharge occurs.

The price range of photovoltaic cells is shown in Figure 4 [11]. These photovoltaic cells are marketed by manufacturers such as Kyocera, Shell, BP, Sharp, Unisolar and Isofoton. It is evident that the price of photovoltaic cells increases linearly with the increase in electrical power output.

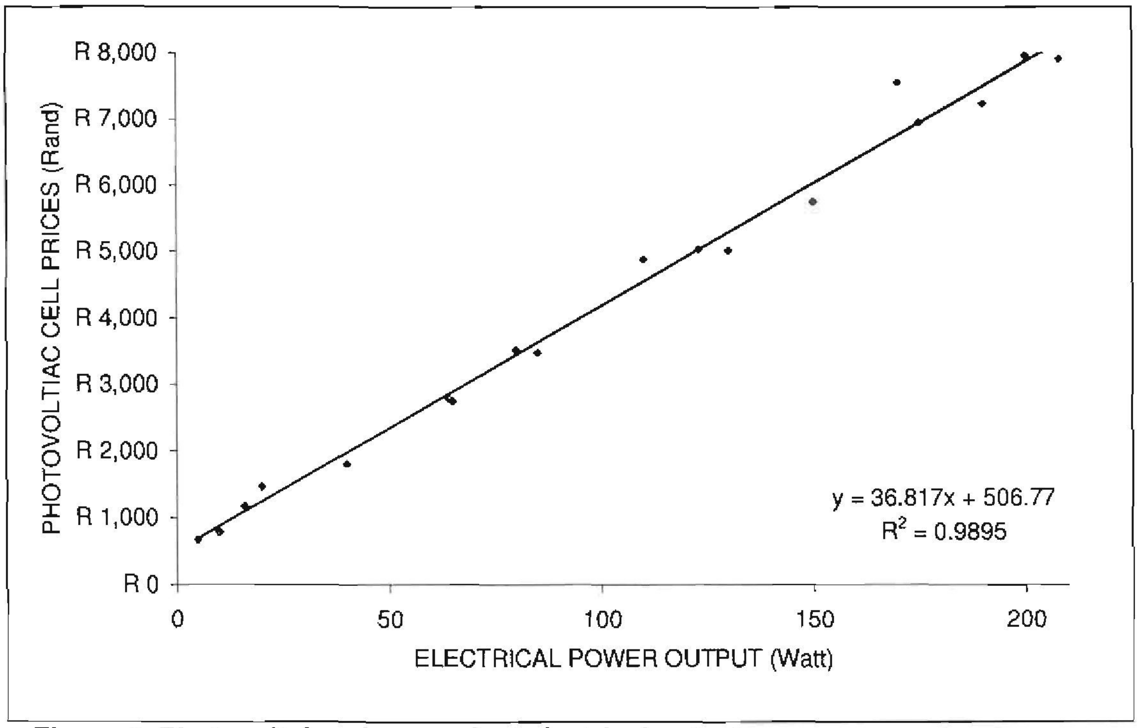

Figure 4: Photovoltaic prices against electrical output

Source: Oasis Montana Inc.[11]

Figure 5 [11] shows the price of photovoltaic cells per kilowatt. The price per kilowatt remains between R 45 500 and R 38 000 from a 40 W supply and upwards. These prices do not include auxiliary equipment to convert the direct current (DC) power to alternating current (AC).

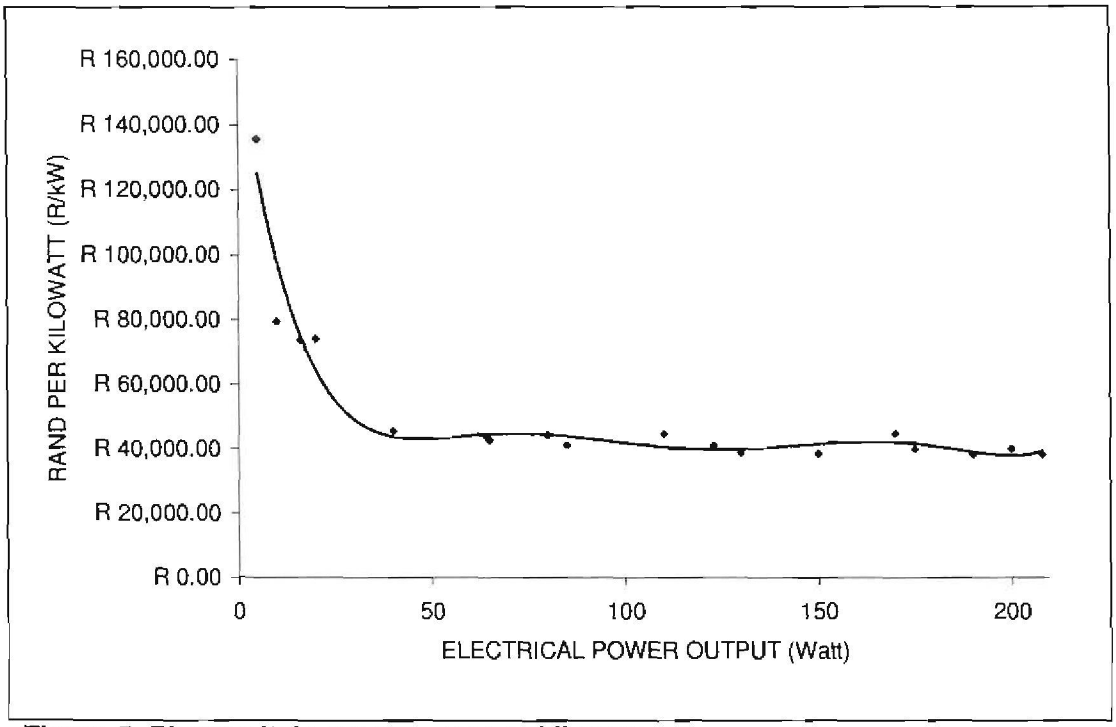

Figure 5: Photovoltaic energy cost per kilowatt

Source: Oasis Montana Inc.[11]

Utilizing photovoltaic cells as a primary power source for stand-alone business units will not be financially viable. This is due to the unpredictable availability of sunlight, which is needed to deliver the electrical power. Batteries could be used as a backup system, but the greater the electrical demand, the larger the battery backup system should be. Maintenance of batteries in remote areas has been found to be a major problem.

Advantages of photovoltaic cells are simplicity, versatility, reliability, quietness and sustainability. Photovoltaic technology does not have any moving parts and can be scaled to the size which is needed.

Using photovoltaic cells as the prime power source for the soya business unit would not be reliable or cost-effective. The dependency on sunlight to produce electricity renders it an unreliable option. Photovoltaic electrical power per kilowatt is the most expensive of all the available technologies.

2.3.3 Wind turbines

Wind turbines have been used extensively since the 11th century [12]. Wind turbines have gained and lost popularity as the price of fossil fuel fluctuated. The real so-called wind turbines appeared in Denmark in 1890 and in 1940 the largest of its kind at the time, known as Grandpa's Knob, was installed, with a capacity of 1,25 MW at about 30 mph (48 km/h or 13,3 m/s) wind speed.

Wind energy is generated by wind that blows over the blades of the turbine and forces the blades to turn. The blades are fastened to a generator via a gearbox to increase the speed of the generator. Wind energy is only available in areas with high yearly wind speeds [10]. The available wind power is related to the cube of the wind speed, but practically, more closely related to the square of the average wind speed. Modern wind turbines need a wind speed of 4 m/s, which is a gentle breeze, to start operating. The rated wind speed is around 15 m/s with maximum wind speeds around 25 m/s.

Wind energy is defined as a clean renewable fuel source and the design life of a wind turbine is 30 years, with regular maintenance every 6 months. Advantages of wind turbines are simplicity, versatility, reliability, sustainability and quietness relative to other mechanical devices. Small surface areas are needed by wind turbines and therefore they have a very high power to size or area ratio [9, 13].

Disadvantages of wind turbines are that they might not be cost-effective and that a higher initial investment is needed compared to fossil fuel installations. Maintenance cost for wind turbines is higher relative to the maintenance cost of solar energy. Wind is intermittent and, therefore, not a reliable continuous power source. Suitable wind sites are often located in remote sites away from the site where the electricity is needed. Blade noise, aesthetic impact and occasional killing of birds are some of the other listed disadvantages.

Wind turbines are unsuitable for use as a prime power source for the soya business unit, due to its unreliability to produce power on demand and its initial capital cost. The capital cost is high and part of this is the cost of a survey to determine the availability of wind, which is done at the site where the turbine is planned to be erected. The duration of a wind survey must be at least one year to estimate the suitability of the site for generating wind.

2.3.4 Gas turbines

Electricity is generated by a generator which is connected to the gas turbine. The gas turbine compresses air in a compressor, mixes the compressed air with fuel and combusts the air fuel mixture. The highly pressurized, high temperature combustion gases are then expanded over a turbine which produces the power. Various fuels can be used as primary power source. Natural gas and fossil fuels are the most common sources which are used.

Gas turbines have an advantage over internal combustion engines in that they produce high-grade waste heat, low maintenance cost, low vibration levels, compact size and low weight per unit power [14]. The high quality of the exhaust gas makes it extremely useful for industrial processes. However, internal combustion engines at the lower power ranges have higher efficiencies. It is mentioned that the efficiency of a gas turbine engine decreases significantly at part load conditions. Maintenance of gas turbines needs more skilled staff than internal combustion engines.

Small gas turbines are more expensive than internal combustion engines with the same rated power. The overall efficiency of a gas turbine, in combination with a heat and power system, can be as high as 80 %. The electrical generator must be a high-speed device, rotating at speeds of up to 100 000 revolutions per minute. Additional equipment is needed to convert the high frequency electricity to the desired frequencies [14, 15]. Gas turbines react slower on fluctuating loads, compared to internal combustion engines, and the start-up of internal combustion engines is faster than that of gas turbines.

Ehyaei *et al.* [16] investigated the use of micro-turbines, by utilizing gas fuel, as the prime power source for a building in Iran. It is reported that ambient air conditions have a noticeable effect on the efficiency of a micro-turbine. Ten micro-turbines produced just over 1 500 kW at an ambient temperature of 3 °C. The same ten micro-turbines produced close to 990 kW operating at an ambient temperature of 33 °C. This leads to a 36 % power loss with a temperature change of 30 °C. A report from the Energy Nexus group [15] reports a 15 % to 20 % increase in power with a decrease in inlet temperature of 10 °C.

The theoretical maximum work output of a gas turbine is calculated as follows:[17]

$$w_{max} = c_p . \left(T_3^{1/2} - T_1^{1/2} \right)^2 \tag{2.1}$$

where C_p is the specific heat capacity at constant pressure, T_3 is the maximum cycle temperature and T_1 is the inlet air temperature or minimum cycle temperature. Using Equation (2.1) the power loss per 10 °C inlet temperature rise is between 3 % and 6 % with a maximum temperature (T_3) of between 1200 K and 800 K respectively.

Gas turbines are suitable for generating electricity, as well as thermal heat, due to the high quality of exhaust gas which is available [15, 18]. Heat is normally recovered in steam generators or hot water generators. This recovered heat is then utilized as space heating or even electrical generation with a steam turbine. Natural gas, synthetic gas, landfill gas and fuel oils can be utilized by the gas turbine with overall system efficiency reaching 70 to 80 %. Mechanical failure is accelerated by frequent starts and stops, due to thermal cycling of the gas turbine.

Gas turbines could be utilized as a prime power source for the soya business unit, due to the energy which could be delivered on demand, the power to size ratio and the advantage that the primary source or fuel could easily be stored in large quantities. However, the initial capital cost, the availability of this technology in rural areas, the specialized maintenance skills needed and the poor part load performance, makes it less attractive for the business unit.

2.3.5 Fuel cells

Fuel cells generate direct current (DC) electrical power similar to batteries, through an electrochemical process [15]. Although still under development, and not yet commercially available like other power sources, fuel cells show great potential for the future in terms of alternative fuel power supplies. Fuel cells can be divided into five different types, which are phosphoric acid (PAFC), proton exchange membrane (PEMFC), molten carbon (MCFC), solid oxide (SOFC) and alkaline (AFC).

Table 1 gives a summary of typical fuel cell parameters [15]. The efficiencies of the different fuel cells correlate very well with that of internal combustion engines. However, it is still a new technology with limited availability and very high prices. The other advantages are the use of alternative fuels and the reduction in green house gases. A fuel cell will cost twelve times more than a conventional internal combustion engine.

Table 1: Typical fuel cell performance parameters (2002)

	PAFC 200 kW	PEM 200 kW	MCFC 250 kW	SOFC 100 kW
Cost per kilowatt (R7,21 = US$1)	R 27 760	R 21 270	R 31 360	R 20 550
Electrical efficiency (%)	36	35	43	45
Heat to power ratio (HPR)	0,92	0,95	1,95	1,79
Overall efficiency (%) CHP	75	72	65	70

Source: Energy Nexus Group [15]

The part-load efficiency of a fuel cell is very good, with 98 % of the maximum efficiency available from 50 % load and higher. Below 50 % the efficiency reduces significantly due to auxiliary equipment which is needed such as air blowers and fuel processors.

Advantages of fuel cells are low emissions, quietness, versatility, simplicity, flexibility and reliability. Different fuel sources can be used and maintenance is low due to the few moving parts [9].

Disadvantages of fuel cells are the current prices and the start-up time. Fuel cells can not deliver full power from start-up, because it takes time for the electrochemical process to deliver its full potential.

Fuel cell technology is comparable to internal combustion engines, with a wide range of power available, thermal efficiencies in the same range, part-load energy supply and the available heat to power ratio. Utilizing fuel cells as a prime power source was not considered due to the limited commercial availability and the current price of fuel cells.

2.3.6 Internal combustion engines

Internal combustion engines are utilized in various applications and configurations worldwide. Internal combustion engines can be divided into spark-ignition engines and compression-ignition engines [15].

Compression-ignition engines have better thermal efficiencies than spark-ignition engines due to higher compression ratios which are needed for the combustion to take place and less pumping losses under part-load.

The standard air cycle thermal efficiency of a spark-ignition engine (Otto cycle) is given as: [17]

$$\eta_{th} = 1 - \frac{1}{r_v^{k-1}} \qquad (2.2)$$

where r_v is the compression ratio of the engine. The standard air cycle thermal efficiency of a compression-ignition engine (dual cycle) which represents a modern diesel engine is given as:

$$\eta_{th} = 1 - \frac{1}{r_v^{k-1}} \left[\frac{r_c^k . r_p - 1}{k.r_p.(r_c - 1) + (r_p - 1)} \right] \qquad (2.3)$$

where r_v is the compression ratio of the engine or the ratio between the volume at bottom dead centre and top dead centre. The pressure ratio r_p is the ratio between the maximum pressure of the engine and the pressure after the compression stroke. The cut-off ratio r_c is the ratio between the volume at which injection is stopped and the clearance volume. If r_c is selected as 1, Equation (2.3) represents an Otto cycle and therefore the compression-ignition engine with the higher compression ratio will be more efficient.

Thermal efficiencies for the compression-ignition diesel engines range from around 30 % for small high-speed engines, to around 48 % for the larger bore slow speed engines [15]. Thermal efficiencies for natural gas engines range from 28 % to around 42 %.

Large generator sets are driven by compression-ignition (diesel) engines or natural gas engines (spark-ignition). Natural gas engines are limited in their application due to natural gas which is not readily available.

The prices of different diesel generator sets are shown in Figure 6 [19]. The information was limited to 200 kVA, because it was regarded as the relevant range of prime power sources which will be used for the soya business unit.

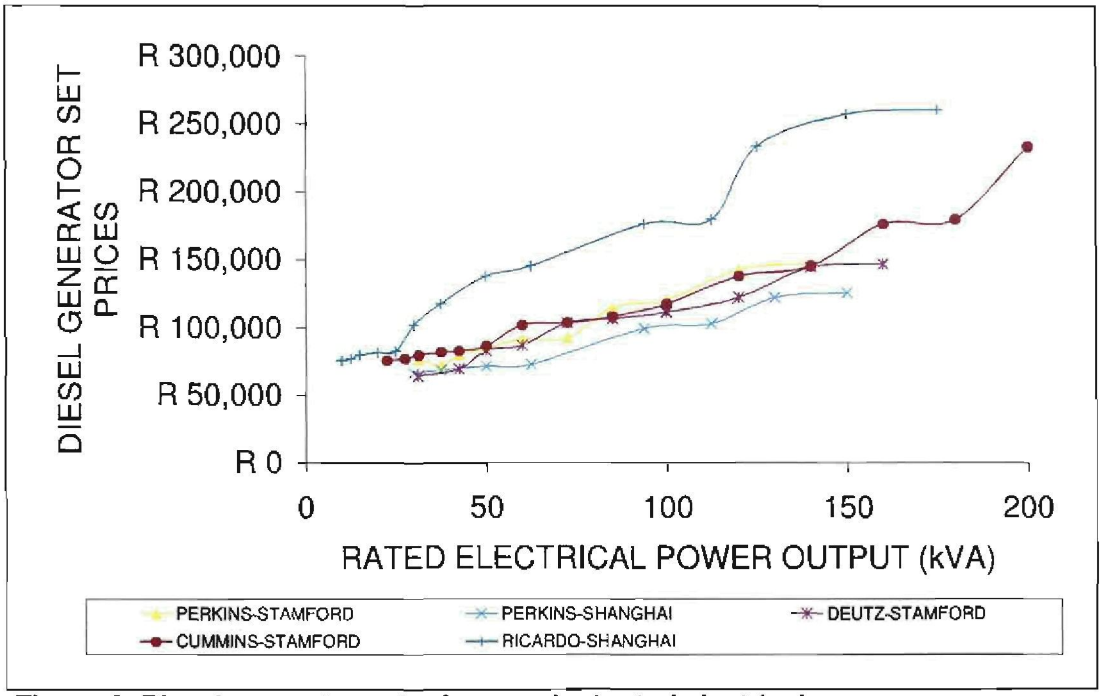

Figure 6: Diesel generator set prices against rated electrical power

Source: Jetman Power Equipment [19]

The price of the generator sets increase with the increase of rated power, but various other factors influence the final price. The enclosure of the generator set, sound proofing, specific diesel engine manufacturers and specific alternator manufacturers all contribute to the price of the diesel generator set.

Fitting a linear trend line to the data by using a least square method gives a $R^2 = 0{,}6682$. R^2 is defined as the square of the multiple correlation coefficient and is the statistical measure of how successful the curve fits the data points. A value of $R^2 = 1$ indicates a perfect fit to the data points. A 6th order polynomial trendline was fitted to the data points to increase the goodness of the fit and a R^2 = 0,6876 was obtained. Using this information as an accurate tool to estimate the price of an unknown diesel generator set, will result in a possible error estimation of 31 %.

Taking the estimated power which is needed by the soya business unit as 35 kW as a base, the combinations of engines and alternators which have a 35 kVA rated generator set, have a price range from R 68 200 to R 117 800. This gives a price difference of R 49 600 or 72,3 % for the more expensive one, compared to the least expensive one. Disregarding the Ricardo engines with the Shanghai alternators, which can be seen in Figure 6 to be more expensive than the other engines and alternators, results in a price range difference of R 13 400 between the remaining engines and alternators.

The price of the diesel generator sets per kilovolt-ampere is shown in Figure 7 [19]. The price of diesel generators at 50 kVA and above is less sensitive and remains fairly constant.

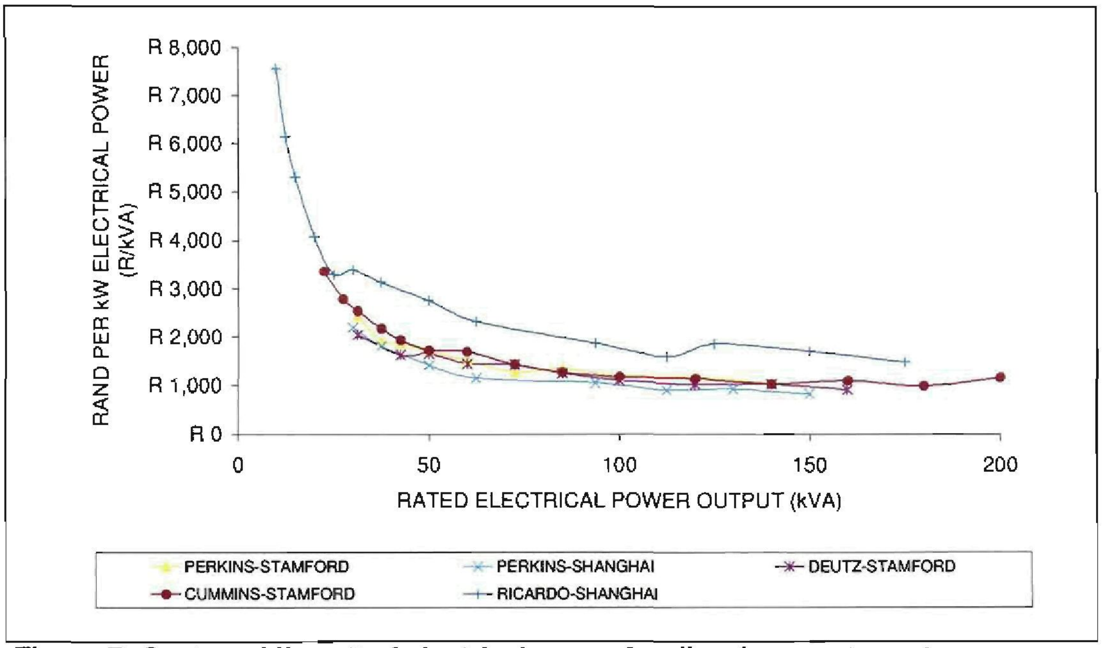

Figure 7: Cost per kilowatt of electrical power for diesel generator sets
Source: Jetman Power Equipment [19]

The most expensive generator set per kilovolt-ampere is the 10 kVA Ricardo engine, with a Shanghai alternator at R 7 700 per kilovolt-ampere. The highest price per kilovolt-ampere at the estimated required energy of 35 kVA is R 2 200. The Ricardo engines with the Shanghai alternators were ignored due to the very high prices.

Power losses for an internal combustion engine, due to atmospheric conditions, are between 3 % and 4 % per 300 m increase in altitude and 1 % for every 5 to 6 degrees Celsius temperature increase [15, 20]. The power loss due to increase in altitude can be reduced, or even eliminated, with the use of a turbocharger or a supercharger.

The efficiencies of prime power sources are low if it only needs to deliver electrical power, but if thermal heat is needed a heat recovery system can be incorporated to increase the efficiency and reduce the running cost. The thermal heat that can be recovered from prime power sources such as internal combustion engines, are defined as low-grade heat which can only be used for hot water or low-grade steam [15].

The soya business unit will be powered by a diesel generator set due to the low initial capital cost, the low maintenance cost, the relatively low level of skill needed to maintain the unit, the reliability to produce power and the ease of obtaining diesel as a fuel.

Electrical and thermal energy is needed by the soya business unit to produce its products and, therefore, a suitable prime power source has to be selected. Determining heat recovery from a diesel engine which is fully characterized is fairly straightforward, but predicting the possible energies available from unknown diesel engines is not all that straightforward. Determining the energy available for an unknown diesel engine and at part-load conditions is even more difficult. Therefore, a clearer understanding is needed of the characteristics of a diesel engine at full-load, as well as part-load conditions.

Power outputs, fuel consumption and efficiencies of diesel engines are quoted throughout the literature, with diverse findings. Alturdyne [7] supplies diesel generator sets and data of 45 diesel generator sets was obtained and is used for further explanations.

Comparisons were done of four different manufacturers to try and establish common trends in diesel generator sets. Only diesel generators were considered in this summary, although information of gas generator sets was also available. All the data which was obtained for these engines were at full-load and at an engine speed of 1 500 revolutions per minute, which implies a direct drive to the generator to produce the rated power at 50 Hz.

2.4 Engine efficiencies

Electrical thermal efficiency is defined as the electrical energy available relative to the fuel energy input. Therefore it includes the brake thermal efficiency of the diesel generator, the mechanical losses of transmission, as well as the electrical losses in the alternator.

The electrical thermal efficiency of different diesel generator sets, according to Alturdyne [7], increases as the rated power increases, as shown in Figure 8. From the Cummins generator sets it can be noticed that the electrical thermal efficiency of the 1 500 kW generator set is the highest and the electrical thermal efficiency decreases for the 1 750 kW and 2 000 kW generator set. The maximum electrical thermal efficiency of 42 % was obtained by a 1 500 kW Cummins generator set and the lowest efficiency of 29 % was obtained by a 40 kW John Deere generator set. The John Deere generator sets showed the greatest fluctuation in electrical thermal efficiency over their range of generator sets.

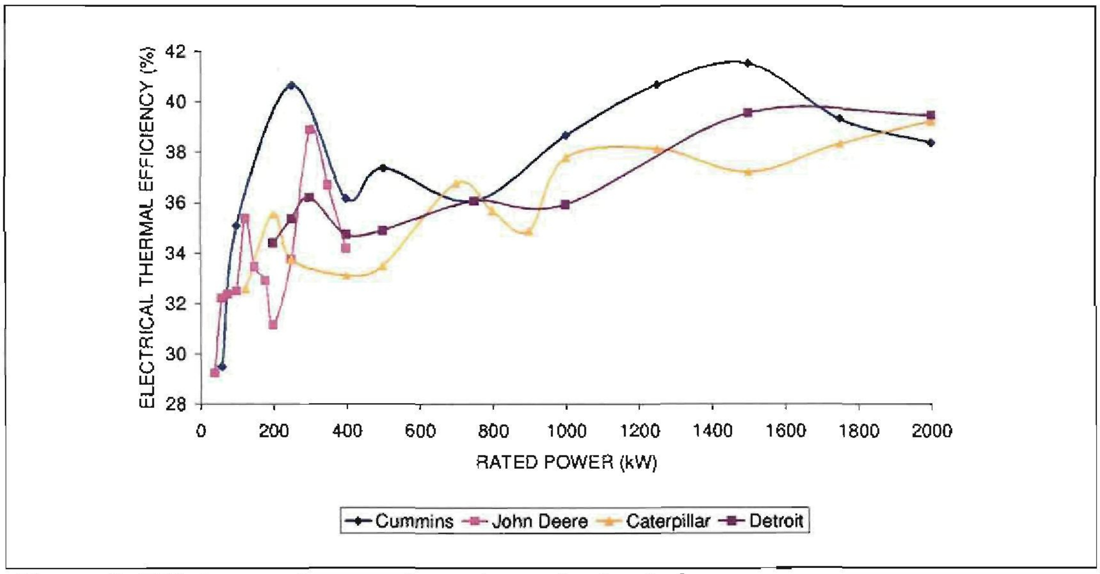

Figure 8: Efficiency of generator sets against rated power

Source: Alterdyne [7]

Figure 9 [7] indicates a trend line which was fitted to all the data of the diesel generators. The general trend is that the efficiency increases as the rated power increases, but with goodness of fit of the data of $R^2 = 0,6343$. Using this information to predict the efficiency of an unknown diesel generator set, will result in inaccurate predictions.

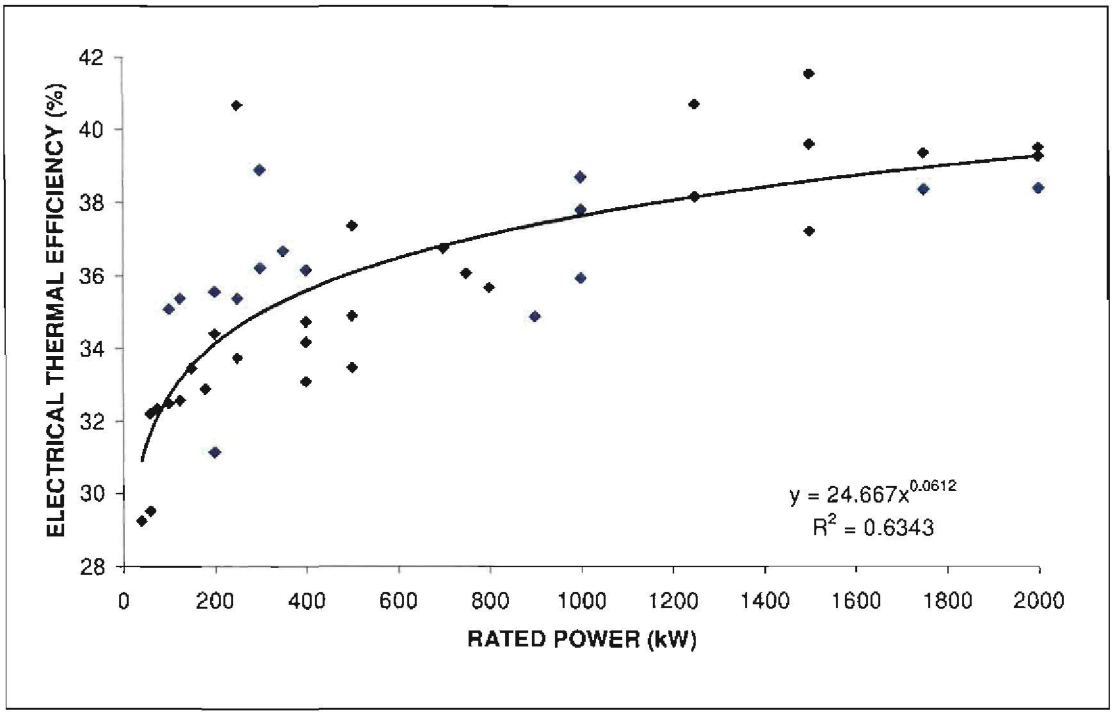

Figure 9: Trend line of the electrical thermal efficiency

Source: Alterdyne [7]

The electrical thermal efficiency of gas engines, reported by the Energy Nexus Group [15], increases from around 31 % for the 100 kW engine, to around 39 % for the biggest 5 000 kW engine. The overall efficiency, which includes heat recovery of these engines, ranged from 81 % for the smallest engine to 74 % for the largest engine.

Thermal balancing on a 10 hp (7,4 kW) single cylinder engine at 1 500 rpm by Ajav *et al.* [21] indicated that 29,7 % of the energy which is supplied, is available for useful work, 17,7 % is lost through the cooling system, 18,6 % is lost through the exhaust, 18,8 % is lost through the lubrication oil and the remainder 16,2 % is unaccountable for. These results were obtained by loading the engine at 25 % load intervals.

Taymaz [22] investigated the influence of ceramic coating on the parts of a Ford 6,0 litre turbocharged diesel engine. The standard engine was tested before modifications were done. Table 2 shows the results of this testing. The brake thermal efficiency increased as load increased to a maximum of 37 % at 80 % engine load. The available heat in the cooling system decreased from 49 % to 27 % and the available exhaust heat increased from 24 % to 29 %. The heat to power (HPR) ratio from the engine decreased from 2,8 to 1,5.

Table 2: Summation of available energy against engine load - Ford 6,0 litre turbo-charged diesel engine

Load	Brake energy (%)	Coolant energy (%)	Exhaust gas energy (%)	Unaccounted energy (%)	HPR
20	26	49	24	1	2,8
50	32	36	23	9	1,8
80	37	27	29	7	1,5

Source: Taymaz [22]

The efficiency of engines increase as the size of the engine increases, but no correlation exists between the data available. The efficiency of an engine increases as the load increases. The reason for this is that the losses in the engine remain fairly constant, while the useful work increases as the load increases, and this leads to an increase in efficiency.

No correlation could be found in literature to describe the efficiencies of an engine. Predicting the efficiency of an unknown engine from data of a known engine would not be accurate enough. Efficiency comparisons between different kinds of engines are also very diverse, due to the way they function.

2.4.1 Exhaust gas heat recovery

Heat recovery from the cooling system and exhaust gases are limited by conditions such as engine operating temperatures, the extent of the cooling in the exhaust system and the type of heat exchanger which is used. The engine's operating temperatures vary for different engines, but are in the region of 90℃. Heat recovery from the exhaust gases is limited to the condensation temperature of the water in the exhaust gases.

Condensation of water in the heat recovery equipment must be avoided to reduce the corrosive effect of the water on the equipment. This leads to about 15 % of the energy in the exhaust gases which will not be recovered [23].

The possible heat that could be recovered from the exhaust gas can be calculated as follows:[24]

$$Q_{exh} = (m_a + m_f).Cp_g.(T_{exh} - T_a) \tag{2.4}$$

where m_a is the air flow rate, m_f is the fuel flow rate, Cp_g is the specific heat capacity of the exhaust gas, T_{exh} is the exhaust gas temperature and T_a is the atmospheric temperature.

The exhaust gas temperatures of the diesel engines, according to Alturdyne [7], are shown in Figure 10. The possible heat which can be recovered from exhaust gases is dependant on the exhaust gas temperature. The lowest temperature was 395 °C for the John Deere engine with a rated power of 300 kW. The highest temperature was 604 °C for the Caterpillar engine with a rated power of 500 kW. The John Deere engines had the biggest differences of 205 °C between their maximum and minimum exhaust temperatures. The Caterpillar engines had the smallest difference of 97 °C between the maximum and minimum exhaust temperatures.

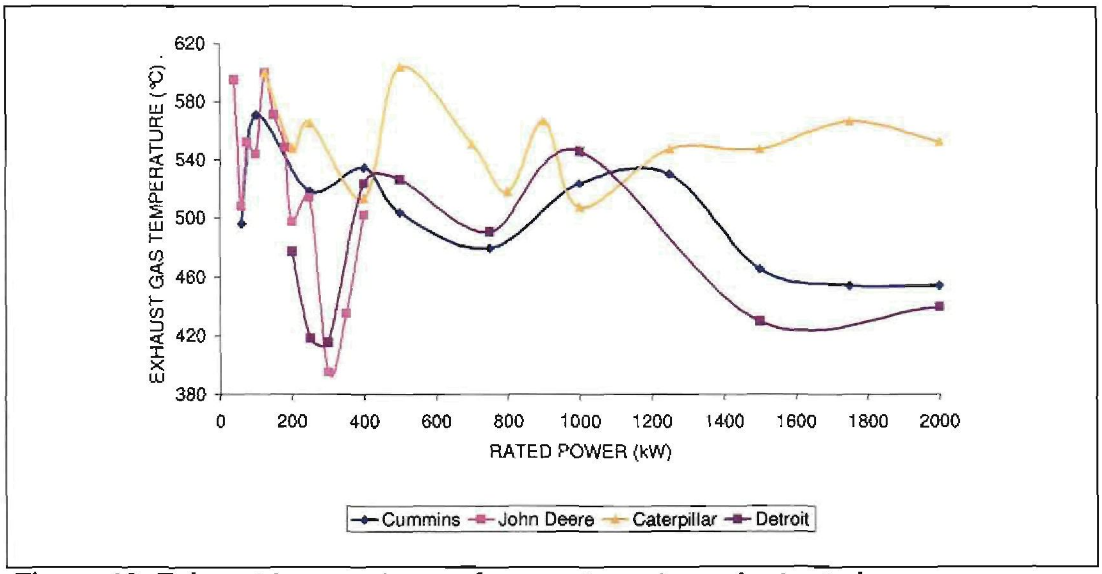

Figure 10: Exhaust temperatures of generator sets against rated power

Source: Alterdyne [7]

No trends could be detected from any range of engines or even from any single supplier of engines. There were no correlations between the engine configurations such as number of cylinders, normally aspirated or forced induction. The exhaust gas temperatures of an unknown engine cannot be predicted or estimated from known data.

Investigations by the Energy Nexus Group [15] showed that heat recovered from the exhaust gases from different gas engines was 16 % from a 5 000 kW engine to around 26 % from a 800 kW engine. The overall efficiencies of these engines increased as the rated power of the engines increased to about 800 kW and then started to drop as the size of the engine increased.

Predicting the amount of heat rejected through the exhaust system of an unknown diesel engine would be very difficult. No trends exist in the data available and the range of exhaust temperatures is large.

2.4.2 Cooling jacket heat recovery

The amount of heat rejected from the cooling systems from different engines, according to Alturdyne [7], is shown in Figure 11. The amount of heat rejected increases with the increase of rated power, but no definite trend is present.

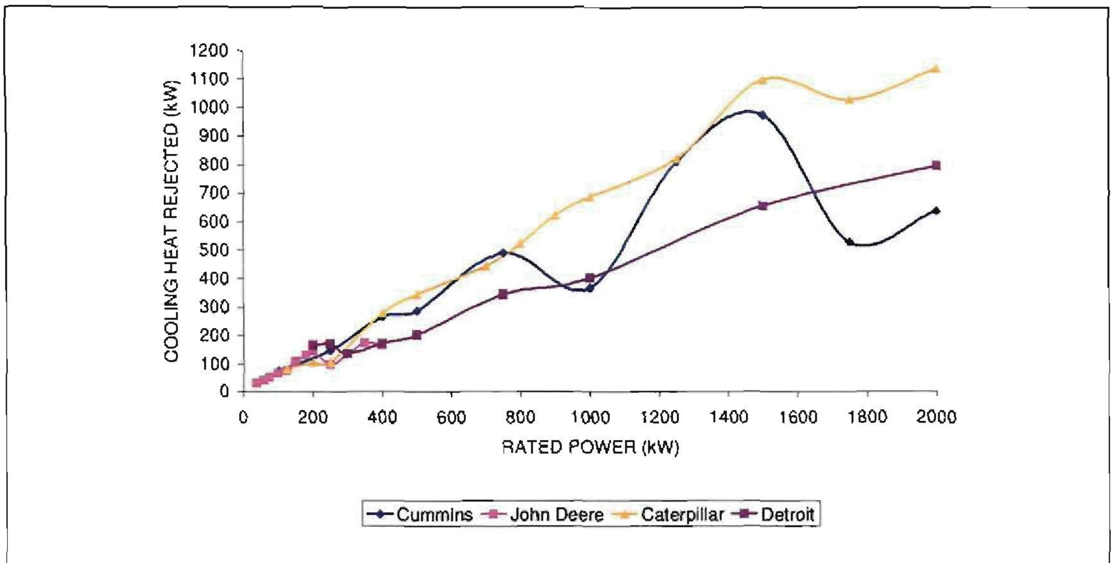

Figure 11: Cooling system heat loss (kW) against rated power

Source: Alterdyne [7]

The percentage of energy which is rejected through the cooling system is shown in Figure 12. The 200 kW rated Detroit engine rejects a total of 29 % of the thermal energy supplied through the cooling system. The heat rejected for the bigger Detroit engines drops to below 16 %. The 1 750 kW rated Cummins engine rejects 12 % of the thermal energy supplied through the cooling system. The Cummins engines had the greatest difference between the percentages of heat loss of 15 %. This is between the 1 500 kW and the 1 750 kW generator sets.

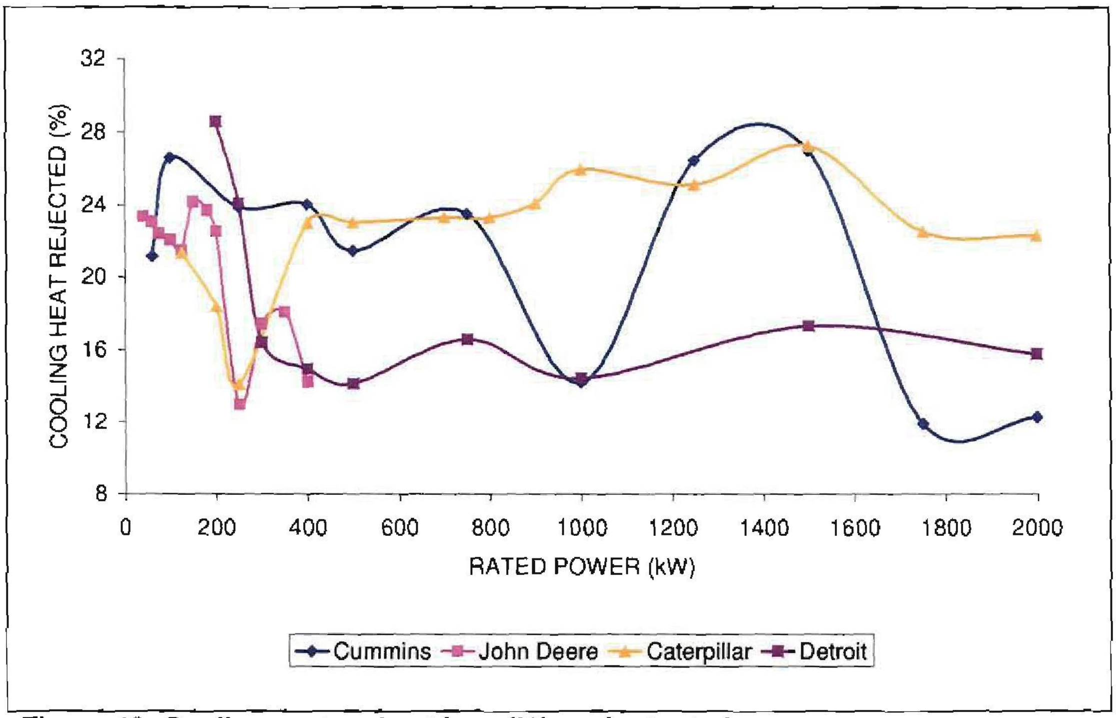

Figure 12: Cooling system heat loss (%) against rated power

Source: Alterdyne [7]

The gas engines which were reported by the Energy Nexus Group [15] showed a decrease in the energy that could be recovered from the cooling system as the engine size increased. The maximum heat which was recovered from the cooling system was 33 % from the 100 kW engine and it decreased to around 13 % for the 800 kW engine, and remained more or less constant for the bigger engines.

Accurately predicting the amount of heat rejected through the cooling system of an unknown diesel engine would be very difficult. No trends exist in the data available, not even for a single manufacturer.

2.4.3 Fuel consumption

The fuel consumption of the diesel generator sets, according to Alturdyne [7], is shown in Figure 13. The fuel consumption against rated power follows a straight line very closely. A least square method trendline was plotted to the set of data and it indicated a goodness of fit of $R^2 = 0{,}9974$. By using the data of fuel consumption from different diesel engines to predict the fuel consumption of an unknown diesel engine at full load would result in a fairly accurate prediction. The trend of fuel consumption against rated power for gas engines appeared to be the same, according to the study by the Energy Nexus Group [15].

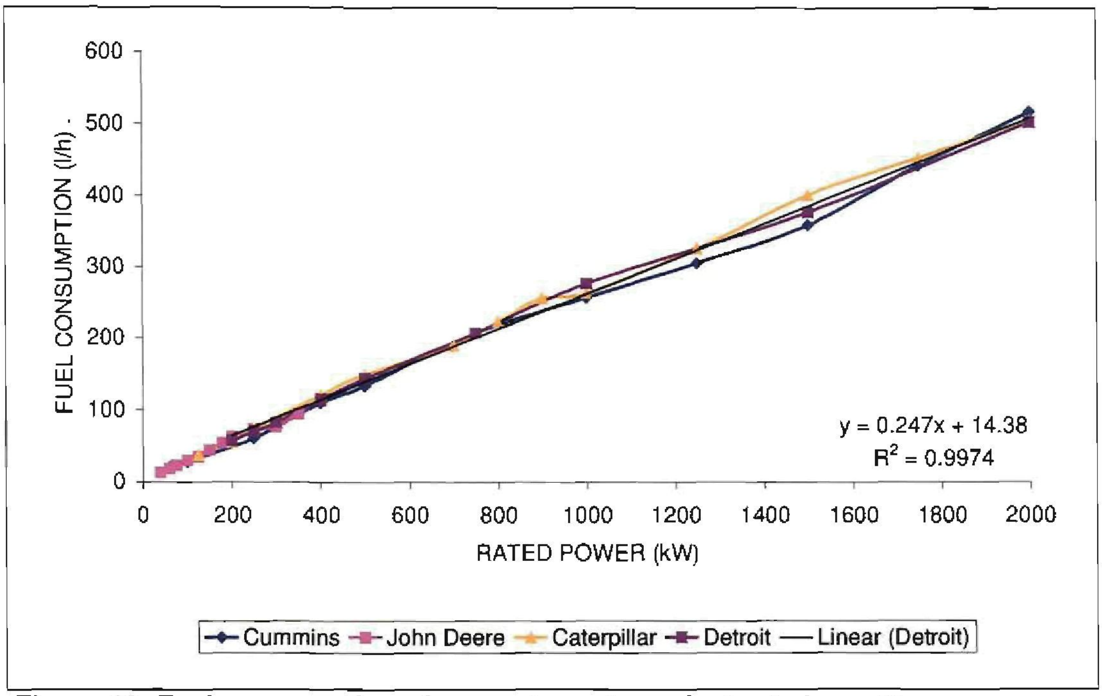

Figure 13: Fuel consumption of generator sets against rated power
Source: Alterdyne [7]

Table 3 indicates the ranges of the data which was discussed in the previous sections on the different manufacturers and different types of internal combustion engines. It is evident that the information in the literature has a wide range.

Table 3: Available energy ranges of different engines

Description	Range
Exhaust gas temperatures	395℃ – 604℃
Exhaust gas heat available (%)	16 % - 29 %
Cooling system heat available (%)	12 % - 49 %
Electrical thermal efficiency at full load	29 % - 42 %
Overall efficiency (Combined heat and power)	74 % - 81 %

The above data only examined exhaust gas and cooling jacket water as possible energy sources for heat recovery. Large internal combustion engines will have significant heat losses through engine oil cooling systems and intercoolers, after the turbochargers could be recovered. Smaller internal combustion engines will have heat loss in the oil cooling system and intercooler, but the cost of recovering heat from these systems will not justify the equipment.

Accurately predicting the possible energy available for an unknown engine by using data from known engines would be very difficult. The results from the same engine manufacturer with the same configurations, varies significantly enough to conclude that the prediction will not be sufficiently accurate.

2.5 Cogeneration

Combined heat and power (CHP) is defined as an integrated system located at or near a facility, which satisfies at least a portion of the facility's electrical demand, and utilizes the heat which is generated by the electric power generation equipment to provide heating or cooling to an industrial process [23]. Combined heat and power systems are called cogeneration systems. In some instances trigeneration systems are used or defined as combined cooling, heating and power (CCHP) systems.

The first cogeneration plant, Pearl Street Station in lower Manhattan in New York, was built more than 100 years ago by Thomas Edison in 1882 [25]. It is therefore not a new technology, but it has become more important worldwide due to electricity shortages in the United States of America, Canada, Europe, as well as in South Africa at the moment. CHP units will have a power source or prime mover which will drive a generator to generate electricity with heat recovery equipment to recover the heat from heat sources such as exhaust gases, coolant water, oil coolers and turbo charged cooling. CHP systems can be categorized into Rankine cycles or steam generation cycles, Brayton cycles or gas turbine cycles and reciprocating cycles, which include internal combustion engines (ICE), Stirling engines and fuel cells [15, 26, 27].

CHP systems can be defined as topping cycles, where the primary function is to generate electrical power and subsequently heat is generated or bottoming cycles, where the primary function is the generation of heat to be utilized with subsequently power generation [20, 28]. This is one of the main points of consideration when making a final decision on CHP units. The decision is based on the load profile of the energy which is needed.

The basic outlay of a cogeneration system of a diesel power source is shown in Figure 14. Depending on the size of the power source, heat can be recovered from the exhaust gas, cooling water system, intercooler and oil cooling system. Heat recovery from the intercooler and oil cooling system is financially viable for large power sources, but not for small scale power sources.

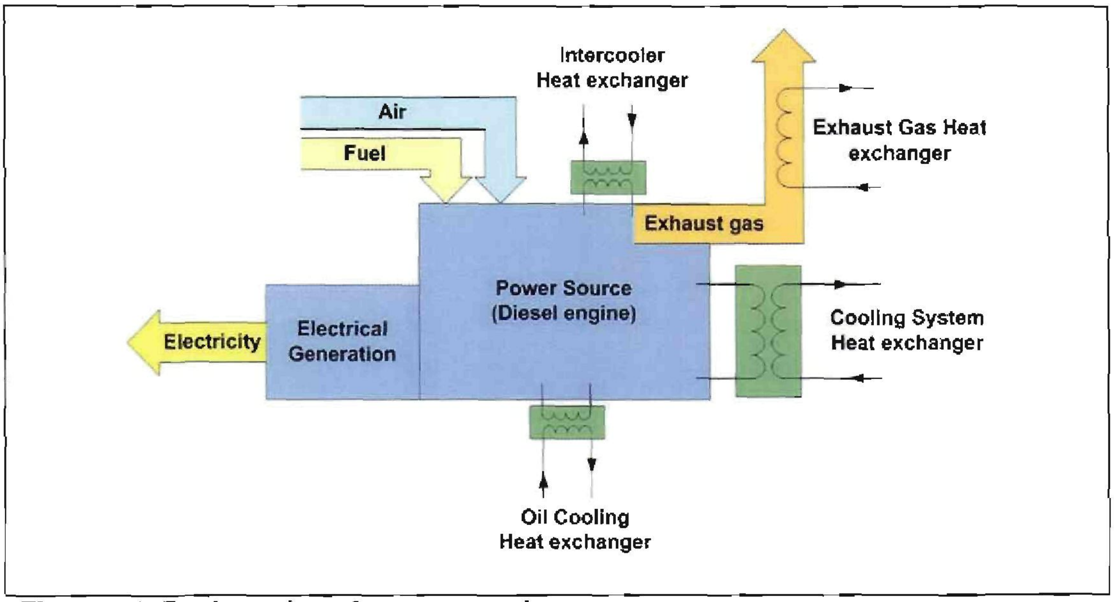

Figure 14: Basic outlay of a cogeneration system

The efficiency of cogeneration is defined as the total useful energy available, electrical and thermal energy, divided by the energy supplied, or fuel, to the system [15, 29].

Efficiency calculations and energy saving equations are used to make decisions and influence choices, but it is usually taken over a long period of time [30].

$$\eta = \frac{P_e + P_{th}}{Q_{in}} \quad (2.5)$$

with P_e the electrical power, P_{th} the actual thermal energy and Q_{in} the energy input from the fuel.

The efficiency of a prime mover is increased with a CHP approach, but only when thermal heat and electricity is produced and needed at the same time [31]. It offers the possibility of distributed generation with advantages such as power generation in small urban areas and industries and the use of local biomass resources which can replace fossil fuels.

De Paepe *et al.* [29] evaluated five different micro-CHP systems for utilization in residential applications, which includes one fuel cell combined heat and power (CHP) system. Table 4 gives a summary of the evaluation that was done of the available CHP technologies.

Table 4: Comparison of CHP Technologies

CHP Technology	Installation cost (1€ = R8)	P_e (kW)	η_{ele} (%)	P_{th} (kW)	η_{th} (%)
Senertec internal combustion gas engine	R 110 000	5,5	27	12,5	61
Ecopower internal combustion gas engine	R 94 000	4,7	25	12,5	65
Solo Stirling engine	R 200 000	2-9,5	24	8-26	72
Whispertech Stirling engine	R 81 000	1	12	4,9-8	80
Idatech fuel cell	R 1 120 000	4	25	9	55

Source: De Paepe *et al.* [29]

Cardona *et al.* [30] studied sizing a CHP unit to a hotel in the Mediterranean areas for the purpose of trigeneration. The demand load of the hotel is for electricity, heating and cooling for various processes, as well as for winter and summer conditions.

It was suggested that considering the efficiencies and fuel saving alone, was not enough to select an appropriate CHP unit. The way the system is managed, is also important. Producing mainly electricity will produce heat and excess heat which cannot be used by the system, and will be discarded. Producing mainly thermal heat will produce electricity and excess electricity can be sold back onto the grid.

The final recommendation was based on selecting a system with a chiller which could handle 70 % of the peak demand load. Within the set-up it resulted in an energy saving of 25 – 35 %. This is only possible when, as was emphasized, additional energy can be purchased from the grid.

Table 5 is a summary of information from various prime movers and the critical parameters which have to be considered [15, 20]. The power density is defined as the power needed per square meter of surface area occupied by the prime mover.

Table 5: Summary of different prime movers

	Steam turbine	Diesel engine	Gas engine	Gas turbine	Micro-turbines	Fuel cell
Overall efficiency	60-85 %	60-85 %	60-80 %	60-80 %	60-85 %	65-90 %
Part-load	Ok	Good	Ok	Poor	Ok	Good
Heat to power ratio (HPR)	2-10	0,4-1,25	1,4-2	1,2-2	1,2-2	1-1,25
Hours to overhauls (thousand)	>50	25 – 30	24 – 60	30 – 50	5 – 40	10 – 40
Start-up time	1 h – 1 day	10 s	10 s	10 min - 1 h	60 s	3 h - 2 days
Power density (kW/m^2)	>100	35 - 50	35 - 50	20 - 500	5 - 70	5 – 20

The overall efficiencies vary, depending on the system set-up and the different configurations between power and thermal demand. Start-up time is important to consider for small scale CHP systems, because more frequent start-ups are needed. The part-load characteristics are important for systems with no secondary power supply, because they will have to operate at part-load conditions.

A 5 MW gas turbine generator was used by Lafarge Gypsum Division in Silver Grove delivers 12,9 MW of heating to the gypsum plant. The heat to power ratio (HPR) of the gas turbine was 2,6 and a total of 96 % of the thermal energy was utilized in the process [32]. The gas turbine utilized a 200 kW chiller to reduce the inlet temperature of the gas turbine from 35 ℃ to 13 ℃, and by doing this increased the output by 600 kW. The temperature of the exhaust gas was 600 ℃.

Lin *et al.* [33] conducted an investigation into a trigeneration CHP unit for a household application. A Lister-Petter diesel engine was connected to an electrical generator and the waste exhaust gases were recovered and used to drive an absorption refrigerator. The diesel engine was tested before any alterations were made for the trigeneration, to obtain base data. These results were used to compare the engine performance after the alterations. No significant difference in electrical power generated was detectable between the electrical generation alone, the trigeneration engine system and the electrical, heat and cooling generation system.

The engine was tested under loads from 0 % to 100 % in steps of 25 %. Cooling in the absorption cooler was established at 50 % load and higher. Useful available energy ranged from 5,5 kW at no engine load to 17,8 kW at full-load. The engine was rated at 9,5 kW and the maximum electrical power obtained was 6 kW. The maximum heat to power ratio (HPR) of the engine was calculated as 3. The thermal efficiency of the trigeneration system ranged from 64 % to just over 67 % and remained stable throughout the loading range. This proves the impact of small-scale CHP units and the savings which can be obtained. It was reported that very few experimental studies had been done on trigeneration, although many theoretical and computational studies were done.

Miguez *et al.* [34] tested a Honda GX 360-K1 engine which was directly connected to an electrical generator producing 9,6 kW at 3 600 revolutions per minute. An electromagnetic clutch connected the engine to a heat pump compressor to be used in a heating / cooling system. Exhaust gases passed through a heat exchanger which was connected to a heat accumulator. The cooling-water heat was recovered and stored in the heat accumulator. The heat pump system can be utilized for additional cooling or heating, depending on the requirements.

This combined heat and power system could operate in different modes, depending on the different energy and thermal demands. During the electrical demand, the efficiency of the system ranged from 20 % to 24 %. The thermal energy which was rejected during this operation was as high as 80 % of the consumed energy.

During the cogeneration mode, in which the system must meet an electrical demand, as well as a thermal demand, the total efficiency was as high as 73 %. In this mode the primary function was to generate electrical power and any additional thermal energy was rejected into the atmosphere. The thermal energy available was the highest at low loads and reduced as the load increased. The engine load was varied with engine speed. Therefore, the increase in efficiency is due to the increase in speed. Additional testing done by Porteiro *et al.* [35] on the same system, indicated that the heat to power ratio of the system was 1,93.

Talbi *et al.* [36] used a software program, SPICE, to simulate a cogeneration system which uses exhaust gases to drive an absorption cooler and an air conditioner. The maximum overall efficiency which the cogeneration system could obtain was 60,6 %. The available energy in the exhaust was 46,2 kW with 30,9 kW cooling capacity available from the absorption cooling system. The cooling capacity of the air conditioning system was 27,3 kW and the cooling capacity in the intercooler was 3,6 kW.

Junhong *et al.* [37] reported a 34,1 % heat recovery from a truck exhaust system with a heat transfer oil heater. The oil which was heated by exhaust gases was pumped through a water tank. Parlak *et al.* [38] used the first law of thermodynamics and calculated that a maximum of 47 % of the exhaust gases is recoverable.

Honda Motor company [39] reported that they had developed a 163 cm^3, 4-stroke, water-cooled, single-cylinder compact household cogeneration system. The system delivers 1 kW of electricity and 3,25 kW of thermal energy. Heat is recovered at 65 % and the thermal electrical efficiency is 20 %. This gives an overall efficiency of 85 %.

Badami *et al.* [40] reported on a new 120 kWe gas cogeneration system. The part-load efficiency of the engine is increased through power electronics, whereby the engine is run under ideal circumstances at part-load and the electrical supply is corrected with the power electronics. The output from the generator can be increased with the increase of the engine speed, but is limited by the temperature which the alternator is able to handle.

Godefroy *et al.* [41] used a Senertec Dachs mini-CHP unit in a trigeneration system to model it mathematically. This unit had a rated electrical power of 5,5 kW_e and a rated heat power of 12,5 kW_{th}. This gives a heat to power (HPR) ratio of 2,27. The electrical efficiency was 24 % with the thermal efficiency 54,8 % and the overall efficiency of 78,2 %. The thermal energy was recovered from the engine jacket, lubrication oil and the exhaust gas. This small 578 cc spark-ignition engine has an operating life of more than 80 000 hours, with maintenance intervals of 3 500 hours.

Entchev *et al.* [42] studied the system performance characteristics of a small scale CHP and its integration into a house. A Stirling cycle engine was used as the CHP and it generated 736 W_e of electricity and 6,5 kW_{th} of thermal heat. This gives a HPR of 8,8. The CHP unit's thermal efficiency varied between 74 % and 79 %. The electrical efficiency was very low and varied between 5,5 % and 9 %. The overall efficiency of the CHP unit varied between 79,5 % and 88 %.

This CHP unit was thermal load driven and reacted to the thermal load of the heat storage tanks. The heat storage tank was connected in the house in two ways. It was either used as a supplementary supply to the hot water tank, or in series with the hot water tank. The efficiency varied from 41 % to 80 % during the testing, with the series connection showing a slightly better electrical efficiency.

Smith *et al.* [43] investigated a CHP unit which was connected to a heat pump to try and satisfy the domestic market. This was done especially to try and satisfy the great heating load without the need to export electricity. Heat was recovered from the exhaust gas and the heat pump utilized some of the generated electricity. Depending on the load conditions the system could run as a CHP unit which supplies electricity and the heat is recovered, or as a heat pump where sufficient electricity is generated to drive the heat pump and lastly, as a combination between the two systems. The CHP unit achieved an overall efficiency of 59 %, the heat pump system achieved an overall efficiency of 70 % and the combined system achieved an overall efficiency of 73 %.

Supplying heating with a boiler or furnace with a fuel can result in an efficiency of more than 90 % [44]. The energy savings of a CHP system is sensitive to the prime mover efficiency. A 26 % efficient micro-turbine reduced primary energy consumption of a building in New York City by 4 % compared to a 42 % efficient internal combustion engine which reduced the primary energy consumption by about 30 %. The reason for this was that the building had no thermal storage and could only utilize between 30 % and 40 % of the waste heat.

Petrov *et al.* [45] investigated the dynamic performance of a 30 kW micro-turbine CHP unit. The study showed that transient time between load changing can be considerable. The gas turbine reaches steady state electric power output after about 4 minutes after start up and the heat recovery unit reaches steady state conditions 55 minutes after start up. A step change from 30 kW_e to 20 kW_e shows an electric power output stabilization after 20 seconds, but a heat recovery stabilization occurs after 5 minutes. This leads to the point where the heat load which is expected from the unit, must be lower than what it can deliver, at all times. If this is not done, the unit will not be able to satisfy the heat load which is needed.

Huangfu *et al.* [46] reported on a micro-combined cooling, heating and power system utilizing a 12 kW rated generator set with a 9 kW adsorption chiller. It was reported that with a varying electrical load the heat recovery from the jacket cooling water changes slowly compared to the heat recovery from the exhaust gases which shows sharp variations in the curves which were plotted.

Key factors that influence the financial attractiveness of CHP are the coincidence of the need of electrical and thermal load, the price difference between electrical power from the grid and that of fuel, the cost involved with the installation of the CHP system and the reliability of power [23].

Advantages of CHP systems are efficiency, flexibility, reliability and improved environmental performance. Overall efficiency is much higher than individual systems with much less emission gases per energy unit produced [9].

In summary, the overall efficiency of cogeneration systems are high and the technology has been tested and proven in various research projects and industrial applications. Cogeneration features can be summarized as follows:

- Efficiencies vary from around 50 % to as high as 88 %. The Lafarge Gypsum Division is a very good example of a 96 % utilization of the thermal load. This is dependent on the specific application and auxiliary equipment utilized.
- Cogeneration can be electrical demand driven or thermal demand driven, depending on the system set-up. In many of these applications electricity could be sold back to the grid or bought from the grid. The grid is used as a backup system and this forms an important part of the final decision. Lower risk and better efficient systems can be utilized because a back-up exists.
- The type of power source is important because the quantity and quality of heat needed is important. The heat to power ratio (HPR) is a good indication of the ratio of energy available per power source.
- The efficiency of the power source and the energy demand from the required source should match one another. Buildings and domestic applications with heating and cooling need low quality of heat.
- The reaction to a change in load is very important because electrical load change can be handled within a short period of time, but the thermal load change takes longer to react.
- Small scale CHP is more beneficial to small rural communities with no electricity and new established communities or businesses where the cost of getting connected to the grid is too high.

2.6 Factors influencing CHP

Literature indicates that CHP has a high efficiency compared to a power source without heat recovery equipment, but careful consideration should be taken before a CHP system is selected. A clear understanding is needed of the process, as well as the possible technologies which are available.

A highly variable demand load must be based on hourly demand load profiles and stable demand loads can make use of monthly or seasonally based demand loads. It is reported that key factors for a choice of fuel is dependent on the quality of fuel, availability, cost and delivery to the site [47]. Utilizing hourly demand loads for a load profile that is completed in eight hours, will not be sufficiently accurate. A smaller time interval is needed to determine a more accurate load profile.

Hawkes and Leach [48] specified five constraints which should be adhered to during the optimization of a CHP system. The electrical demand must be met, the heat demand must be met or exceed the required amount, the CHP capacity must not be exceeded, the boiler capacity must not be exceeded and the change in conditions may not exceed the ramp time of the CHP generator.

The temporal demand block which was considered during the study was five minutes, 10 minutes, 30 minutes and one hour. They concluded that the 10 minutes demand block was sufficiently accurate for the assumed constraints. It was concluded that the lifetime cost of the system can vary by up to 16 % between temporal precisions.

Alanne *et al.* [49] did a comprehensive study regarding small scale combined heat and power technologies in buildings. In this study it is mentioned by Vanhanen, in a report only available in Finnish, that to evaluate small scale combined heat and power technologies one has to look at eight criteria, namely the electrical efficiency, length of life cycle, space needed to install the technology, emissions, flexibility of control, availability of fuel in the short term, level of noise generated and cost.

The selecting of a prime power source for a specific application can always be debated and various personal preferences can influence a final decision. Combined heat and power (CHP) resource guide [23] suggests that a heat to power ratio (HPR) should be determined.

$$HPR = \frac{P_{th}}{P_e} \tag{2.6}$$

This ratio is then used to assist, by using the data in Table 6.

Table 6: Recommended prime mover based on HPR ratio

HPR	Consider
0,5 to 1,5	Engines
1 to 1,5	Gas turbines
3 to 20	Steam turbines

Khan *et el.* [50] suggest that the size of the prime mover generator is determined as follows:

$$\text{Required generator size} = C_{res} \times \left(\frac{P_{req}}{\eta_{T\&D} \times \eta_G} \right) \quad (2.7)$$

where C_{res} is the reserved capacity, P_{req} is the required power, $\eta_{T\&D}$ is the transmission and distribution efficiency and η_G is the generator efficiency.

The heat recoverable from a cogeneration system depends on the quality of the heat available from the prime mover, as well as the equipment which is used to recover the waste heat. The system is then sized according to power matching, thermal matching or a combination of electrical and thermal matching. In this study three different prime movers were selected and tested against three different load profiles, a base load, an intermediate load and a 70 % peak load profile.

The prime power source for the base load was selected to produce the minimum electricity required and the additional electricity was purchased from grid electricity. This prime mover had a heat to power ratio of 1,08 and the energy saving was 16,1 %. The prime power source for the intermediate load was selected to produce electricity between the peak load and the base load. This prime power source had a heat to power ratio of 1,11 and the energy saving was 18,7 %. The prime power source for the 70 % peak load profile had a heat to power ratio of 0,97 and an energy saving of 19,66 % was obtained.

Throughout the literature the decisions concerning cogeneration are based on the availability of grid electricity or the possibility to sell excess electricity back to the grid. None of the above strategies would have been possible if no grid electricity was available. Alternative energy supplies are part of the criteria which were used in all the studies as mentioned before.

Bhatt [28] developed a model to compare the overall efficiency, the HPR and the electrical efficiency. The overall efficiencies are calculated with the following equation:

$$\eta_o = [HRR + \eta_e(1 - HRR)] \tag{2.8}$$

where η_o is the overall efficiency, η_e is electrical thermal efficiency and HRR is the heat recovery ratio.

This model can be used to assist in making a decision. The overall efficiency of a CHP system against the electrical thermal efficiency with different heat recovery ratios (HRR) is plotted in Figure 15 using Equation (2.8).

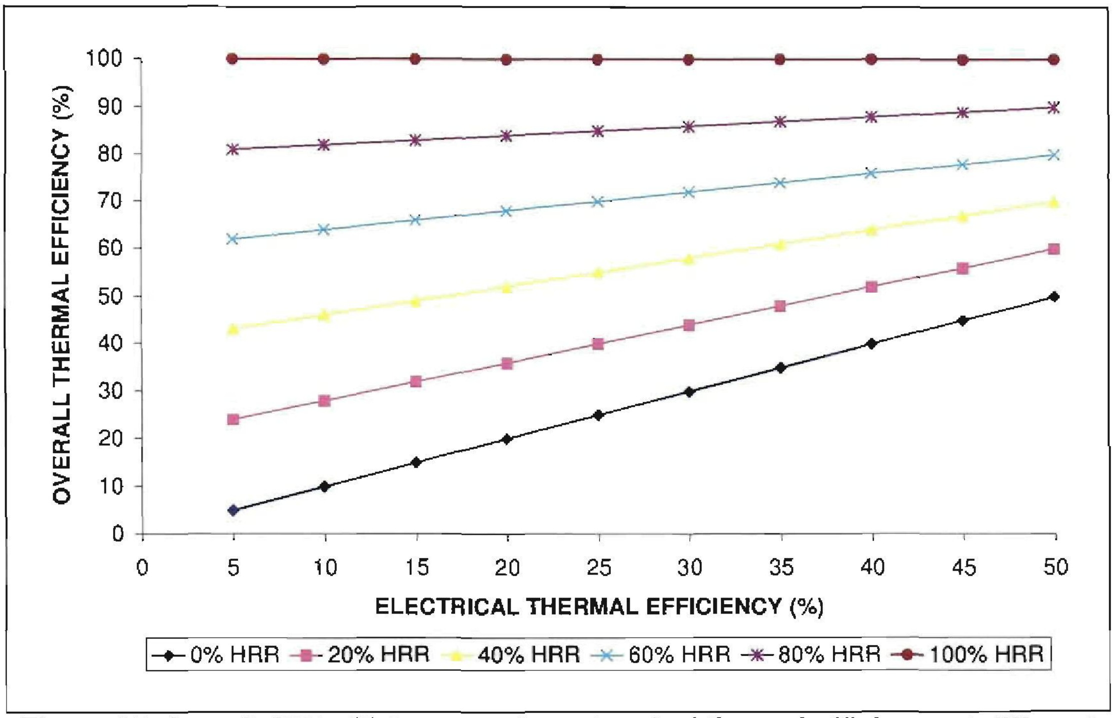

Figure 15: Overall CHP efficiency against electrical thermal efficiency at different heat recovery ratios.

The heat recovery ratio is defined as the ratio of heat that could be recovered from the available heat, or more commonly known as the effectiveness of a heat exchanger [24, 51].

Lower efficiency implies that more heat is recoverable and higher efficiency that less heat will be recoverable. Thus the assumption was made that all the energy which was not utilized for electrical generation will be available for heat generation. This is, however, not possible, because not all heat can be recovered due to the quality of the available heat. The quantity and quality of the available heat and the complexity of recovering heat from specific systems, all influence the final efficiency.

Figure 16 shows the HPR of a CHP system against the electrical thermal efficiency with different heat recovery ratios. The HPR was obtained by using Equation (2.9).

$$HPR = HRR \times \left(\frac{1}{\eta_e} - 1 \right) \tag{2.9}$$

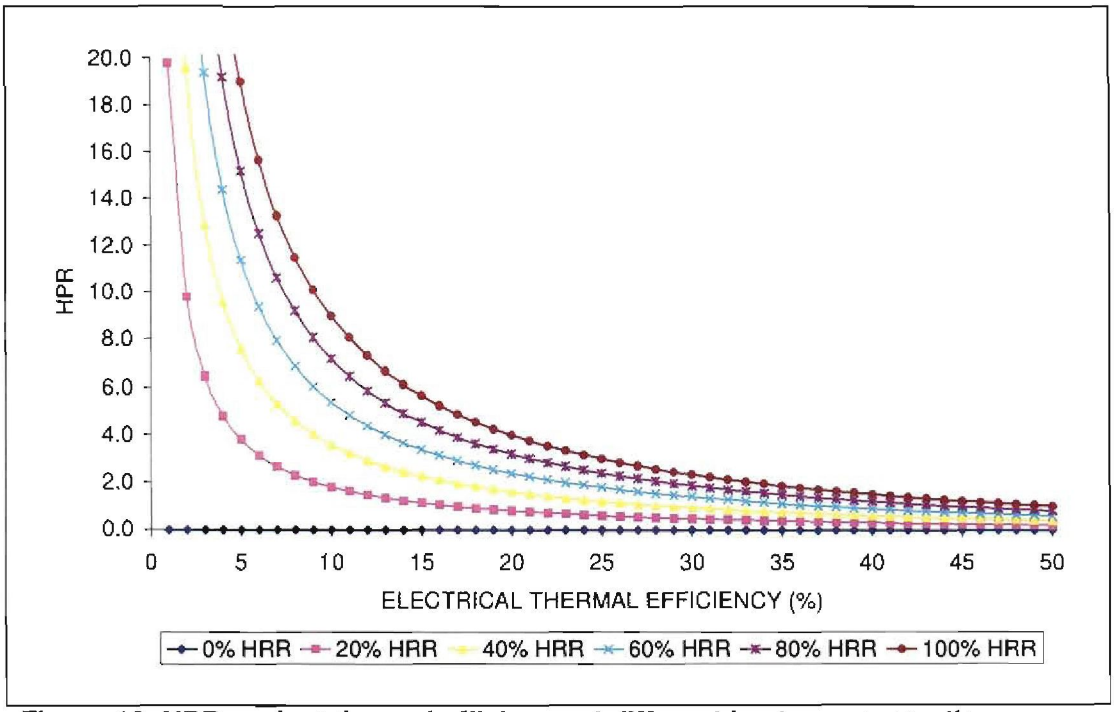

Figure 16: HPR against thermal efficiency at different heat recovery ratios.

The importance of this is that the HPR of a system can be plotted on these graphs and it would indicate what the maximum obtainable efficiency would be. It would assist in evaluating systems which run on part-load. On the other hand, if the effectiveness of a heat exchanger is known, the required HPR can be determined for a specific efficiency to be obtained.

Using the efficiencies obtained from literature, assuming a heat recovery ratio of 1 and making use of Equation (2.9), the highest HPR's obtainable from internal combustion engines are between 1,4 and 2,5. Higher HPR ratios can be obtained from external thermal sources or converting generated electricity to heat.

The type of cogeneration technology, the number of prime power sources, the heat recovery equipment, the connections to the grid, the need for electrical and thermal storage and the operating mode of the system, influence the final decision which has to be made in selecting the optimal cogeneration system [20]. The availability of space and the compatibility of the thermal loads, as well as the available loads, are as important to make a final decision. Determining the thermal load and deciding on the load profile to be followed all contribute to the final selection.

The final choice of a CHP system is dependent on the electrical and thermal load which is required by the process. The electrical and thermal energy which can be supplied by the power source have to be matched with the needed load. Technologies available with specific requirements around electrical and thermal loads will help in achieving the matching of the supply and demand. The time interval of the load profile is important for accurate estimates. Finally, the load-following strategy that will be implemented, will determine the technology which will be needed.

2.7 Financial models

Various financial models are used to determine the cost-effectiveness of a cogeneration system. The internal rate of return, net present value, pay back period, initial cost, annual savings, operating cost, time of payment and life cycle cost are mainly used for financial considerations to assist in making a final decision [46, 52].

CHP economics are characterized by high initial investments and depreciation which is influenced by fuel price, electricity price, price of standby electricity, yearly operational hours, the efficiency of the system, as well as support of the system [53]. Feasibility studies should include the economics of a range of combined heat and power system sizes, unit performance, maintenance cost, control strategy, alternative fuels and electricity prices [54].

Khan *et al.* [50] used the following parameters as part of the financial consideration. Investment cost included purchase cost of the prime mover, site preparation, installation and commissioning cost, control equipment cost and transmission and distribution cost. Operation and maintenance cost include the fuel used, oil used, regular maintenance on the prime mover and salaries of staff to maintain the prime mover and auxiliary equipment. Insurance and interest was used to do the cash flow analysis.

Hawkes and Leach [48] studied the impact of temporal precision on combined heat and power systems when fuel cells and Stirling engines are used. They looked at minimizing the net present value for the life time of the combined heat and power generator. The lifetime cost, as they defined it, was the summary of functions of various aspects of a combined heat and power system. These functions were the capital cost of the CHP plant, the capital cost of the boiler, the cost of fuel, the electrical power imported, the maintenance cost of the CHP system, the maintenance cost of the boiler and the cost of exporting electricity.

Ren *et al.* [55] used a mixed integer non-linear programming model to determine the minimum annual cost of a CHP plant for a residential energy system. The model considers the sums of all costs over time periods. The cost included buying electricity power, running cost of the plant, running cost of the back-up boiler, annual system investment cost for the CHP plant and back-up boiler, as well as the cost for carbon emissions. The running cost was considered to be fuel cost and maintenance cost.

Life cycle cost (LCC) is defined as an economic method of evaluating a project which includes all cost of owning, operating, maintaining and disposing of a project [52]. Life cycle cost is a consistent method of accounting for all of the costs mentioned above, over the lifespan of the equipment. Evaluating a project in respect of payback period gives a shortest payback period, but does not evaluate a project in terms of economic performance or profitability over the lifespan of the equipment.

LCC considers costs incurred over the lifetime of the project and discounts it to the present value. The discount rates which are used during these calculations are based on the investor's time value of money [52, 56]. LCC can be summarized with the following equation:

$$LCC = C_i + C_{repl} - C_{res} + C_e + C_w + C_{om\&r} + C_o \tag{2.10}$$

where all the values are the present values calculated with a discounted rate over the time of the project. C_i is the cost of investment, C_{repl} is the cost of replacement, C_{res} is the residual cost after the life of the project, C_e is the energy cost, C_w is the cost of water, $C_{om\&r}$ is the cost of non-fuel operating, maintenance and repair cost and C_o is other costs incurred which are directly related to owning and operating a project or equipment.

In determining the present value of cost incurred in the future, one has to look at defining a couple of scenarios. Single present value (SPV) factor is used for single future cost incurred, discounted to the net present value (NPV).

$$NPV = F_t \times SPV \tag{2.11}$$

$$SPV = \left(\frac{1}{(1+d)^t}\right) \tag{2.12}$$

where F_t is the future cost incurred, d is the discount rate and t is the time in future years from the base date. Uniform present value (UPV) factor is used for annually recurring uniform amounts incurred, discounted to the net present value.

$$NPV = A_0 \times UPV \tag{2.13}$$

$$UPV = \left(\frac{(1+d)^n - 1}{d(1+d)^n}\right) \tag{2.14}$$

where A_0 is the recurring annual amount, d is the discount rate and n is the time period in years. Modified uniform present value (MUPV) factor is used for annually recurring amounts that change from year to year at a constant escalation rate. The escalation could be positive or negative.

$$NPV = A_0 \times MUPV \tag{2.15}$$

$$MUPV = \frac{(1+e)}{(d-e)}\left[1-\left(\frac{1+e}{1+d}\right)^n\right] \tag{2.16}$$

where A_o is the recurring annual amount, d is the discount rate, e is the constant escalation rate and n is the period in years.

The residual values of a system or equipment with remaining useful life can be calculated by applying a linear pro-rating of its initial cost over the time of consideration. Comparing alternative equipment or systems, the same base date must be used and the duration of the time of consideration must be the same when calculating the life-cycle cost.

LCC analyses are limited by how it is used and what assumptions are made. The estimations are made early in the life of a project and this leads to a degree of accuracy which cannot always be trusted [57]. Omission, misinterpretation of data or the use of wrong estimation techniques contribute to the degree of accuracy.

The economics of a CHP depend on the local utility rates, electrical demand charges, natural gas prices and the initial capital cost. Adding reliability and availability to maintenance cost contribute to a barrier against CHP [44]. The availability of large volume prime movers is a problem with an extensive support structure and servicing. Internal combustion engines are the only prime movers which have this infrastructure as the possible CHP prime movers.

Fischer [58] studied the value of CHP for the building owner or operator. Industries can offset the benefit from CHP against heat loads for space heating, domestic hot water, chilled water for air conditioning. Other aspects which are not mentioned are the benefit of selling excess electricity back onto the grid or making use of alternative fuels.

Fischer investigated the avoided cost if CHP is used and used it to determine the payback period of the capital investment. A model was developed, but it investigated the heat recovery from CHP against a boiler which supplied the heat in the first place. Heat is used for the chilling of water with an absorption chiller.

The payback period is determined by dividing the capital cost with the saving per kilowatt hour, multiplied with the amount of operating hours. The method shows that the payback period is very sensitive to the amount of heat which is recoverable. The model which was used showed a payback period of 4,6 years with a 100 % heat recovery of the waste heat. A payback period of 6,4 years is obtained for a heat recovery of 75 % and a payback period of 10,5 years for a heat recovery of 50 %.

Blakemore *et al.* [59] investigated the effect of economy of scale on the selection of CHP units. The conclusion was that the cost per kilowatt electrical output decreased as the size of the CHP unit increased, however this was only applicable up to about 1000 kWe. Units which are larger than that become more expensive, due to their size and the engineering works which are needed to install the units. The maintenance cost follows the same trend in that it reduces as the CHP unit's output increases, but a limit exists and at that point the size of the unit becomes too large.

The selection was done with a process in which a matrix was drawn up and experts in the field had to rate and rank 6 criteria. The criteria are minimization of energy cost, operational management, capital cost, maintenance cost, timescale and the potential for expansion. The weighting and ranking values were multiplied and the highest scoring system was selected.

Fantozzi *et al.* [18] investigated the possible solutions to CHP units for a pasta factory in Italy. The selection had to be done between internal combustion engines and gas turbine engines. The financial tool which was used was the payback period, net present value based on the discounted cash flow and the internal rate of return. The advantages of this pasta factory are that additional electricity can be purchased off the grid or excess electricity can be sold onto the grid.

Economic analyses or feasibility studies are as accurate as the data which is available. Equipment cost, installation cost and other project cost all contribute to the overall investment cost [20]. Operating and maintenance costs are calculated by fuel cost, personnel, maintenance, insurance, management fees, interest and taxes.

Shen [26] proposed that the fixed investment cost can be distributed over time and can be calculated with an annuity factor as shown below:

$$AF = \frac{1-(1+r)^{-n}}{r} \tag{2.17}$$

where AF is the annuity factor, r is the discount rate and n is the time consideration of the equipment. The annualized fixed investment cost is then calculated as

$$PV = \frac{I_c}{AF} \tag{2.18}$$

where PV is the annualized present value and I_c is the investment cost. This is the same as the uniform present value defined before.

Total cost per year can be calculated as the annualized cost of investment over time plus the variable cost which includes fuel cost and maintenance cost. Advantages are that future estimates and guesses do not have to be done and the time duration of the different components does not have to be the same.

Differences between prime power sources are the installation cost, thermal efficiency of generating electricity, emissions of the exhaust gas, fuel options which can be utilized with the prime power sources, life expectancy of the prime power sources, noise levels, vibration levels and service requirements. The best option is, therefore, the best compromise at the lowest life cycle cost.

Different financial models are available to be used to predict the optimum power source which is to be used for a CHP system, but the most often used models are the LCC or the NPV. Both these systems present problems with future predictions and the time of consideration. Therefore the annualized method used by Shen simplifies all calculations and reduces possible errors which could be made with future estimations.

Life cycle cost will be used in the development of a design tool, but all values will be annualized to the current date. The literature describes various possible CHP systems which are based on the possibility of buying or selling electricity from the grid, having boilers on standby for thermal energy and supplying energy for heating, cooling and power. All of these aspects have to be considered in a financial model, but will be simplified for the soya business unit, as none of the above-mentioned options are available.

2.8 Software tools

Tools to assist with the decision making in respect of different parts of combined heat and power systems are available, some at cost and others at no cost. Discussions will be limited to the tools which are available without cost. The reason for this is that some of these tools are more expensive than the initial capital investment cost for a small scale CHP unit. The cost involved to purchase software to assist in the decision making process does not warrant it.

Hinojosa *et el.* [54] did a comparative study on SEA/RENUE, CHP Sizer 2, Ready Reckoner and Energy Pro 5 which are all software packages available to assist with the decision making process. By using fictitious loads and comparing the results the following conclusions were made: CHP applications are very complex due to all the different possible variables needed to define the process. Some of the free programs lack flexibility and transparency. Custom-built spreadsheets are easily modified for different scenarios and the methodologies used in acquiring the results are transparent to the user. The final conclusion made was that if a flexible, transparent and fully comprehensible feasibility program is needed an in-house development would be the preferred option.

2.8.1 Cogeneration Ready Reckoner Version 3.1

This program is used in a preliminary evaluation of cogeneration at a site. The software is distributed by the Australian Commonwealth Department of Industry, Tourism and Resources (DITR). The software is used to evaluate the cogeneration system (cogen case) against a non-cogeneration system (benchmark case) [60].

A benchmark case is evaluated against a cogeneration case. The benchmark case defines the steam or thermal load and the electrical load if cogeneration is not installed. The software makes provision for electrical growth over time and incorporates operational and maintenance cost, as well as capital cost. Various tariffs paid for fuel and electricity can be utilized.

A cogeneration case permits the selection of a cogeneration unit and the fuel which is used. Different cogeneration units can be selected. The fuel which is used for the cogeneration may be different from that of the base unit. The same costs are used as in the benchmark case. Financial calculations are made in terms of net present value (NPV), internal rate of return (IRR), payback and cash flow.

The time considerations are between 10 and 20 years and each of these can be subdivided into 12 periods. Different heat and electrical loads can be loaded for each period in the year. The software provides for equipment degrading between overhauls. The software considers that electrical energy can be imported as needed and that the thermal heat is supplied by a boiler.

The software provides for internal combustion engines to be selected as power supply units. The outputs for the internal combustion engines can be customized, but the maximum values are considered during the calculations and no considerations are given to part load conditions.

2.8.2 ORNL CHP Capacity Optimizer

This software was developed in Microsoft Excel to determine the optimal capacities of distributed energy prime movers and absorption chillers [61]. The software algorithm tries to maximise the net present value (NPV) of a CHP system with that of a non-CHP system. The software makes use of hourly demand load data.

The heat to power ratio is used to determine the heat available from the power source. The efficiencies of part-load conditions of different power sources are calculated with assumed mathematical equations as shown below.

Fuel Cells: $$\eta = 0{,}9896x^3 - 2{,}4204x^2 + 1{,}9439x + 0{,}4869 \quad (2.19)$$

Gas Turbines: $$\eta = -0{,}4821x^2 + 1{,}1542x + 0{,}3279 \quad (2.20)$$

Internal Combustion Engines: $$\eta = -0{,}508x^2 + 1{,}0214x + 0{,}4866 \quad (2.21)$$

where x is the relative power output of the power source. Different energy tariffs can be entered for different times of the year.

The software is not user-friendly. Heat is supplied from a boiler. The software was developed for building owners to evaluate the possibility of installing CHP systems. Part-load conditions are obtained by using Equation (2.19) for fuels cells, Equation (2.20) for gas turbines and Equation (2.21) for internal combustion engines.

2.8.3 RETScreen Combined Heat & Power Project Model Version 3.6

This software is developed in Microsoft Excel and is used for clean energy awareness, decision making support and as a capacity building tool. The software evaluates energy production, life cycle cost and greenhouse gas emission reductions for various types of energy efficient and renewable energy technologies.

The software considers only monthly electrical and thermal loads. A single peak thermal load is entered into the software and the percentage of time which the thermal load needs, is entered. A selection can be made between power load, heat load and full power output.

Various different power sources can be used with different fuel sources. Provision is made for worldwide weather data, but only Northern American data is available. Data can be downloaded from a NASA site.

Cost analyses incorporates feasibility studies, development cost, engineering cost, power system capital cost, heating system capital cost, operating and maintenance cost, fuel cost and periodic costs. Financial viability is given in terms of internal rate of return (IRR), simple payback period, net present value (NPV), annual life cycle savings, benefit-cost ratio and debt service coverage.

The software does not consider process heating alone, as well as part-load conditions of the power sources. The software is not user-friendly.

2.8.4 Homer Version 2.5

Homer software was developed for design evaluation of grid-connected and stand-alone applications. It evaluates a large range of technologies and combinations of technologies in respect of net present cost (NPC) or known as life cycle cost. Homer is one of the most comprehensive software tools available.

A wide variety of power sources can be selected as stand-alone units or as a combination of power sources. The power sources are: solar photovoltaic (PV), wind turbine, run-of-river hydro power, different fossil fuel generators, alternative and custom fuels, co-firing systems, electric utility grid, micro-turbines and fuel cells. Energy storage can be added with battery banks and hydrogen tanks. Daily load with seasonal variation can be entered.

Up to three different size generators with different cost and fuel can be used. Homer ranks the generators in an economically optimal way. It considers replacement, O&M, and fuel cost when making its analysis, as well as the value, if any, of the waste heat which is recovered from each generator.

Homer cannot calculate the payback or the internal rate of return because these calculations have to compare the economics of two different system configurations. A boiler is added immediately when a thermal load is added. Any shortfall of thermal heat is supplied by the boiler. The software can accommodate load profile with time intervals as small as 1 hour.

Currently no design tool exists for stand-alone power sources for small scale CHP systems. The required load profiles are over long periods of time considering CHP systems for buildings. Energy can be bought or sold from various sources. Homer version 2.5 is the only system which considers a realistic part-load condition for the power source, but it cannot compare different power sources.

None of the design tools can give a comparison between the performances of a power source against the load which is needed. Transient conditions from one load point to the next are not considered by any of the design tools. The design tools cannot make a suitable prediction from a list of power sources to satisfy the load which is needed.

2.9 Conclusions

The soya business unit is unique in concept, but simplified, it is a process which has to be supplied with electrical energy and thermal energy. The added uniqueness is that this business unit should operate in rural areas and has to be self-sustainable. This has led to part of this investigation aimed at finding suitable power sources for the business unit.

Different possible power sources are available, with some very promising power sources in terms of renewable energy. Dependency on sunlight or wind makes a power source less attractive because the reliability of the primary source is not guaranteed. The power source must be reliable, quick to react to load changes, easy to maintain and cost-effective.

The initial decision which was made to utilize a diesel generator, proved to be the best option for the remote application. Finding a suitable diesel generator for the business unit is straightforward if it is accepted that all energy will be supplied by the diesel generator in terms of electrical energy. The maximum electrical load has to be determined and the suitable diesel generator can be selected. This solution, unfortunately, has one major drawback and that is that the overall efficiency is between 29 % and 42 %, and using diesel as prime energy source, it will not be financially attractive to prospective entrepreneurs.

Due to the application of the business unit where electrical and thermal energy is needed, some of the waste thermal energy can be recovered and used for the thermal load of the business unit. Literature has shown that CHP systems are viable and up to 85 % efficient. The overall efficiency depends on factors such as the load management strategy being used, the quality of available heat and the quantity of available heat.

It becomes more complex to find a suitable power source which will utilize heat recovery technology to reduce the overall cost of a business unit. The characteristics of the power source are needed to make an accurate prediction. Literature has shown that very little trends exist with diesel generator sets, and to predict the outcome of an unknown diesel generator set from the known diesel generators, will result in inaccurate predictions.

A flexible design tool is needed to predict the possible power source which will be used. However, the accuracy of the final prediction depends on the accuracy of the data which is used. This includes the data which is used to determine the required electrical and thermal load, as well as the data for the power sources. The time scales which are used and the reaction times which are needed to satisfy the loads, are important for an accurate prediction.

Finally the prediction must be cost-effective and a financial model has to be adopted. Literature indicated that the most obvious models are LCC and NPV which can be adopted for any number of possible financial influences on the process. Both models have the same drawback, in that future predictions have to be done and a common study period is therefore needed. This leads to even more future estimates which are needed if the lives of items of equipment are not the same.

A financial model proposed to make use of the LCC, but to annualize all values to the current information and year, will simplify the model in that future estimations are not needed. The aim of the financial model is to simplify the information which is needed to make a final decision. The more estimated information which is used, the greater the possibility of making an inaccurate prediction.

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CHAPTER 3: CHARACTERISATION OF THE DIESEL GENERATOR SET

3.1 Introduction

Literature claims various performance parameters for internal combustion engines, and especially, the efficiency and possible heat available from exhaust gases and the cooling system. Although information and performance statistics are provided by suppliers of these engines, it is usually limited, or only specified at full-load conditions.

The load profile of the soya business unit is shown in Figure 17 and will be discussed in more detail in chapter 5. Initially 5 kW of energy is needed, which then increases to 35,3 kW at about halfway through the cycle and drops to 32 kW for the remainder of the cycle until the production of new batches is stopped. From this it can be seen that the power source will be operating at full load conditions for a short period of time and the remainder of the time will be operating at part load conditions.

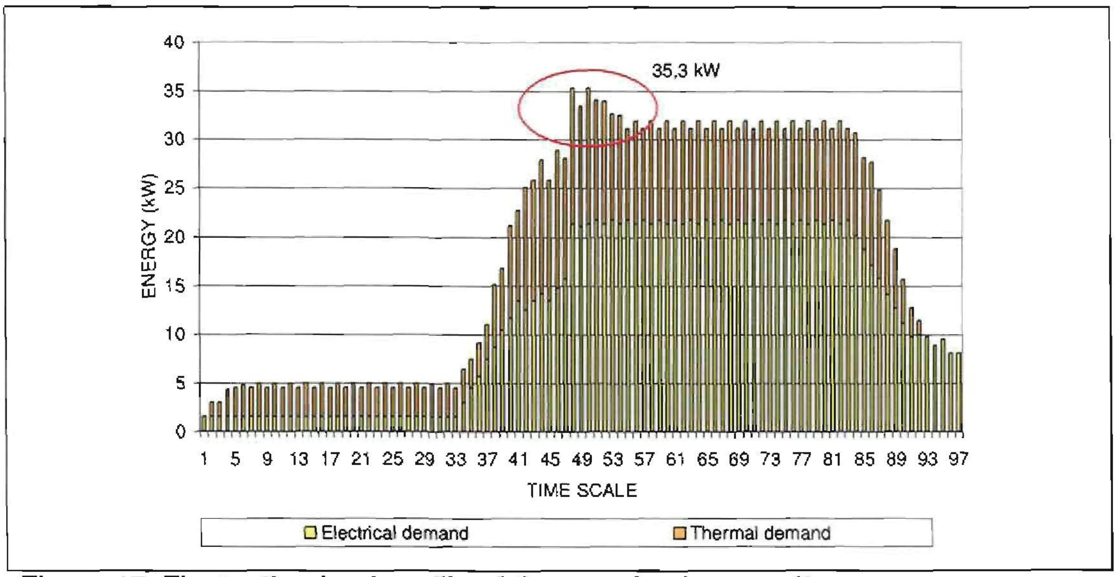

Figure 17: Fluctuating load profile of the soya business unit

Information in respect of part-load conditions is seldom available. This has led to the testing of a diesel generator set to verify the literature and to determine the efficiencies and available heat of an engine under part-load conditions.

The remainder of this chapter will discuss the experimental set-up of a diesel generator set that will be used in the soya business unit. The findings and results from the experimental set-up are also discussed.

3.2 Power source

The power source, a stand-alone Cummins power generator set, which was used during this testing, is one of the generator sets which will be used in the soya business unit. The generator set was installed in a laboratory to facilitate a better controlled environment for the testing. The loading of the generator was accomplished with electric hot water geyser elements which were connected to the generator. The outlay of the geyser elements will be discussed later.

The main power source was a Cummins Power Generator, Model Number ES 62,5. The engine was a model S3,8.G7, which was a 3,8 litre, four cylinder, turbocharged engine with inter-cooling between the compressor of the turbocharger and the inlet of the engine. The electric generator connected to the diesel engine was a Stamford AC generator model UC22F. Table 7 shows the specification of the Cummins Power Generator.

Table 7: Diesel generator set specification

Application	Prime power supply	
Rated power (kW)	50 (Prime)	55 (Standby)
Rated power (kVA)	63 (Prime)	69 (Standby)
Rated current (A)(0,8 PF)	91	100
Voltage (V)	230 / 400	
Frequency (Hz)	50	
Rotation speed (rpm)	1500	
Battery volts (VDC)	12	
Control system	D520	
Engine prime power (bhp)	76 (57 kW)	
Number of phases	3	

The diesel generator was set-up in an engine test cell as shown in Figure 18. This simplified the measuring of data as it is a controlled environment with standard equipment available, such as a fuel flow meter and air flow meter.

Figure 18: Cummins power generator set-up in laboratory

3.3 Data acquisition

Data acquisition was done with a Compact Fieldpoint cFP - 2020 Labview RT controller and input modules for the different measurements. A cFP – AI - 110 module was used for data acquisition of all the analogue 4 - 20 mA signals. A cFP – TC - 120 module was used for data acquisition of all the temperatures. Remote starting and switching off of the generator was controlled through a cFP – DO - 401 module.

Labview was used as the software interface with the Compact Fieldpoint controller. A Labview program was written to capture all data and store it in a comma delimited file which could be exported to Excel for further manipulation. The Labview block diagram is shown in Appendix B. The Labview program was written to do safety checks on the engine, especially on the temperatures. One of the most important safety checks was the electrical load on the three phases from the generator and to assure that an unbalance between the phases did not occur due to a failure of a heater element. This was accomplished by measuring the current flow through each phase of the generator. In the event of the currents differing significantly, the generator would shut down.

The user interface was written to assist with the display of values obtained during the testing, verifying of the fuel flow rate to the generator and to enter measured values which could not be read into the data file by the Fieldpoint controller. These values were the atmospheric pressure, turbo pressure and geyser element switching configuration.

The monitoring of data was used to establish stabilization conditions of the engine after load changes on the engine. Data acquisition was done every three seconds and values obtained after stabilization was used for calculation purposes.

Figure 19 shows the Labview user interface that was used to verify critical information like engine temperatures and current flow in each phase of the generator. The user interface displays the exhaust temperature, intercooler in temperature and the radiator flow rate, which was considered important to determine when the conditions have stabilized.

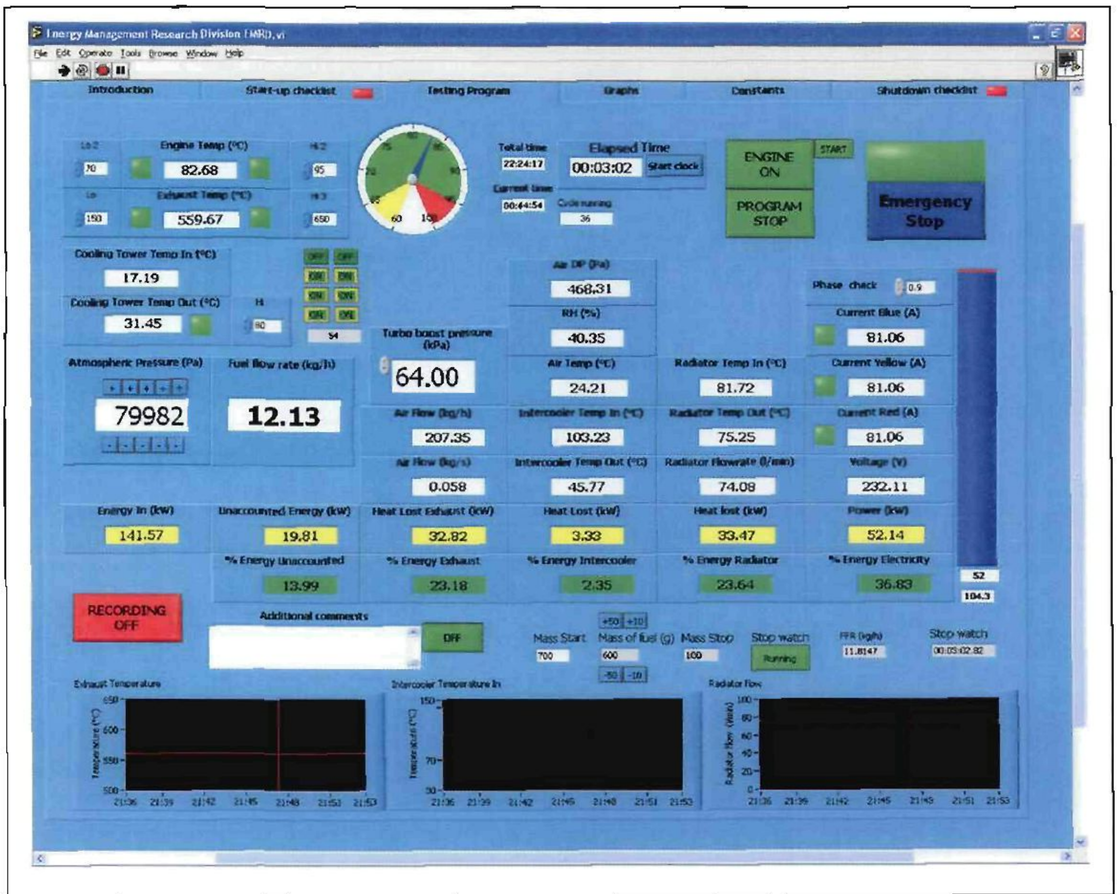

Figure 19: Labview front panel and user interface

The Labview program was used for the data capturing from the Fieldpoint controller. The data was stored in a comma delimited file with column headings which could be imported into Excel for further analysis.

3.4 Loading of the generator set

The generator set had to be tested at various loads. Industrial type geyser elements were connected to the generator to load the engine. The geyser elements were connected in star configuration between the three phases and installed in a water tank. The heat generated in the water tank was rejected through a cooling tower.

The 400 V three-phase electrical supply from the generator was connected in star configuration delivering 230 V between a single-phase and neutral. Two sets of 1 kW elements, totalling 3 kW each, and six sets of 3 kW elements, totalling 9 kW each, were used to apply a load onto the generator. The star configurations of the elements are shown in Figure 20.

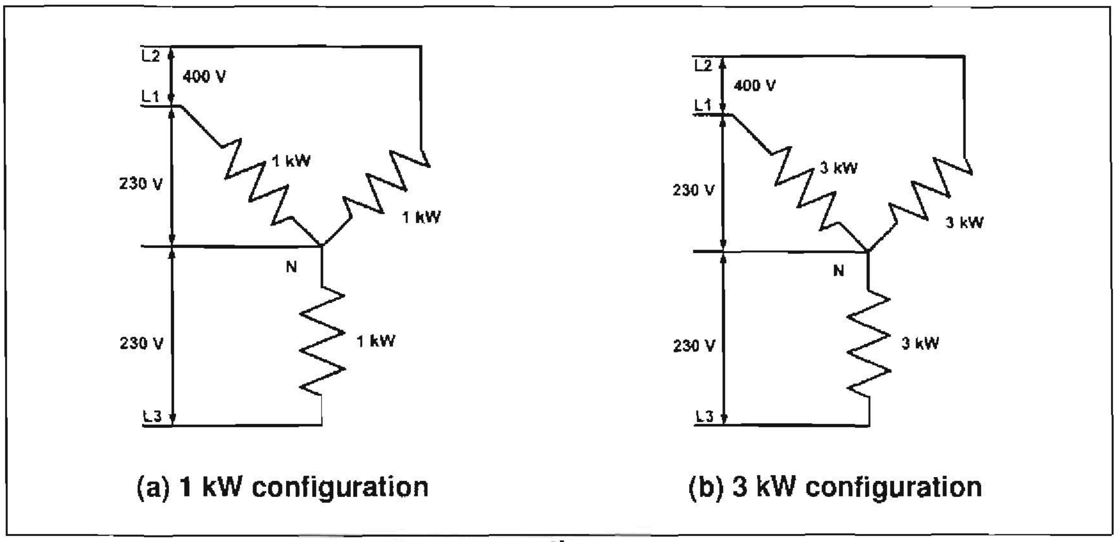

Figure 20: Geyser element configurations – three-phase star connection

The geyser element configuration mentioned above could load the generator set in 3 kW steps. A total of 20 loading points could be obtained over the range from no load to full load. The 3 kW sets of elements would load the engine with 9 kW in total and the 1 kW elements would load the engine in 3 kW increments.

The apparent power to the heater elements was measured with three current transformers on each phase and one voltage transformer between phase one and two. The real power was calculated with Equation (3.1) [1].

$$P_t = \sqrt{3}.V_L.I_L.\cos\theta \qquad (3.1)$$

where V_L is the line voltage (volts) between phases, I_L is the line current (ampere) or phase current and Cos θ is the power factor of a balanced three-phase circuit.

Each set of geyser elements was connected to the generator with a three-pole isolator and a three-pole contactor with a 230 VAC relay. This was done to simplify the switching in and out of the loads on the generator, obviating stopping the generator for adjusting the loads. The isolators were installed to isolate the elements in the event of maintenance or an emergency.

Measuring the current in each of the three phases was done with a LEM APR 400 - B420L series AC current transducer, with a measuring range of 0 - 400 A. The signal output was 4 - 20 mA and the accuracy of the current transducers was < ± 1 % of nominal current.

Voltage supplied by the generator was measured with a LEM ATVR D420L series voltage transducer, with a measuring range of 120 - 400 volts. The signal output was 4 – 20 mA and the overall accuracy of the voltage transducer was < ± 1 % and with a linearity error of < ± 0,5 %.

Voltage was measured between two phases and a more accurate calculation would have been obtained if the voltages were measured between all three phases. The fluctuation and differences between the phase voltages were verified with a handheld voltmeter and no significant differences could be detected.

3.5 Fuel flow measurement

A gravity flow meter, shown in Figure 21, was used to measure the fuel flow to the engine. Diesel is stored in a storage tank and pumped to the flow meter when required. When filled the gravity flow meter would hold 843 g of fuel. The fuel flow meter would start to fill when 100 g of fuel was left. This limited the available fuel for testing to 677 g. This influenced the time which the engine had to stabilize, as stabilization had to take place within the available 677 g.

Figure 21: Gravity fuel flow meter

Fuel flow measurement is taken as the weight of fuel consumed over a time period of 60 seconds. Once the fuel meter is filled with fuel the fuel flow rate would indicate a negative value, because the fuel has increased instead of decreased. It would take at least 60 seconds after refilling, before the fuel flow rate would be accurate. The average fuel flow rate is taken to eliminate any instantaneous fuel flow rate changes. It is very difficult to measure instantaneous fuel flow rate, due to the fact that an engine with an injection systems is supplied with more fuel than is consumed, and the surplus fuel is then fed back to the tank. In this case the surplus fuel is fed back to the fuel flow meter. The average flow rate over time is considered much more accurate compared to instantaneous flow rates.

At maximum power only about three minutes and twenty seconds were available for the flow measurement to stabilize, before the fuel flow meter ran out of fuel and had to be refilled. Calculating the time for the fuel to fill, and the time for the fuel flow to stabilize, added to about five minutes. Filling the fuel flow meter cannot take place at any point in time and therefore it was decided to work within the time available between fills. This implies that the engine had to stabilize within that time or that the engine had to run an additional fuel flow meter fill to obtain a reading. At lower loads it was not a problem, because more than one load setting could be measured with one fuel flow meter fill.

The fuel flow to the engine was additionally verified by hand. Verification was done by recording the time and weight of fuel used during the tests. Calculated fuel flow correlated with the gravity flow meter. Verification was done to assure that the values which were obtained from the fuel meter could be trusted.

Different brands of diesel could give different results and it was decided to use one brand of diesel for all tests. The lower heat value ($CV_{f,LHV}$) of the diesel was taken as 43,04 MJ/kg, and with a density of 813 kg/m^3 [2]. Specific heat capacity (C_p) of liquid diesel was taken as 1,93 kJ/kg.K from information which was obtained from the U.S department of transportation's CHRIS system [3].

According to a report from TSI Incorporated [4] the specific heat capacity (C_p) of exhaust gases varies with temperature and a good estimation is given as:

$$C_p = 0{,}0003 \times T_{flue} + 0{,}9782 \qquad (3.2)$$

The exhaust flue gas in the original equation was in degree Fahrenheit and the specific heat was in Btu/lbs. In Equation (3.2) T_{flue} is in degrees Celsius and the specific heat is in kJ/kg.K. The hydrocarbon fuel type has very little influence on the ultimate specific heat of the exhaust gas mix. Equation (3.2) was used to determine the specific heat capacity of the flue gas in the exhaust system.

3.6 Airflow measurement

Airflow to the engine was measured with a long radius nozzle in an air box with a damping chamber as shown in Figure 22. Air temperature and humidity of the air was measured with a Rotronic M1 transmitter. Air temperature accuracy was ± 0,3 K and the accuracy of the humidity measurement was ± 1 % of the relative humidity. Analogue output signals were 4 – 20 mA in both cases.

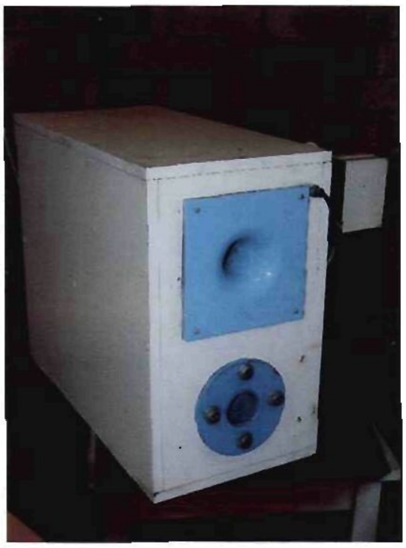

Figure 22: Long radius nozzle airflow meter with damping chamber.

The specification of the long radius nozzle was as follows:

Throat diameter (d) = 50 mm
Pipe diameter (D) = 110 mm
Length = 85 mm

Calculation of the flow rate was done according to the international standard ISO–5167-3 which was obtained from the ISANO website [5]. The mass flow rate (q_m) is determined as follows:

$$q_m = \frac{C}{\left(1-\beta^4\right)^{1/2}} \cdot \varepsilon \cdot \left(\frac{\pi}{4}\right) \cdot d^2 \cdot \left(2 \cdot \Delta p \cdot \rho_1\right)^{1/2} \qquad (3.3)$$

where q_m is the mass flow rate in kilograms per second (kg/s), C is the discharge coefficient of the nozzle, ε is the expansion factor, Δp is the differential pressure in the nozzle and ρ_1 is the density of the air.

The diameter ratio $\beta = \left(\frac{d}{D}\right)$ is the ratio between the throat diameter (d) and the pipe diameter (D).

The density of the air (ρ_1) is calculated by assuming that air is a perfect gas and is determined as follows:

$$\rho_1 = \left(\frac{P_{air}}{R_{air} \cdot T_{air}} \right) \tag{3.4}$$

where ρ_1 is the density of air in kilograms per cubic meter (kg/m^3), P_{air} is the atmospheric air pressure (kPa), R_{air} is the gas constant and taken as 0,287 kJ/kg.K and T_{air} is the air temperature in Kelvin (K).

The discharge coefficient of the long radius nozzle is determined with the following expression:

$$C = 0{,}9965 - 6{,}53 \cdot \left(\frac{\beta}{\mathrm{Re}_D} \right)^{1/2} \tag{3.5}$$

where Re_D is the Reynolds number.

The viscosity of the air (μ_{air}) was calculated by using Sutherland's law, as shown below [6] in Equation (3.6).

$$\mu = \mu_0 \cdot \left(\frac{T_{air}}{T_0} \right)^{3/2} \cdot \left(\frac{T_0 + S}{T_{air} + S} \right) \tag{3.6}$$

where μ is the viscosity of the air, μ_0 is the standard viscosity at 20℃ and taken as 1,80E-5 kg/(m.s), T_{air} is the temperature of the air in Kelvin, T_0 is 273,16 K and S is 110,4 K.

The expansion factor (ε) for the nozzle was calculated with:

$$\varepsilon = \left[\left(\frac{k \cdot r_p^{2/k}}{k-1} \right) \cdot \left(\frac{1-\beta^4}{1-\beta^4 \cdot r_p^{2/k}} \right) \cdot \left(\frac{1-r_p^{\left(\frac{k-1}{k}\right)}}{1-r_p} \right) \right]^{1/2} \tag{3.7}$$

where r_p is the pressure ratio and k is the isentropic exponent.

Reynolds number (Re_D) was obtained with:

$$Re_D = \left(\frac{4 \cdot q_m}{\pi \cdot \mu \cdot d} \right) \tag{3.8}$$

and the pressure ratio in the nozzle was determined with:

$$r_p = \left(\frac{P_{air} - \Delta p}{P_{air}} \right) \tag{3.9}$$

The long radius nozzle has to be used in accordance with the following limitations imposed by ISO-5167-3, as shown in Table 8.

Table 8: Limitations on a long radius nozzle

Long radius nozzle limitation of use	
Pressure ratio	$\geq 0{,}75$
Throat diameter	$d \geq 10{,}0$ mm
Pipe diameter	50 mm $\leq D \leq$ 630 mm
Diameter ratio	$0{,}2 \leq \beta \leq 0{,}8$
Reynolds number	$10^4 \leq Re_D \leq 10^7$
Relative roughness of upstream pipe	$R_a/D \leq 3{,}2E4$

3.7 Temperature measurement

Temperatures were measured by using type K thermocouples with stainless steel 316 probes which were directly read into the Fieldpoint controller with a thermocouple module FP – TC - 120. The thermocouples measured the exhaust temperature, the inlet and outlet temperatures of the coolant water, the inlet and outlet temperatures of the air to the intercooler and the engine temperature. The engine temperature was used for precautionary measures against overheating of the engine under full-load.

3.8 Radiator flow measurement

For determining the heat loss through the radiator, a flow meter had to be installed in the cooling system. It was important to limit the additional flow friction to a minimum to prevent a failure of the cooling system. The diameter of the flow meter was selected just bigger than the maximum size of the standard radiator pipes. The most compact flow meter was an electromagnetic flow meter. A Promag 10P DN50 electromagnetic flow meter was installed with a pipe diameter of 50 mm. The accuracy of the flow meter was better than ± 0,5 % of full-scale. The current output of the device was 4 - 20 mA with a supply voltage of 15 volts.

The installation specifications for the flow meter specify that the pipe to the flow meter must have a length of at least five times the diameter. The pipe from the flow meter has to be at least twice the diameter of the flow meter. Due to the limited space and to prevent additional friction in the cooling system, the minimum lengths were used. Figure 23 shows the installed flow meter with a 250 mm length pipe to the flow meter and a 100 mm pipe after the flow meter. The radiator coolant flows from the radiator down and then up through the flow meter and back into the engine.

Figure 23: Radiator flow meter installation position

3.9 General test procedures

The generator set was allowed to run under no load for 15 minutes to bring it up to temperature. During this time the temperatures were monitored until all temperatures stabilized, which indicated that the engine was warmed up.

Testing of the diesel generator was done by two different methods. The first method was to load the generator from no load to full-load, back from full-load to no load and then back again from no load to full-load in 3 kW increments. The second method was the opposite of the first method, where the engine was first loaded from full-load to no load, then back from no load to full-load and finally back from full-load to no load in 3 kW increments. These methods were followed to ensure that the data which was collected was consistent and repeatable.

During the testing, data was collected every three seconds, but only data collected after the engine stabilized was used for characterization of the engine. During initial set-up and installation it was noted that the exhaust gas temperatures, the intercooler inlet temperatures and the radiator flow rates, were the parameters which took the longest to stabilize and these parameters were used to determine if the engine had stabilized after load changes. Due to the small incremental changes of 3 kW or 5 % on the load, the engine stabilized in less than five minutes.

Figure 24 shows the exhaust gas temperatures and Figure 25 shows the intercooler inlet temperatures over time, after a load on the engine has changed. The top lines indicated changing the load on the generator sets from a high load at 57 kW to a lower load at 54 kW and the bottom line indicated changing the load from a lower load at 51 kW to a higher load at 54 kW.

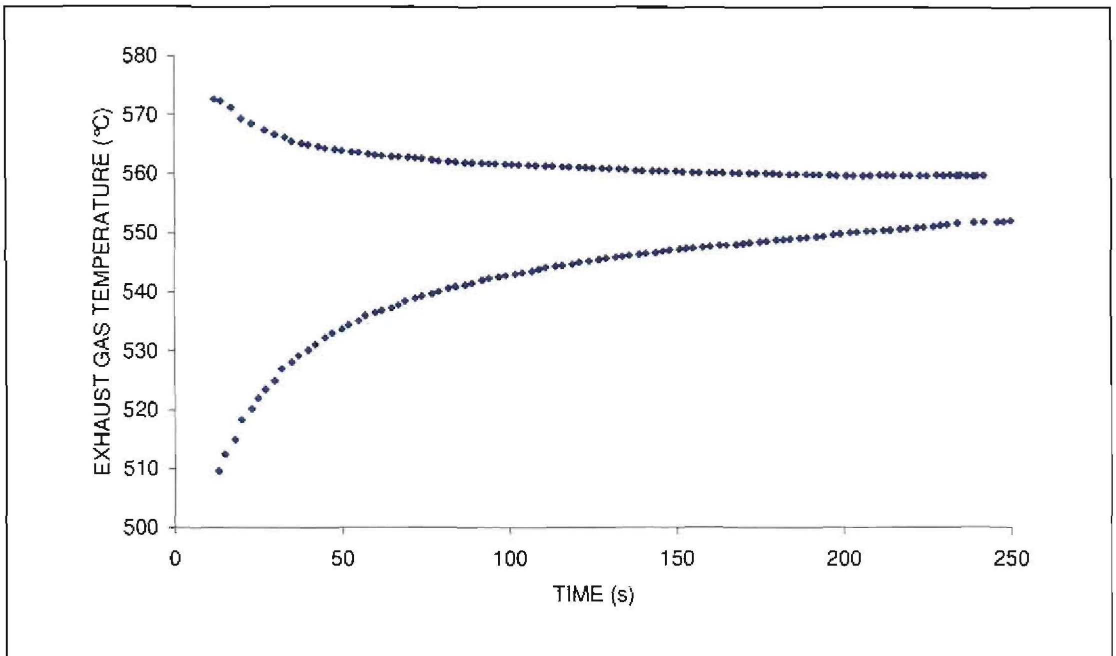

Figure 24: Exhaust gas temperature change with change in engine load

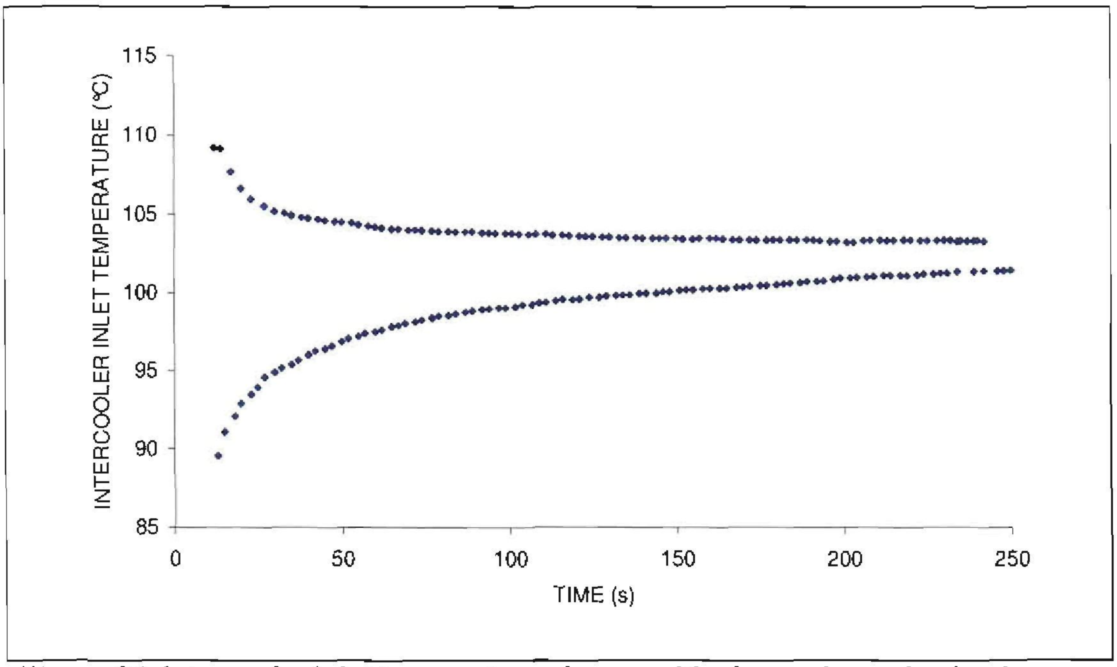

Figure 25: Intercooler inlet temperature change with change in engine load

The temperature differences were 7°C on the exhaust gas temperatures and 2°C on the intercooler inlet temperatures after 242 seconds. This was regarded as the biggest uncertainty in the measurement of the temperatures, due to the limitation of the gravity flow meter. This difference will lead to a maximum error of 1,3 % in calculating the available heat which could be recovered in the exhaust system. The maximum error in the calculation of the available heat which could be recovered from the cooling system is 2 %.

3.10 Test results

3.10.1 Fuel consumption and electrical thermal efficiency

Fuel consumption was measured with a gravity flow meter and verified with a stopwatch. Figure 26 shows the fuel consumption against the engine load. According to Eastop *et al.* [7] and Stone [8] the Willan line theory determines that the fuel consumption of a diesel engine running at a constant speed can be considered as a straight line when the engine load changes.

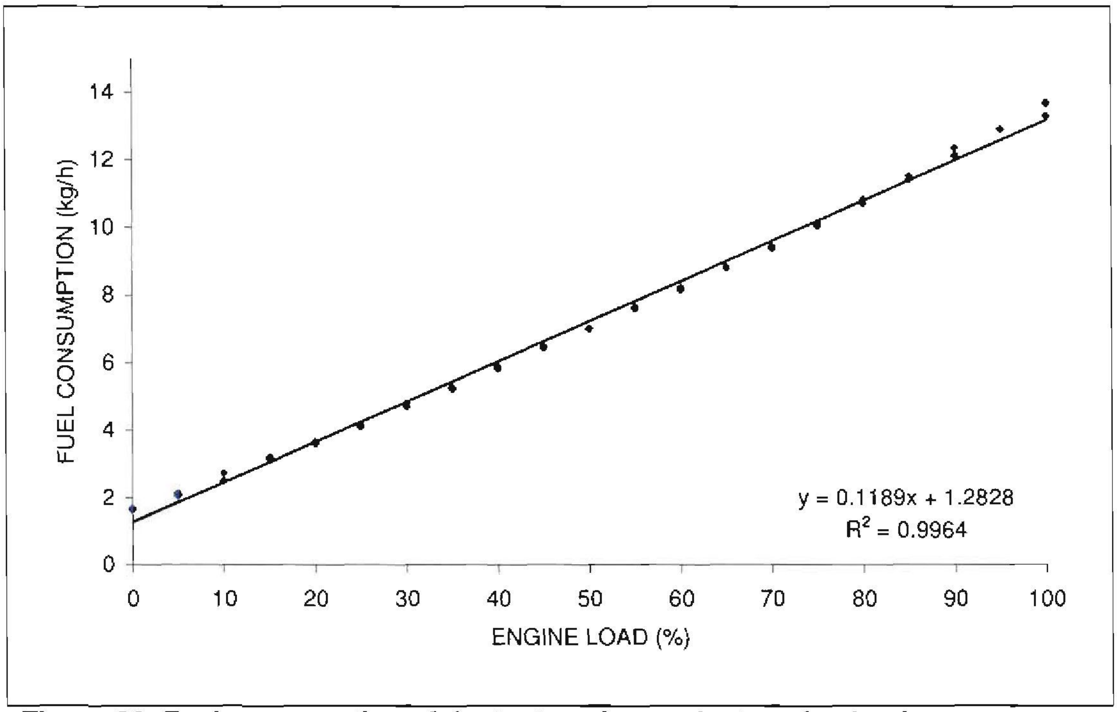

Figure 26: Fuel consumption of the test engine against engine load.

A straight line fitted to the data points obtained from the test gives a coefficient of correlation R^2 of 0,9964. The data obtained verifies the literature and fitting a straight line to the data will result in an accurate result. This data of the straight line was used to generate data in the design model which will be discussed later.

The energy supplied to the diesel generator set against the engine load is shown in Figure 27. The energy supplied (Q_{in}) to the engine was determined with:

$$Q_{in} = m_f \cdot CV_{f,LHV} \tag{3.10}$$

where m_f is the mass of fuel flow rate in kg/s and $CV_{f,LHV}$ is the lower calorific value of fuel in kJ/kg. The lower calorific value of the fuel will be used because the condensation of water in the exhaust gases will not be considered.

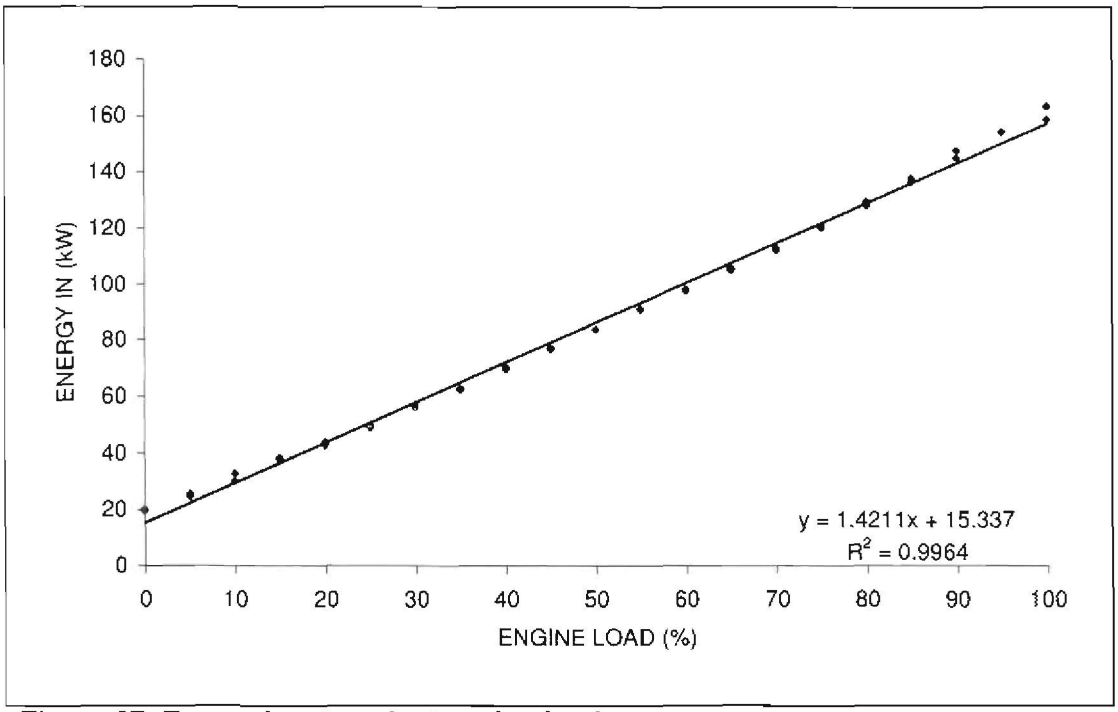

Figure 27: Energy input against engine load.

The electrical thermal efficiency is defined as the apparent electrical power available, divided by the energy supplied in the fuel. The electrical thermal efficiency of the diesel generator set is shown in Figure 28 and the defined equation is shown below.

$$\eta_{the} = \frac{P_e}{Q_{in}} \tag{3.11}$$

where η_{the} is the electrical thermal efficiency, P_e is the apparent electrical power and Q_{in} is the energy supplied by the fuel. A better efficiency will be obtained if the brake thermal efficiency of the engine is taken, but this does not represent the actual usable energy. Considering that the electrical power measured incorporates all electrical and mechanical losses in the generator set. The maximum electrical thermal efficiency obtained was 31 % at 100 % load and the electrical thermal efficiency was higher than 30 % from a 55 % of full-load upwards.

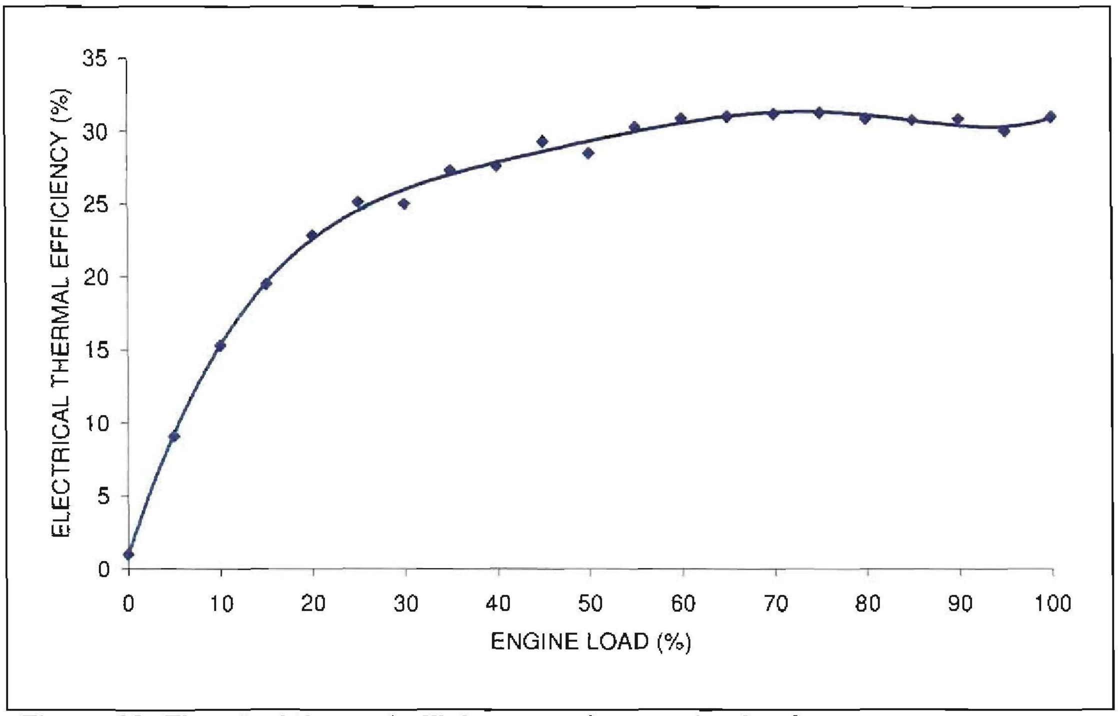

Figure 28: Electrical thermal efficiency against engine load

3.10.2 Exhaust gas heat loss

The exhaust gas temperatures were measured after the turbine of the turbocharger. The measured temperatures are shown in Figure 29. At no load the exhaust temperatures were 167℃, and increased to a maximum of 590℃ at full-load. Fitting a straight trend line to the data points produced a coefficient of correlation R^2 = 0,9869. A second order polynomial line was fitted to the data points and a coefficient of correlation R^2 increased to 0,9984, which represents a better fit for the data. It can be noticed from Figure 29 that the temperature tapers off as the load increases.

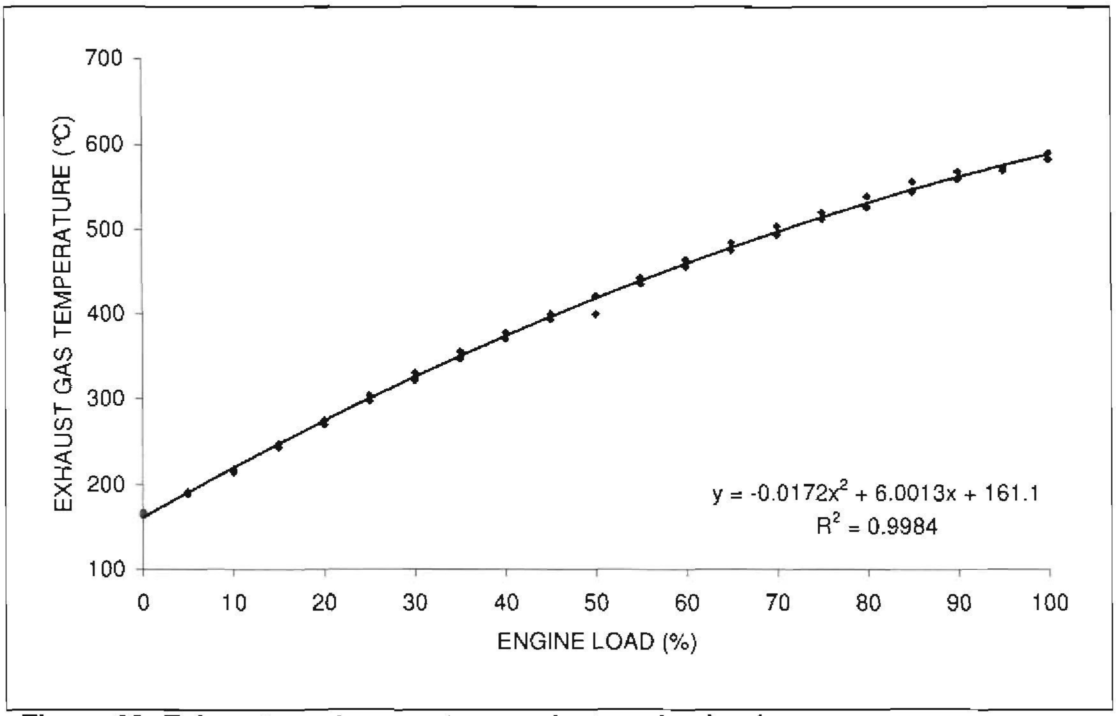

Figure 29: Exhaust gas temperature against engine load

The heat available in the exhaust gases was calculated by Equation (3.12):

$$Q_{exh} = (m_a + m_f) \cdot C_p \cdot (T_{exh} - T_{100}) \qquad (3.12)$$

where Q_{exh} is the heat available in kW, m_a and m_f is, respectively, the mass flow of air and fuel flow in kg/s, C_p is the specific heat capacity of the flue gases, T_{exh} is the maximum exhaust temperature at a particular load point and T_{100} is the temperature at 100°C. It was assumed that the heat in the exhaust gases will not be recovered beyond the point where condensation will start to take place and 100°C was taken as this limit.

The energy available which could be recovered from the exhaust gases is shown in Figure 30. A second order polynomial trend line was fitted with a coefficient of correlation R^2 = 0,9983, which represents a good fit for the given data. The available heat available at no load was 5,9 kW, which increased to 46,9 kW at full-load.

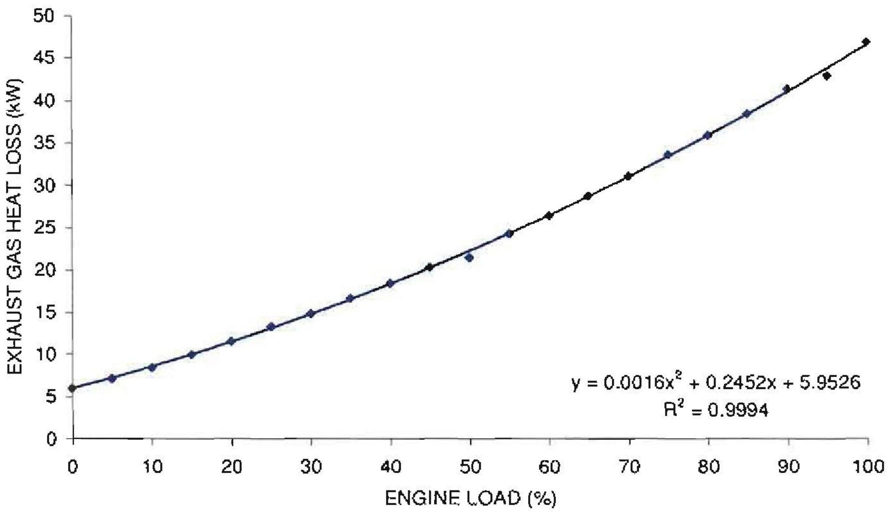

Figure 30: Exhaust gas heat loss (kW) against engine load

Expressing the available heat which could be recovered from the exhaust gases in terms of a percentage of the energy supplied, results in the data in Figure 31. The maximum heat available is at no load with a percentage of 29,8 which decreases around 50 % load after which it slowly increases to 29,1 % at full-load. The average heat loss in the exhaust over the full range is 27,3 %. This correlates with tests conducted by Taymaz [9] on a Ford turbo diesel engine where the available heat increased from 24 % to 29 %.

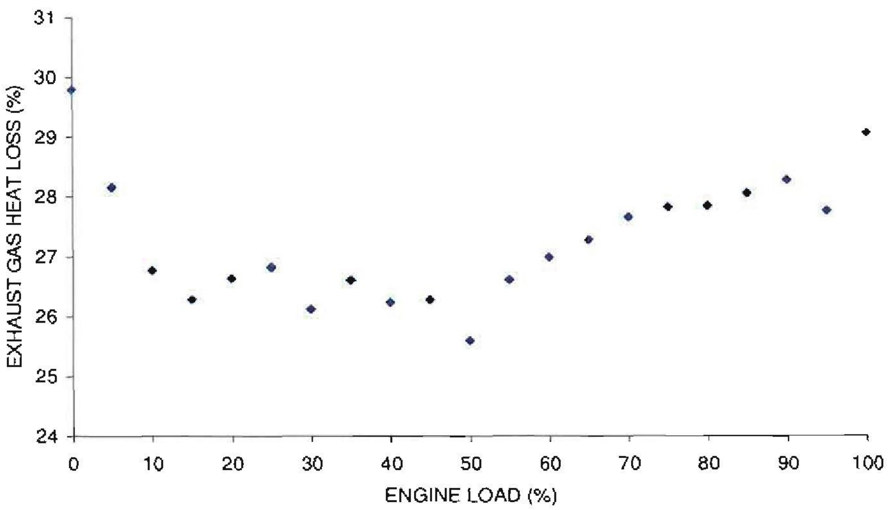

Figure 31: Exhaust gas heat loss (%) against engine load

3.10.3 Cooling system heat loss

The heat available which could be recovered in the cooling system was determined with Equation (3.13):

$$Q_{cool} = m_w \cdot C_p \cdot (T_{in} - T_{out}) \tag{3.13}$$

where Q_{cool} is the heat available in the cooling system in kW, m_w is the mass flow rate of the coolant fluid in kg/s, C_p is the specific heat capacity of the coolant fluid, T_{in} is the temperature into the radiator and T_{out} is the temperature out of the radiator.

The flow rate of the coolant fluid through the radiator is shown in Figure 32. No flow in the cooling system was noticeable at an engine load of less than 25 % of full-load or 15 kW. This was verified with loading the engine from no load to full-load and *vice versa*. This leads to the assumption that sufficient heat is lost through the convection and radiation from the engine itself, to maintain the engine cool enough for operation.

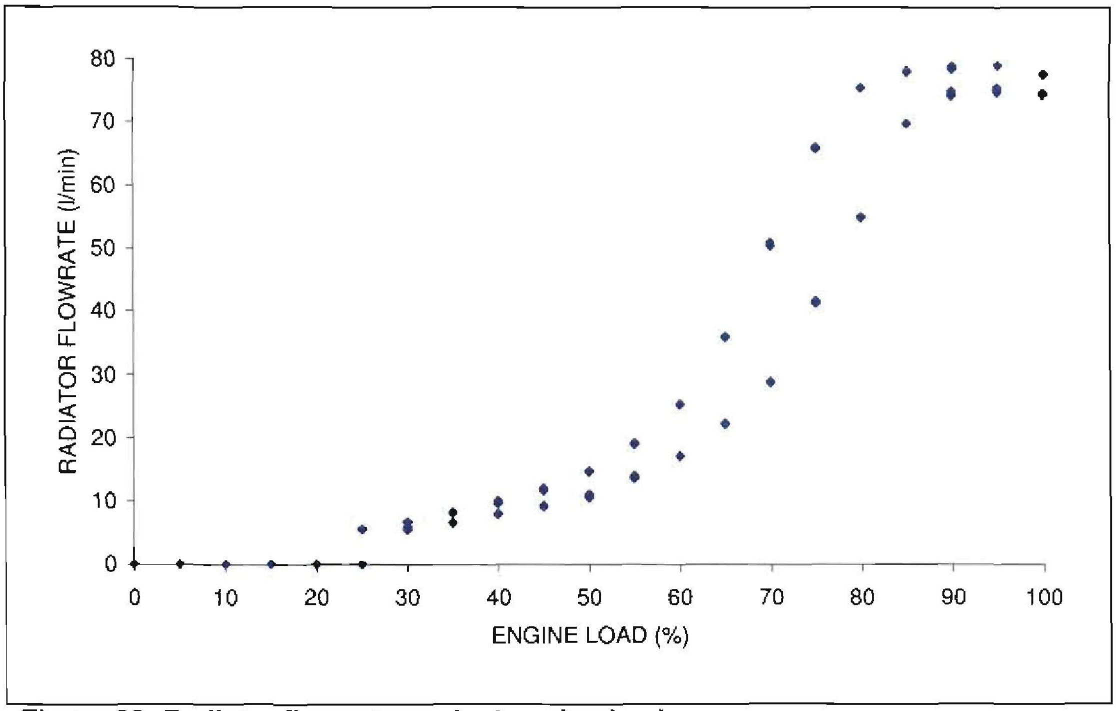

Figure 32: Radiator flow rate against engine load

The cooling fan pushes the cooling air through the radiator. Cold air passes by the engine and is pushed through the radiator for the cooling of the cooling fluid. This will increase the convection and radiation from the engine as in the opposite situation where the air is pulled through the radiator and the warm air from the radiator is blown over the engine. This will decrease the convection and radiation from the engine.

The available heat for recovery from the cooling system is shown in Figure 33. The minimum heat available is 14,1 kW_{th} at 25 % load. This increases to a maximum of 34 kW_{th} at full-load.

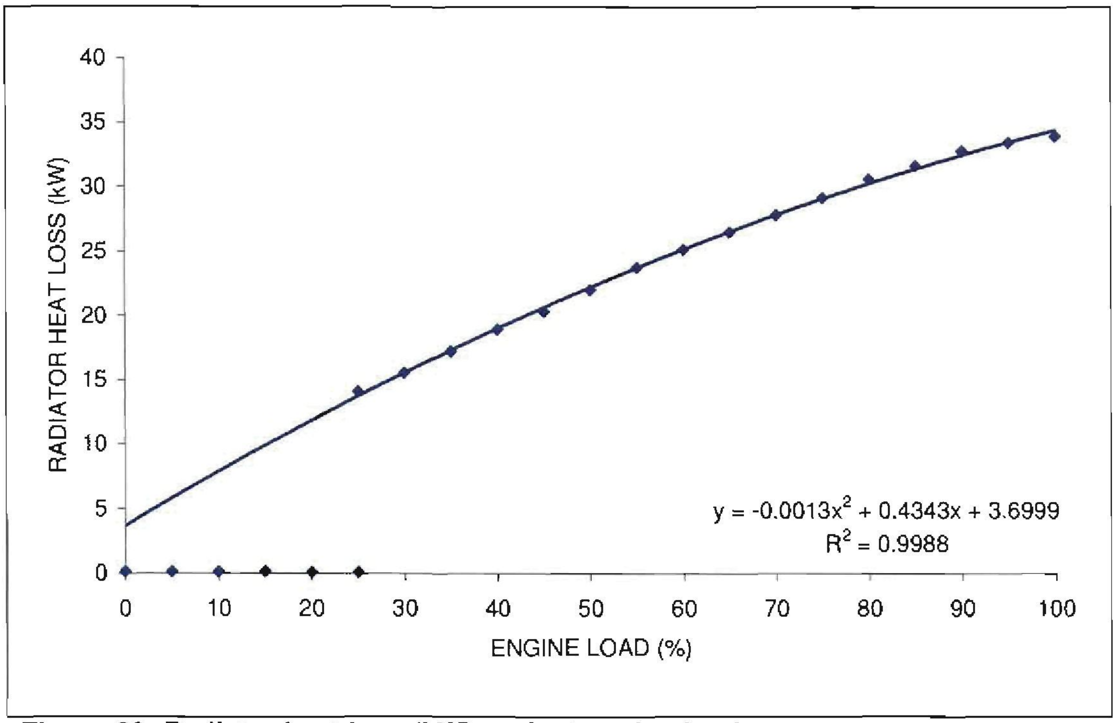

Figure 33: Radiator heat loss (kW) against engine load

Expressing the available heat from the cooling system as a percentage of the energy available, relative to the energy supplied to the engine, is shown in Figure 34. A maximum of 28,7 % is available at 25 % full-load. The available energy drops down to 21,1 % at full-load. The average percentage of energy available in the cooling system is 25,1 % between 25 % full-load and full-load. This trend was also confirmed by Taymaz [9] where the energy available in the cooling system decreased as the rated output increased.

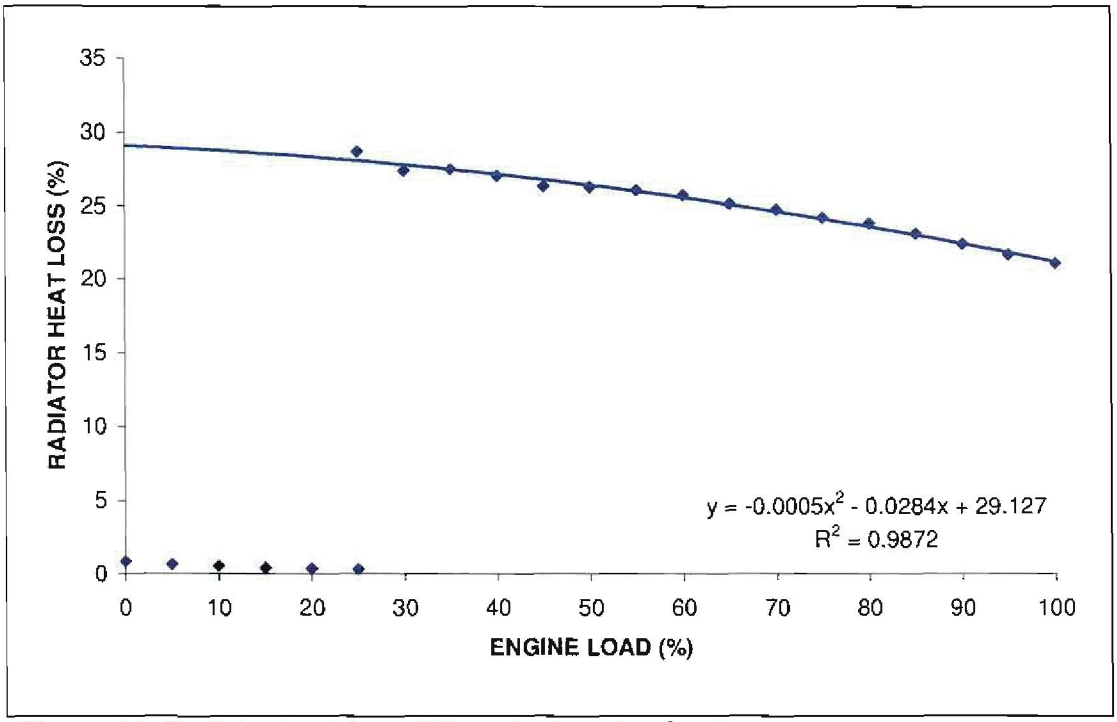

Figure 34: Radiator heat loss (%) against engine load

3.10.4 Intercooler heat loss

The heat available that could be recovered in the intercooler system was determined by Equation (3.14):

$$Q_{inc} = m_a \cdot C_p \cdot (T_{in} - T_{out}) \tag{3.14}$$

where Q_{inc} is the heat available in the cooling system in kW, m_a is the mass flow rate of the air in kg/s, C_p is the specific heat capacity of air, T_{in} is the temperature into the intercooler and T_{out} is the temperature out of the intercooler. The flow rate of the air through the radiator is shown in Figure 35. The flow rate started at 143 kg/h at no load and increased to a maximum of 235 kg/h at full-load.

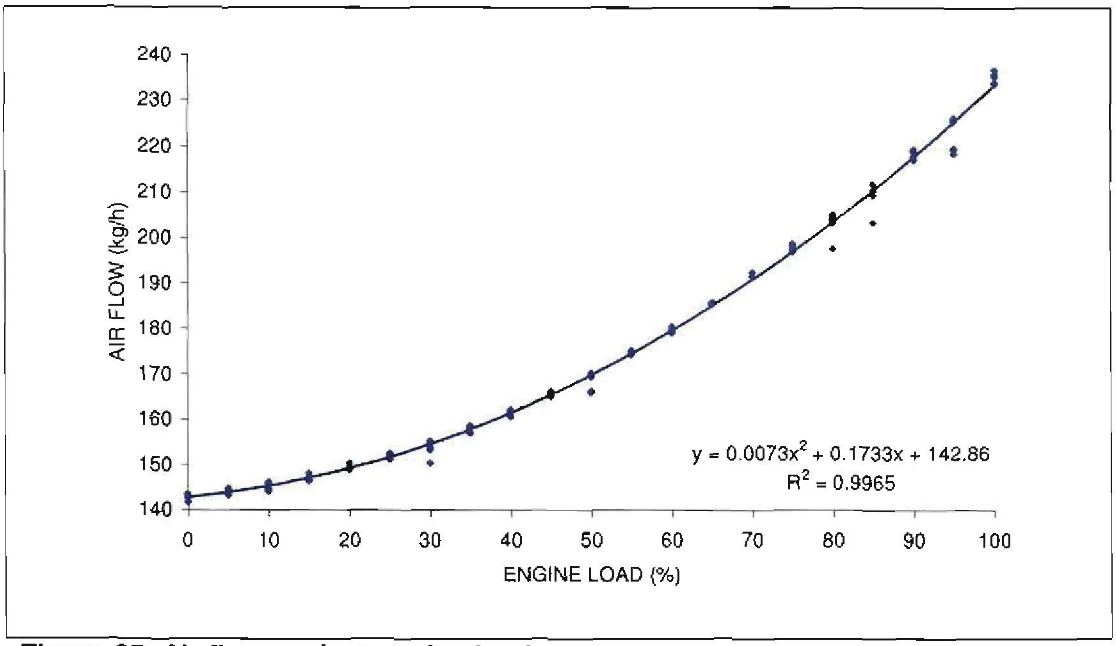

Figure 35: Air flow against engine load

The heat loss in the intercooler is shown in Figure 36. The minimum heat loss was at no load at a value of 0,2 kW and the maximum heat loss was at full-load at a value of 4,5 kW. Figure 37 shows the percentage heat loss relative to the input energy from the fuel. The minimum is 0,8 % increasing to 2,9 % at full-load. Recovery of heat from the intercooler from smaller power sources would not be financially viable, but it would become significant in larger power source applications.

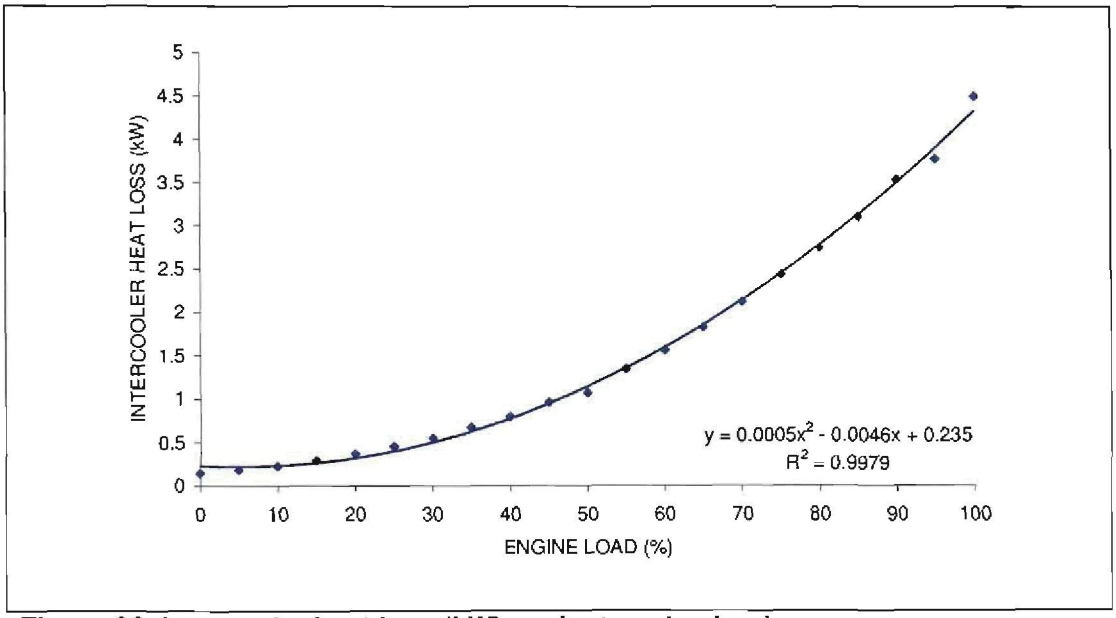

Figure 36: Intercooler heat loss (kW) against engine load

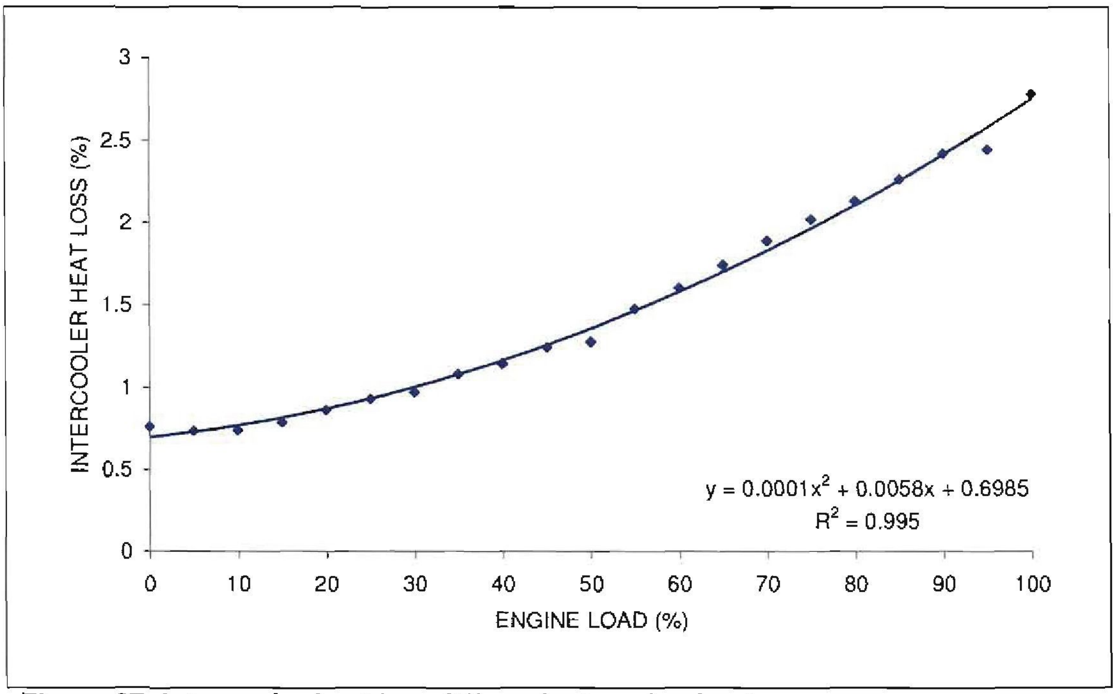

Figure 37: Intercooler heat loss (%) against engine load

3.10.5 Unaccounted heat loss

The unaccounted heat loss from the diesel generator set was defined as the energy which was not accounted for under electrical, exhaust, coolant or intercooler. It was calculated as follows:

$$Q_{unacc} = Q_{in} - P_e - Q_{exh} - Q_{cool} - Q_{inc} \qquad (3.15)$$

where Q_{unacc} is the unaccounted energy calculated from the energy which was measured. Figure 38 shows the percentage energy which is unaccounted for. At no load it is as high as 67,5 % dropping down to around 20 % at 30 % of full-load. The heat loss at loads higher than 30 % remains between 14,4 % and 18,3 %.

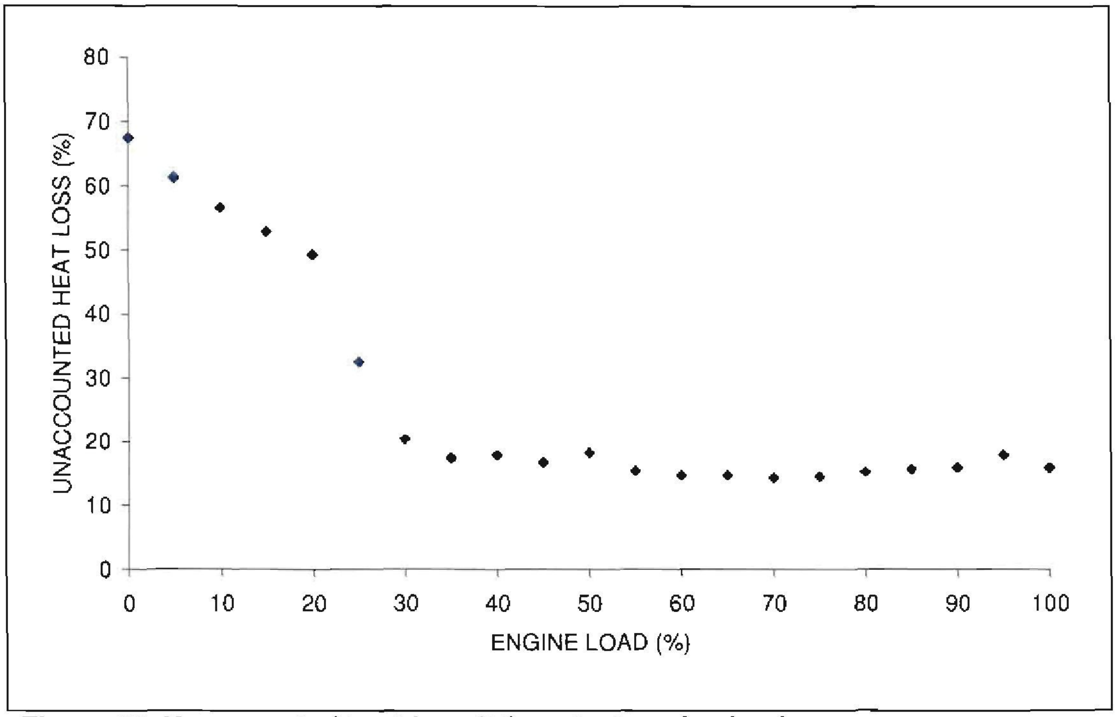

Figure 38: Unaccounted heat loss (%) against engine load

3.11 Conclusions

Literature has shown that the energy available from diesel generator sets is not consistent and predictable, but fluctuates. The results obtained from the tests conducted reiterate this. Predicting the energy available from an unknown diesel generator set by using the data from a known diesel generator set will result in an uncertainty which can be as high as 41 %, when unaccounted energy is used and the mean value is taken.

The results obtained from the testing were consistent and repeatable. Using these results at a particular load point will result in accurate predictions for this particular diesel engine. The use of average values for predicting the results will lead to errors. The use of results from this engine to predict the outcome of a different engine will result in errors. Using these results to indicate general ranges of operation correlate with literature, but cannot be used as a method for predicting an accurate outcome. Table 9 gives a summary of the energy available over the full range of the engine.

Table 9: Summary of energy available

Description	Energy available (%)
Electrical energy	0 % - 32 %
Exhaust heat	25,6 % - 29,8 %
Coolant heat	0 % - 28,7 %
Intercooler heat	0,8 % - 2,9 %
Unaccounted heat	14,4 % - 67,5 %

Figure 39 shows a summary of the energy available per possible source, relative to the output of the diesel generator. The no heat loss through the radiator up to 25 % of the load is noticeable in the figure and has a great influence on the prediction of energy available within the system.

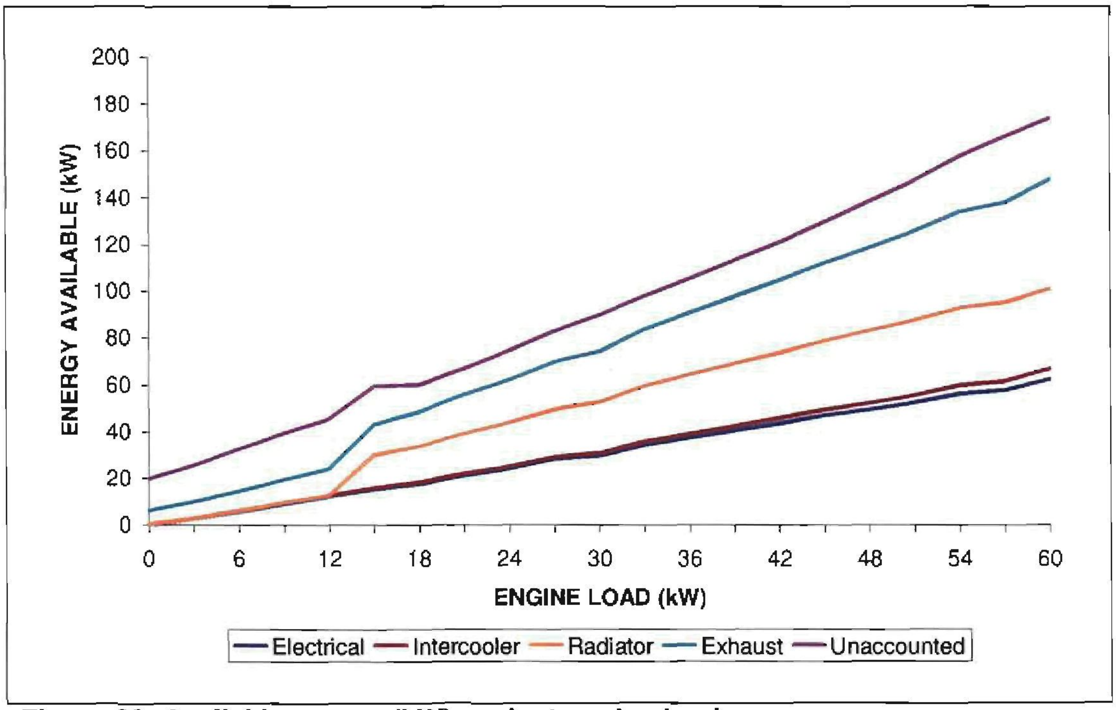

Figure 39: Available energy (kW) against engine load

The percentage of energy available per possible source is shown in Figure 40.

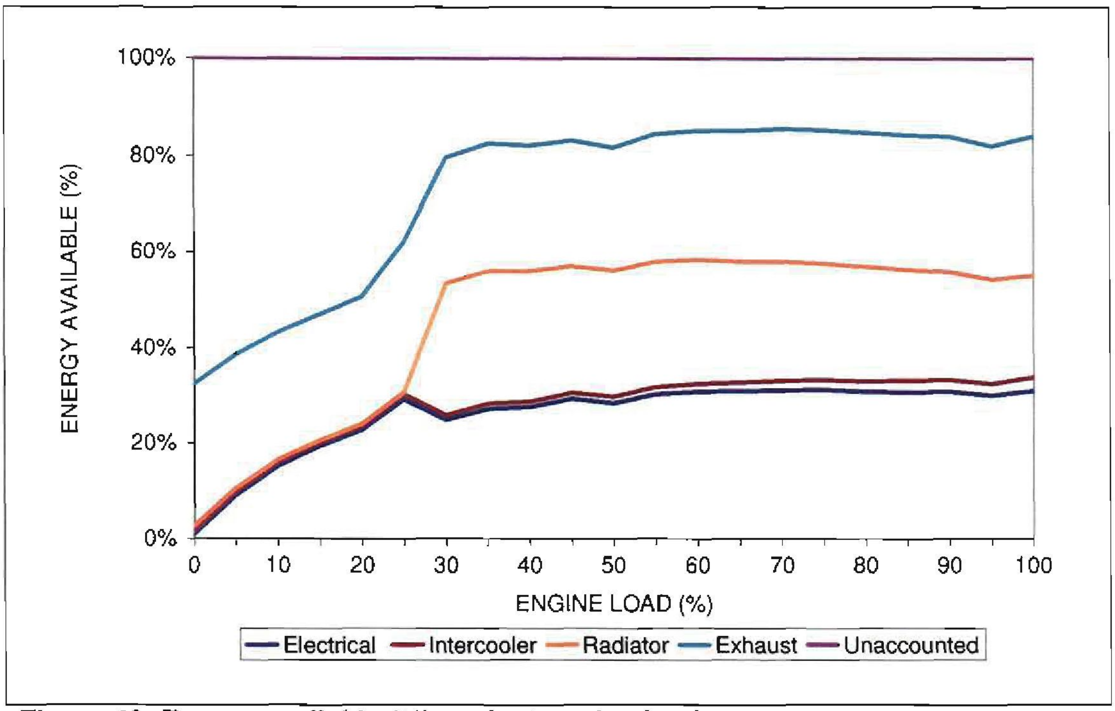

Figure 40: Energy available (%) against engine load

Ultimately more available data ensures more accurate predictions. The results demonstrated that trends exist and that, with a few data points available, one can make use of these trends to predict the outcome, but significant errors can be made if unique aspects are not foreseen or noticed. The radiator heat loss is a very good example of this. Any prediction for this engine at loads lower than 25 % would have been incorrect.

3.12 Bibliography

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CHAPTER 4: DESIGN MODEL

The aim of the design tool is to assist with the decision-making process by determining the optimum power source needed for a business unit when electrical energy, as well as thermal power is required. It will assist with the comparison of different options of components for the power source. The design tool was developed in the Microsoft Excel environment and, because it is a powerful tool, expansion with additional information can easily be done, data can easily be imported into the Excel environment and it is readily available and widely used in the world.

The literature discussed in Chapter 2 indicated various criteria that need to be considered with the design of CHP systems. The following assumptions were made with the development of this model:

- The CHP system will be electrical load following.
- No energy can be bought or sold from or to another system.
- No consideration was given to equipment degrading.
- No consideration was given to price escalation of equipment and fuel.
- Step changes of the load were not considered.

4.1 Design model outlay

Developing a design tool to accommodate different power sources, different fuels, different combinations of heat recovery equipment and looking at part-load conditions needs a flexible approach. Empirical equations can be used to describe each aspect of the information needed, but with a great deal of inaccuracy. This was highlighted by the literature which showed the inconsistency of data which can influence a final decision.

Figure 41 shows the basic outlay of the design tool with the main groups of information which were used in the design tool. The information was divided into four clusters; general data, heat exchanger data, power source data and the business unit load profile which was required. The reason for this division was to keep similar information together and to simplify the information which has to be manipulated. Within Microsoft Excel, manipulation of different data can be handled with ease, and the generation of quality graphs is easy.

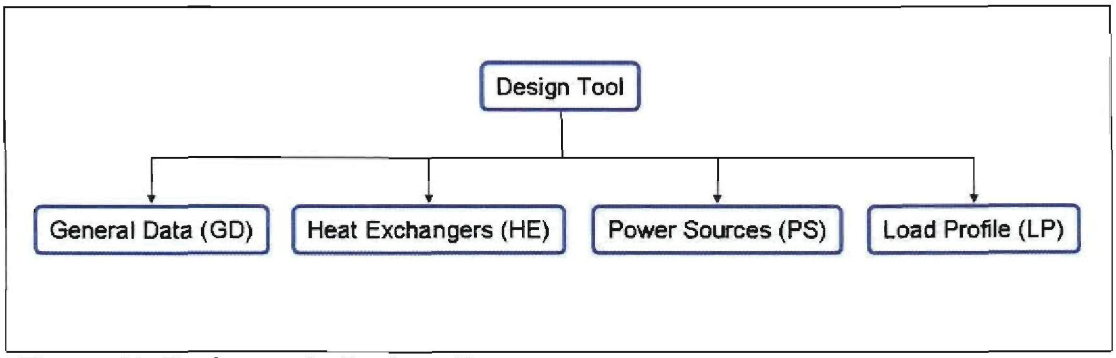


Figure 41: Design tool - Basic outlay

4.2 General data

General data was defined as data which is the same for all power sources and options and changing these values will influence all other power sources and systems. General data is divided into fuel information and the discount rate as shown diagrammatically in Figure 42.

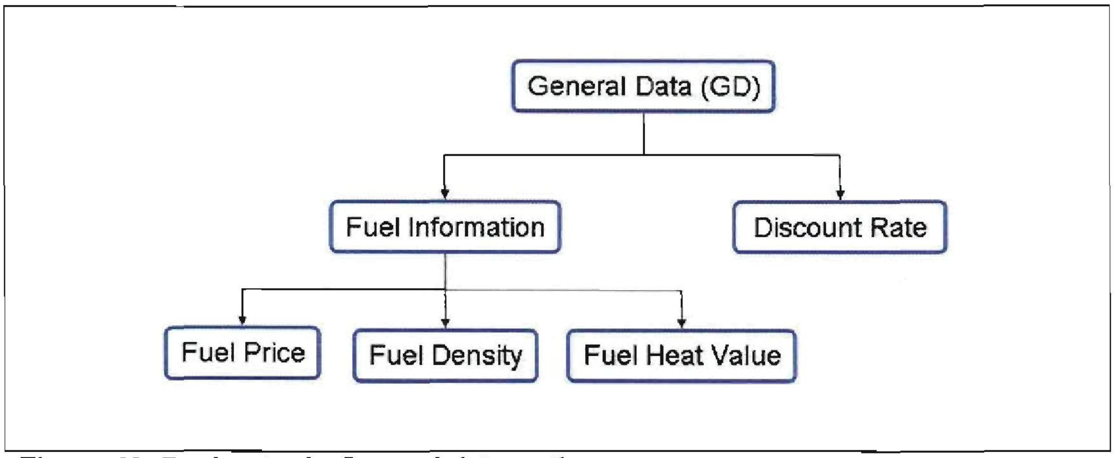


Figure 42: Design tool - General data outlay

Fuel information which was needed is the fuel price in Rand per litre (R/ℓ), fuel density in kilogram per cubic meter (kg/m^3) and the lower heat value in kilojoules per kg (kJ/kg). The lower heat value is used, as the assumption is made that the exhaust gases will not be cooled down sufficiently to utilize the heat of evaporation.

The discount rate, as defined in this design tool, includes all aspects which will have an influence on the future value of a capital expenditure. Inflation, interest and depreciation values must be calculated as one value before it is used as the discount rate. The discount rate is used to calculate the annualized value of the capital expenditure.

Net present value (NPV) regards the future and predicts the value in today's monetary terms. Net present values were not used in this design tool due to limitations and limited information about the base conditions. A common study period is needed for the net present value method and if power sources with different life expectancies are compared, additional information is needed.

The information which is required is the residual values of the equipment with the longest life, which includes the heat recovery equipment. In the event that a longer time is used for the study period than the lifetime of one of the power sources, an estimate has to be done of the future value of this power source. The accuracy of these values depends on the accuracy of the future estimation of prices.

4.3 Heat exchangers

The design tool does not limit the choice of heat exchangers, because many different types are available and are used in industry. The required information in respect of the heat exchanger is the capital cost and the expected life, which is shown in Figure 43.

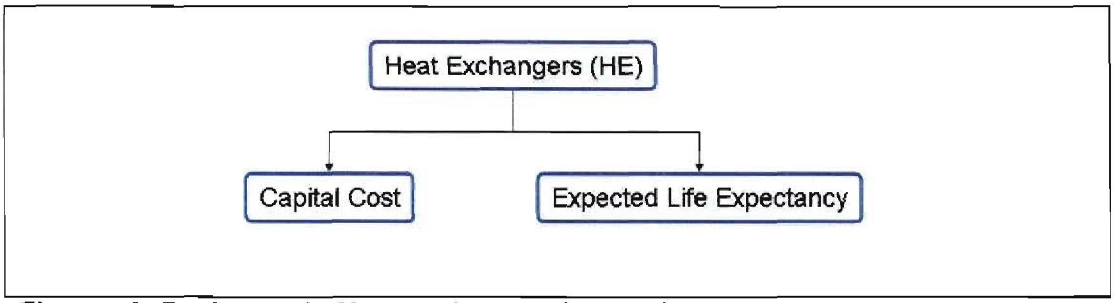


Figure 43: Design tool - Heat exchanger data outlay

The information entered is available from a dropdown list for each power source. The list of heat exchangers can easily be expanded to any number needed and is stored as a database of available information.

The capital cost of the heat exchangers are used to determine the initial capital expenditure, as well as the annualized cost of the heat exchanger. The life expectancy of heat exchangers are normally longer than that of the power source, but this information is used to calculate the annualized cost of the capital cost of the heat exchanger.

4.4 Power sources

Power source information forms the basis of accurate results when selecting the correct power source. The required information is divided into general data, part-load profiles of the power sources, and heat recovery equipment which is shown in Figure 44. Any power source can be used because the design model investigates the available electrical energy and thermal energy at different load conditions.

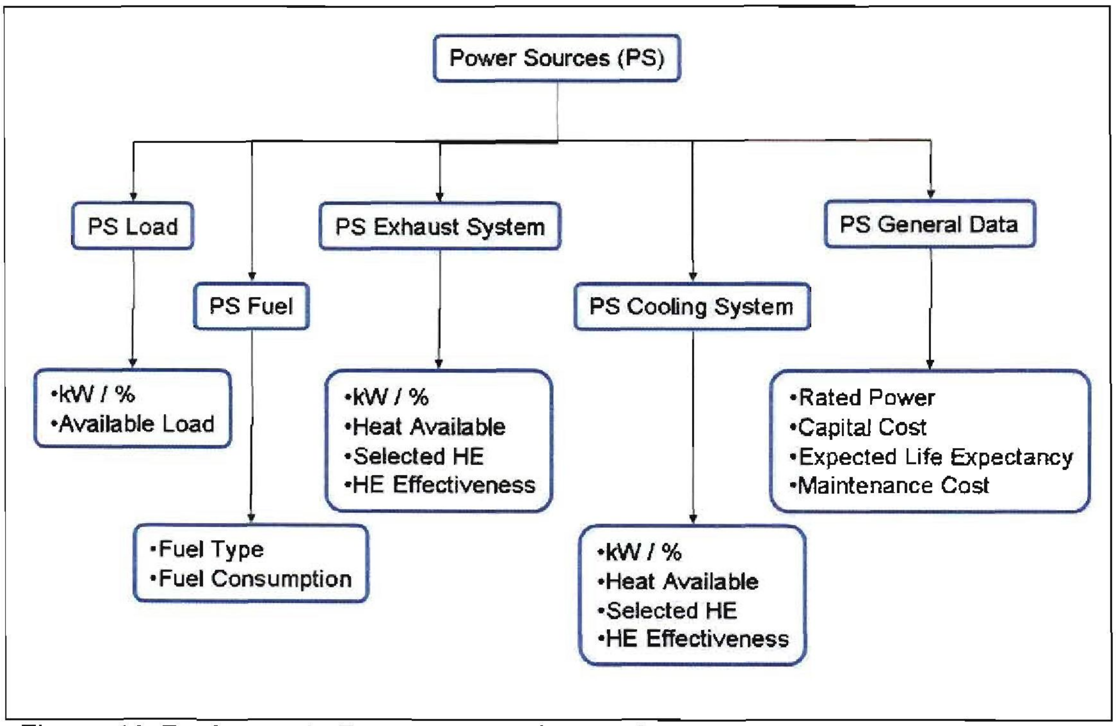


Figure 44: Design tool - Power source data outlay

The general data of all the power sources are entered on a single worksheet. The information which remains constant is the rated power and the life expectancy of the power sources. The information which will change over time is the capital cost and maintenance cost of the power sources.

Part-load profiles of each power source are entered on its own worksheet. This information is not readily available, but it is essential for accurate results. The information can be entered in kilowatts available, or as a percentage of the energy available at full-load.

Each power source can utilize a different fuel source, which can be selected from the previously entered data. Therefore, the same power source can be compared to different fuel sources. The fuel consumption is entered in kilograms per hour (kg/h). The density is used to convert the price of fuel from Rand per litre to Rand per kilogram. The lower heat value of the fuel is used to calculate the theoretical amount of energy available.

In selecting a standard power source to supply the required energy to a business unit, no heat recovery equipment will be added because it is assumed that all the required energy will be supplied by the electricity which is generated. In the event that heat is recovered and utilized, heat recovery equipment is selected for the exhaust system and the cooling system. Heat recovery can be done for the exhaust system, the cooling system or both.

The available heat which could be utilized can be entered in available kilowatts or as a percentage of the input energy available. Heat recovery equipment can be selected from the available list of equipment which was entered earlier. It is important that accurate data is available and used. An example is where no cooling system heat is available at certain loads as in the case of the tested diesel generator set which was discussed in the previous chapter.

The effectiveness of the heat exchanger is required to determine the amount of heat which could be recovered at part-load conditions. The assumption of the design tool is that the effectiveness of the heat recovery equipment will vary as the part-load conditions change.

4.5 Load profiles

The information required for the business unit load profile is the time and the energy needed, as shown in Figure 45. The time used in the design tool can be defined by the user and any possible time can be used, ranging from minutes to days. The energy required is electrical energy and thermal energy per user-defined time intervals.

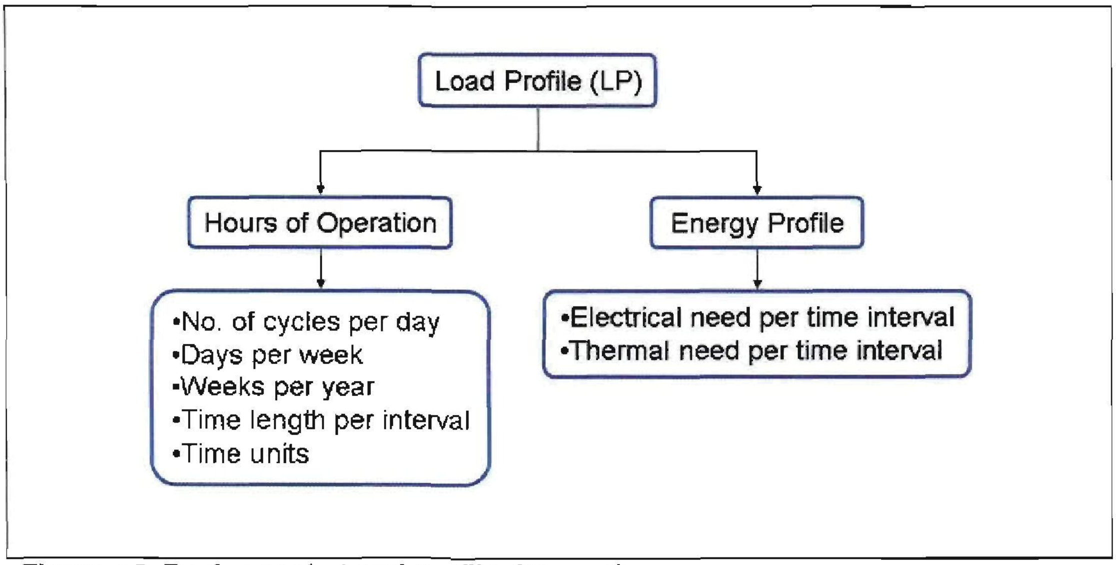


Figure 45: Design tool - Load profile data outlay

The hours of operation are determined by the user-defined information. The user information required is the time per time interval, the number of cycles per day, the days of operation per week and the number of weeks of operation per year. The assumption is made that a single cycle is completed before the next cycle will commence. Overlapping cycles must be entered as such by the user.

4.6 Design model outputs

The data entered by the user is calculated to determine the available electrical and thermal energy for each power source. The running cost of each power source is calculated, based on the capital cost for the power source, the capital cost for the heat recovery equipment, the maintenance cost and the fuel cost. All power sources which can supply the required energy to the business unit, are identified. The identified power source with the lowest running cost is selected as the preferred power source. This initial selection is based on the maximum electrical and thermal energy which is needed by the business unit.

The user can select any other power source to be compared with the recommended power source. The design tool will analyse the recommended and selected power source by regarding every time interval of the load profile and calculating the overall cost per time interval. The cost per cycle is determined and finally the annual cost is determined.

The design tool does not provide for interpolation between data points from the power sources and the lowest load point of the power source which can supply the required energy is selected. If the business unit requires more thermal energy, than which is available from the power source, the design tool assumes that the additional thermal energy will be supplied by additional electricity from the power source through some heating system. No consideration was given to potential losses when electricity is converted to heat. The design tool does not consider the transient conditions from one load point to the next.

The calculated values are summarized and displayed to the user in a single view. The displayed information is shown in Figure 46.

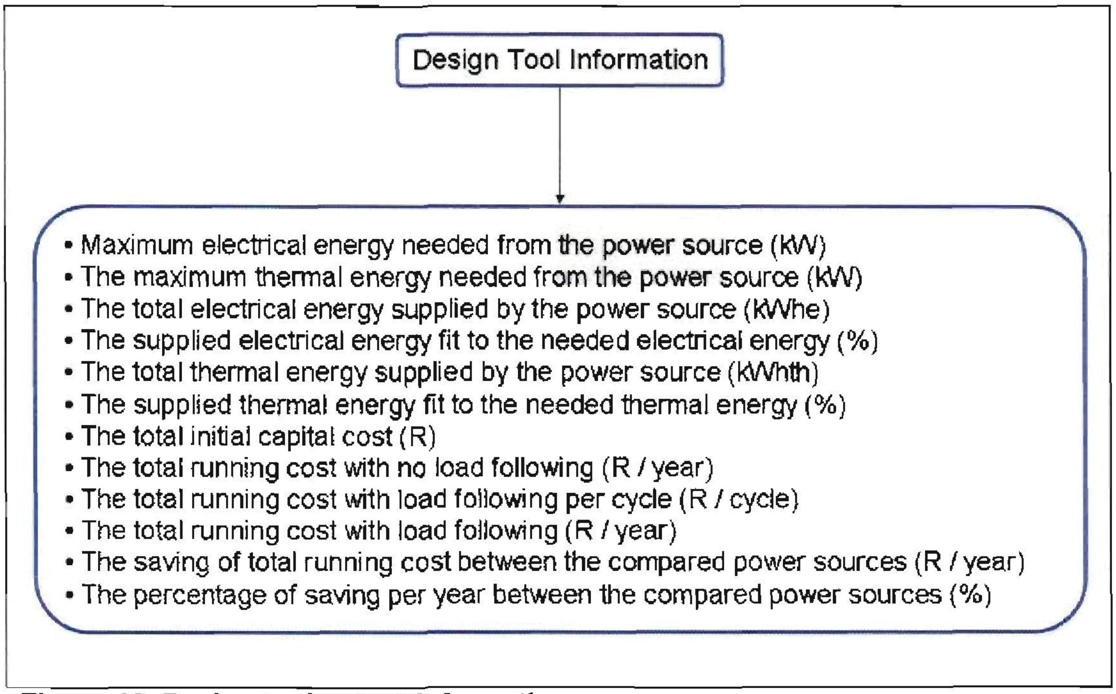


Figure 46: Design tool output information

The running cost per year for all the power sources are shown in Figure 47. The running cost was determined by annualizing all investment cost to an annualized present value after which the annual running cost was added. In determining the running costs it was assumed that the power source would operate at the minimum energy required to satisfy the maximum load. The power sources which would not be able to supply the required energy are highlighted in the darker area of the graph.

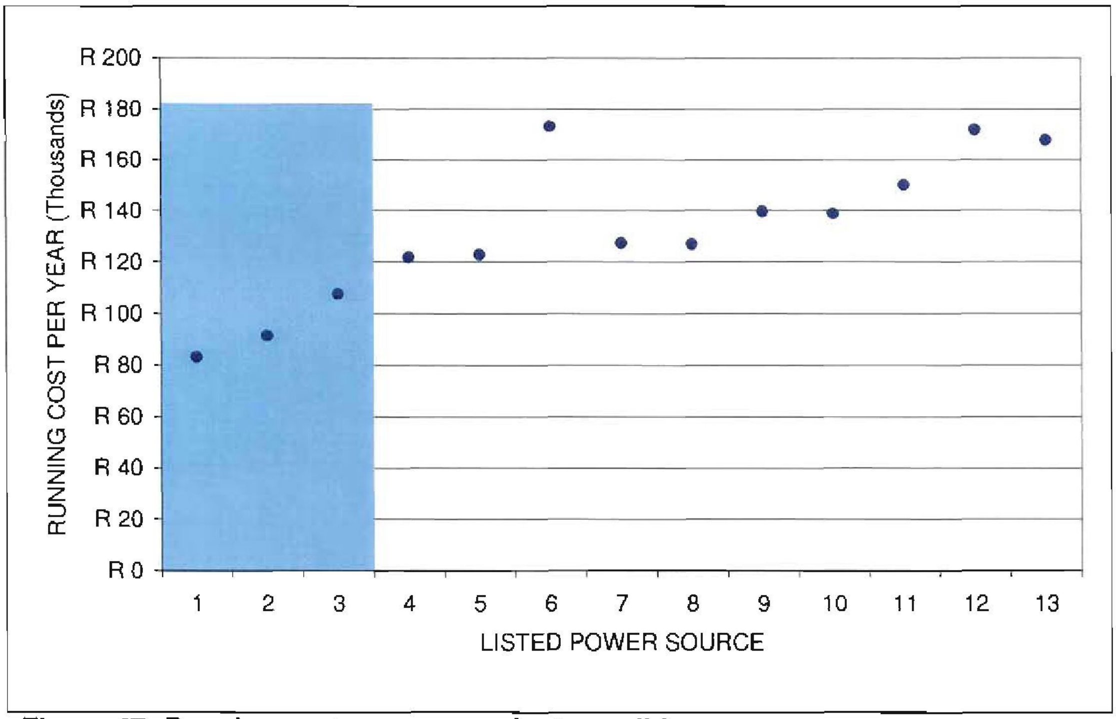


Figure 47: Running cost per year against possible power sources

The information used was from a comparative study for the business unit. All the power sources available had heat recovery equipment, except for power source number 6. Power source number 6, a 38 kW diesel generator set, had no heat recovery equipment because it was selected as a standard power supply. Power source number 6 was compared to power source number 4, a 25 kW diesel generator set, which was the power source recommended by the design tool.

It is evident from Figure 47 that power source no 13, a 175 kW diesel generator with heat recovery equipment, will be more cost-effective than power source number 6, a 38 kW diesel generator set, without heat recovery equipment. In comparison the initial capital cost for power source number 13 is R 243 500,00 compared to R 35 700,00 for power source number 6 and the running cost per year for the fuel is respectively R 125 800,00 and R 163 700,00 for the 175 kW and the 38 kW diesel generator set.

4.7 Conclusions

The design tool which was developed addresses all major inputs which can influence the process of making a decision, except for incorporating heat recovery from intercoolers for charged internal combustion engines. It was assumed that the cost involved in recovering heat from this source of heat will not be financially viable.

The features of the design tool are as follows:

- Flexible time intervals for the load profiles of the business unit. Time intervals can be predefined in minutes, hours or days.
- Different fuel sources can be compared.
- Independent from the type of power source and different power sources producing electricity and thermal energy can be used.
- Part-load conditions of the power sources are considered for each of the time intervals. Part-load conditions are calculated to the smallest load that could supply the required energy.
- Comparative studies can be done between power sources.
- Optimization of components can be investigated.
- Total annualized cost includes capital cost of the power source, capital cost of the heat recovery equipment, the maintenance cost and the fuel cost.
- The capital cost is annualized per year to simplify the assumptions which need to be made with estimations of future values.
- No consideration was given to cost due to environmental effects. It was assumed that all power sources will comply with the minimum environmental regulations.
- The effects of change in atmospheric conditions were not considered. Data supplied by the manufacturers are at sea level and at around 15°C. When these power sources are utilized at different altitudes or temperatures, it will be assumed that the percentage loss in power will be the same for all power sources.
- No escalation of prices for the equipment was considered.
- No degrading of equipment was considered.
- No consideration was given to the possibility to buy electricity from the grid or to sell electricity too the grid. The design tool was designed for standalone

systems and selling electricity back to the grid is regulated and not possible within South Africa.

- The management system of the design tool is driven by electrical demand and excess thermal energy is discarded into the atmosphere.
- No consideration was given for the transient conditions between load points. These transient conditions are influenced by the type of product being produced in the business unit, as well as the heat transfer properties of the equipment being used.

CHAPTER 5: VERIFICATION OF BASE MODEL

The soya business unit project started in 2001 and is still in a developmental phase. Although most of the separate systems in the business unit have been tested, it has never been tested as one complete unit. A complete base model of the business is, therefore, not available, but a base model will be assumed, based on the information known and calculated from the different sub-systems.

The main consideration for the business unit was initially a choice between batch processing or continuous processing of the soya beans. The biggest drive was towards the batch process, because it is much easier to clean the equipment compared to the equipment of the continuous processes. The business unit will be operated between normal working hours and the continuous process is not suited for intermittent times of operation. The equipment needs to be cleaned and flushed after every shutdown to prevent blockages.

5.1 The basic business unit

The basic process of producing any food from soya beans is shown in Figure 48. The soya beans have to be soaked in warm water at 50°C for three hours to hydrate and soften. Thereafter the soya beans are cooked at 95°C for ten minutes. This process releases some of the enzymes from the soya beans, which make it indigestible to humans. The beans are rinsed and cooked for another 10 minutes at 95°C. Finally the soya beans are rinsed and 10 kg of beans are blended with 25 litres of water at 60°C. This will produce mainly two products – soya milk (jun) and soya slurry or also called okara. These two products are then separated and used for different food products.

Soya milk is converted into products such as milk, yoghurt and ice cream, to name a few. Okara is converted into products such as meat replacement products and dough for food, e.g. bread, pizzas and biscuits. The above-mentioned processes utilize electricity and heat as part of the production process.

Electrical and thermal energy of the processes has to be identified and classified. Although many of the processes make use of thermal energy, not all can be extracted from the waste heat of the power sources because the quality of thermal energy is not sufficient. Baking food in an oven at 200°C requires a thermal energy need which will not be met by the recovered heat from a power source.

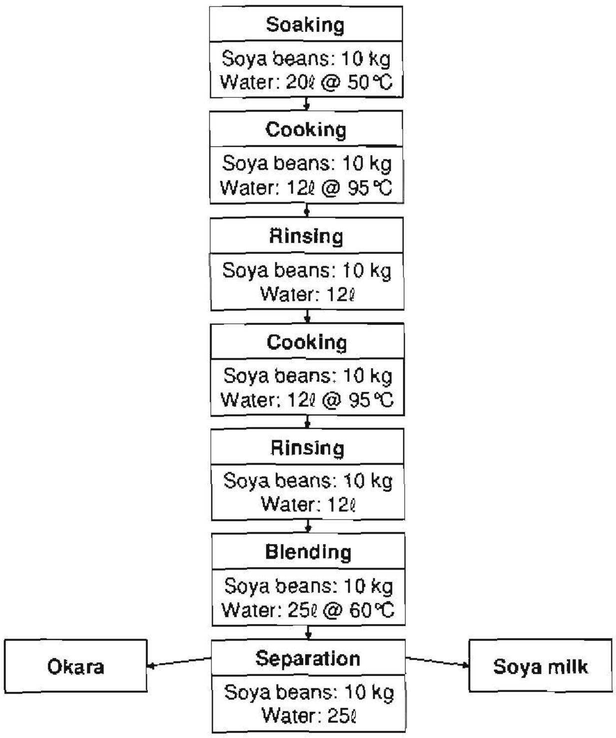


Figure 48: Soya bean preparation process

5.2 The energy required

A total of 25 batches of soya beans can be produced per day. This equates to around 3 000 meals per day. Each 10 kg of dry soya beans will yield around 20 kg of okora and 15 litre of soya milk. These base products will then be converted into different products, as demanded by the consumers.

The soya business unit energy load profile was shown in Figure 17 and is shown in Figure 49 again. This energy load profile of electrical and thermal energy will produce one day's food supply, or 25 batches. The electrical energy initially required is limited to auxiliary equipment until the soya beans are soaked and cooking starts, and the thermal energy is needed for the soaking of the beans. The total energy required peaks at around 35 kW at the point where the last batch is started and all the batches are in process.

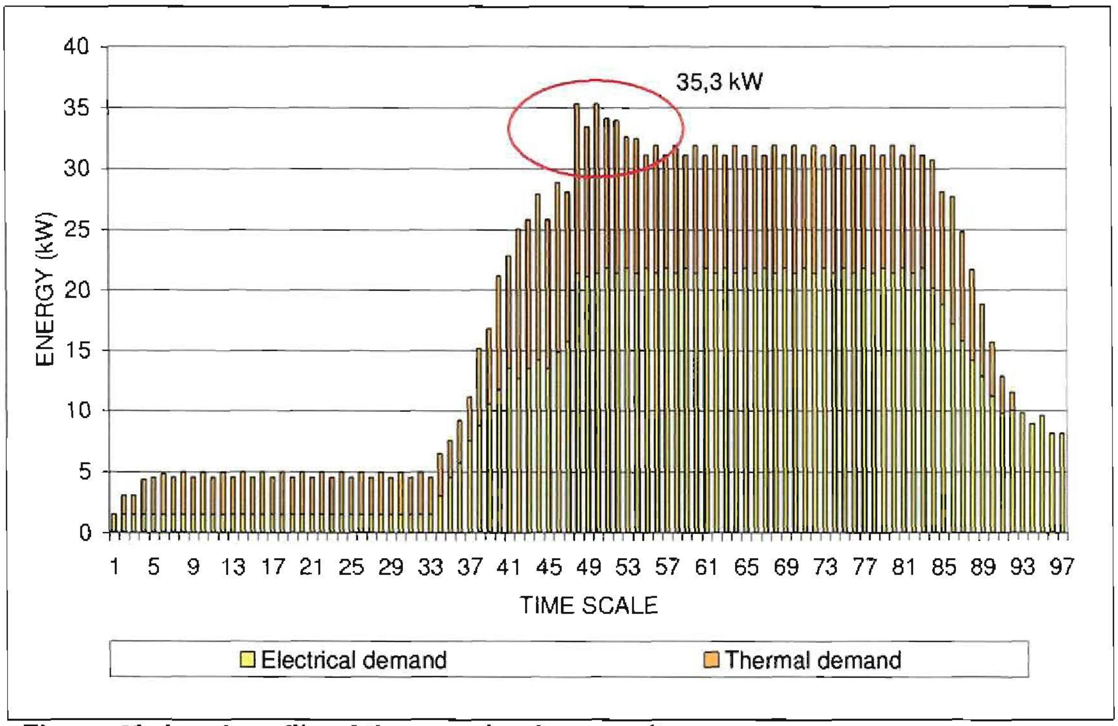


Figure 49: Load profile of the soya business unit

The time for one cycle, or 25 batches, is just over 8 hours, which is a total of 97 five minute time intervals. The assumption was made that the business unit will be in operation for six days per week and for forty-eight weeks per a year. This equates to 2328 hours of operation per year.

5.3 Verifying the design model

The energy load profile of the soya bean business unit is shown in Figure 50, as well as the energy which is supplied by a standard diesel generator without any heat recovery equipment. All the thermal energy is supplied by electrical power which is converted to thermal energy with the required heaters. The smallest diesel generator required without heat recovery equipment, is a 38 kW diesel generator.

The electrical energy required for the process is 95,8 kWh_e and 54,7 kWh_{th} thermal energy. A total of 150,5 kWh energy is required per day of operation for the soya business unit. The 38 kW diesel generator set without heat recovery equipment will deliver 172,4 kWh_e of energy to be able to supply enough electrical and thermal energy to the business unit. This is a total of 14,6 % more energy supplied than the required 150,5 kWh required for the business unit.

The thermal load supplied by the 38 kW diesel generator is 76,6 kWh_{th}. This thermal load is converted from electricity to thermal energy with heaters. The supplied thermal load fits the required thermal load better than the recommended power source. The reason for this is that a power source which supplies energy without heat recovery equipment will be load following. It can be seen from Figure 50 that the electricity which was supplied, follows the total required load very closely.

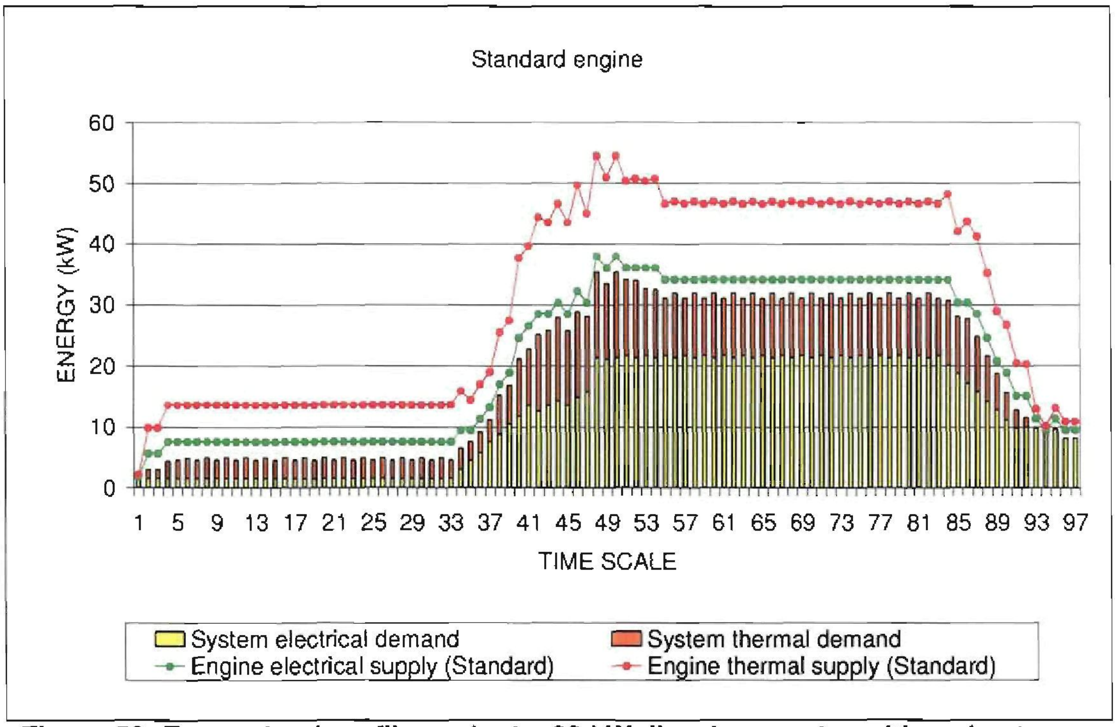


Figure 50: Energy load profile against a 38 kW diesel generator with no heat recovery equipment

The load profile of the soya business unit with the recommended power source, a 25 kW diesel generator set with heat recovery equipment, is shown in Figure 51. The recommended power source was selected by the design tool, based on the lowest running cost per year. Thermal energy is recovered from the waste heat and in the event that insufficient thermal energy is available, it would be generated by the electricity generated by the diesel generator with the required heaters. Excess thermal energy would be discarded into the atmosphere.

The recommended diesel generator set with heat recovery equipment need only deliver 103,2 kWh_e of electrical power. This is a saving of 31,4 % from the required 150,5 kWh energy required.

The thermal energy available to be utilized by the business unit is 99,6 kWh_{th}. This is 82,1 % more than which is required. The ratio of thermal energy supplied to the thermal load required is 1,8:1. As mentioned before, the thermal load for the recommended power source does not follow the thermal load that well, compared to the standard power source. The recommended power source follows the electrical load and supplies only additional thermal load, when needed by converting electrical energy to thermal energy. This can be seen from the figure.

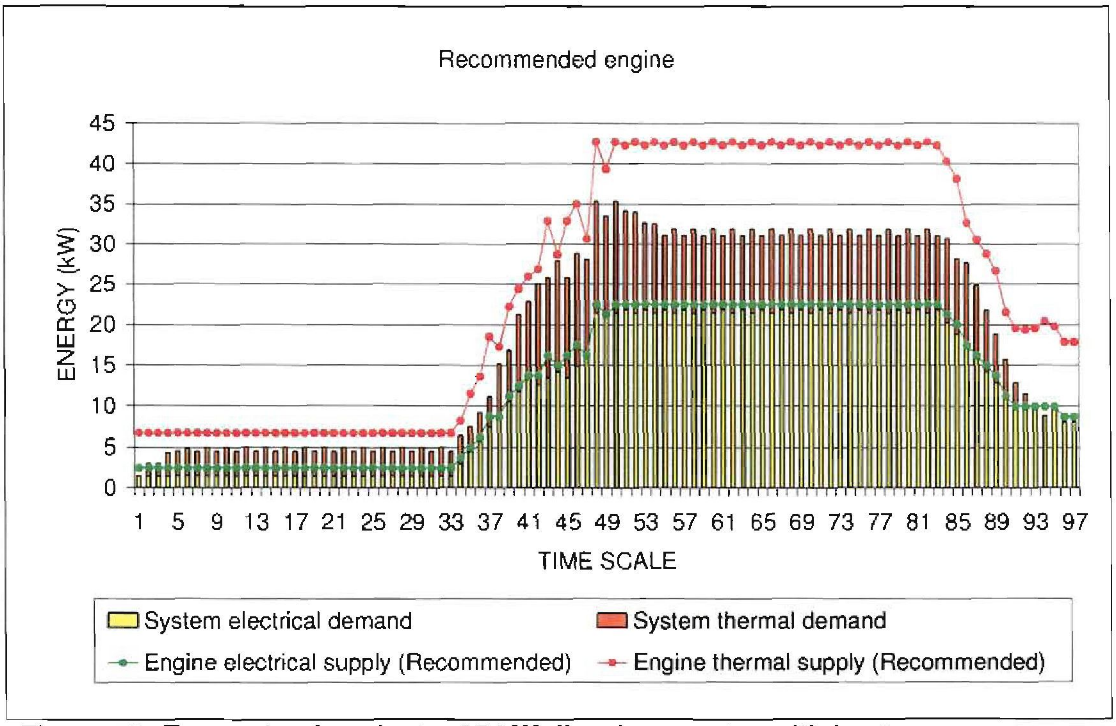


Figure 51: Energy load against a 25 kW diesel generator with heat recovery equipment

The saving in cost is significant when waste heat is recovered and utilized because the major contributor to the overall running cost is the fuel cost. The total capital cost for the recommended diesel generator (25 kW) was R 54 100,00 compared to R 35 700,00 for the standard diesel generator set (38 kW). The running cost for the standard diesel generator set is R 115 900,00 per year compared to R 84 300,00 per year for the recommended diesel generator set. This provides a saving of R 31 600,00 per year or 27,3 % per year. The payback period for the additional capital cost for the heat recovery equipment would be less than 7 months.

The efficiency of a cogeneration system is defined as the total energy available, divided by the energy supplied. The average overall efficiency of the recommended power source, the 25 kW diesel generator set, is 47,1 % and the maximum efficiency is 61,4 %. The average efficiency of the standard diesel generator set is 30,1 % and the maximum efficiency is 36,5 %. The efficiency of the standard diesel generator set without heat recovery equipment can only be as high as the efficiency of the power source itself, whereas the efficiency of the cogeneration system will be higher.

Figure 52 shows the load profile of the business unit with a selected power source which is smaller than the recommended power source. It is clear that the power source will not be able to supply all the electrical energy required and some thermal energy at time scale 49. This information, however, can be utilized to optimize the required load profile with possible load shedding or by reducing the number of batches which are processed per day.

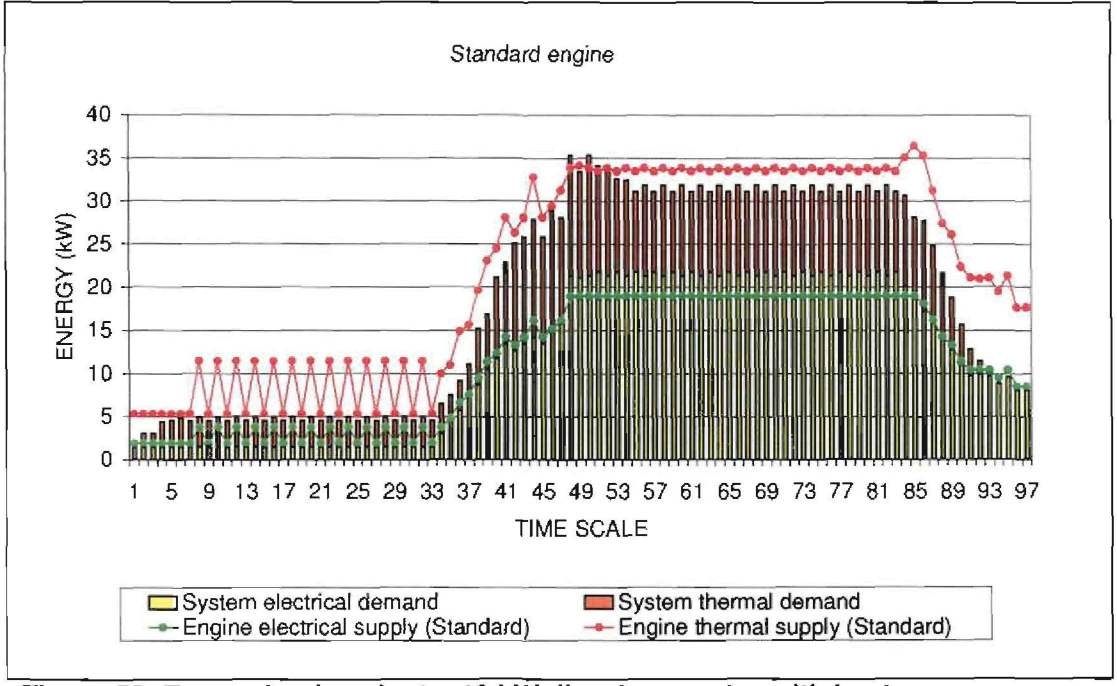


Figure 52: Energy load against a 19 kW diesel generator with heat recovery equipment

5.4 Sensitivity analysis

One of the aims of the design tool is to assist in making informed decisions when selecting possible power sources. The design tool was utilized to determine the effect of various factors on the decision making process and is reflected in the sensitivity plot in Figure 53. The influence of possible factors was investigated.

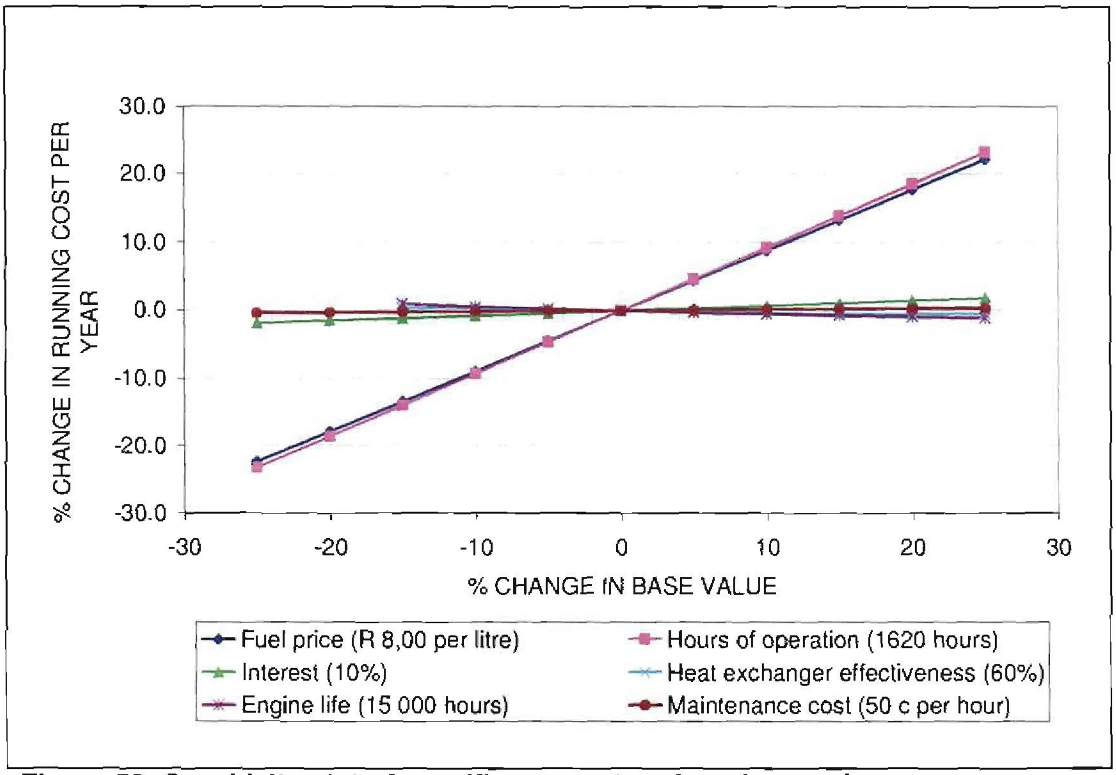


Figure 53: Sensitivity plot of specific parameters from base values.

The total annual running cost of the business unit is divided into approximately 1 % maintenance cost, 8 % capital cost and 91 % fuel cost. The hours of operation and the fuel price had a significant influence on the annual running cost for the business unit. Both are linked to the amount of fuel used, which is the biggest contributor to the running cost. In both instances the percentage change in annual running cost is nearly the same as the percentage change in base conditions. The base condition for the hours of operation was taken as 1 620 hours and the base condition for the fuel was taken as R 8,00 per litre of fuel.

The base conditions for the sensitivity plots where 15 000 hours for the engine life, 10 % for the interest rate or discount rate, 60 % for the heat exchanger effectiveness and R 0,50 for the maintenance cost per hour. Engine life, interest rate, heat exchanger effectiveness and maintenance cost had very little effect on the annual running cost.

The plot for the running cost against heat exchanger effectiveness is shown in Figure 54. The running cost reduces linearly as the effectiveness increases up to about 70 % after which the running cost stays the same at just over R 59 600,00 per year. The reason for this is that all the required thermal energy has been extracted and any additional thermal energy extracted will not be utilized, but will be discarded. This emphasises the fact that the design tool can be used to optimize specific components by selecting the smallest and cheapest which is required for this particular energy load.

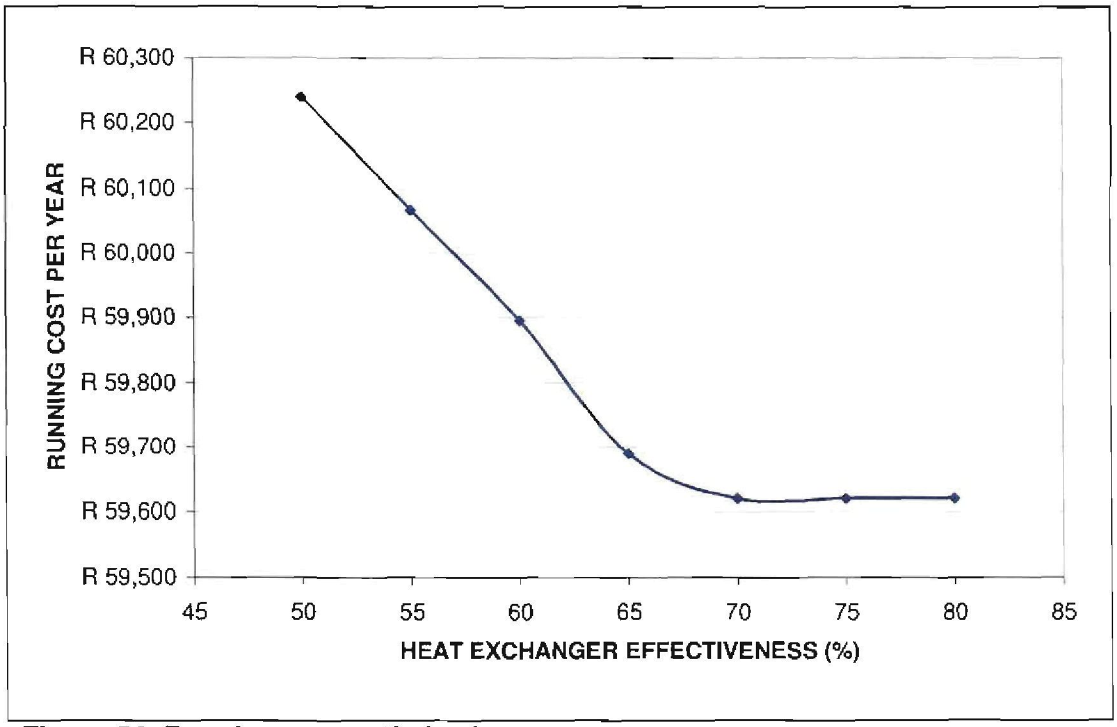


Figure 54: Running cost optimization

5.5 Conclusions

By verifying the results which were obtained from the design tool, with the expected standard selected power source, it was proved to be successful because the life-cycle cost was reduced. Features of the design tool are as follows:

- The design tool assists with the selection of the most cost-effective power source from the possible alternative power sources which are available. The saving in cost for the model used was 27,3%.

- The design tool predicts that with the utilisation of combined heat and power technology on the business unit the overall efficiency is increased by 24,9% and a total of 31,4% of electrical energy is saved.
- The design tool assists with the optimization of the design with the ability to select different components and compare the alternatives with one another.
- The design tool assists with the evaluation of possible influences due to future changes, e.g. fuel prices and hours of operation, to name but two.
- The design tool can be utilized to investigate future expansions of the business units and evaluate the possibility with the current power source.
- The design tool can be used to assist with the optimal load determination of a specific power source.
- The design tool can be used to identify possible load shedding points to attempt to reduce the size of the recommended power source.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

No design tool could be found from available literature and resources that would be able to assist with determining the most cost effective power source required for the soya business unit. The unique features of the soya business unit are that it must be a stand-alone unit and that the time of operation is based on small time intervals. The business unit will operate during normal working hours and therefore will be stopped overnight which will cause the complete process to cool down. The fluctuation of energy required, both thermal and electrical, over a single day's operation is large.

The developed design tool was able to address all the requirements for making a selection, based on minimum annualized total cost, between different power sources for the business unit. During the verification of the design tool against a base load, the design tool suggested a power source for the business unit that showed significant savings in annualized total cost, improved overall efficiency and saving in electrical energy.

The design tool demonstrates other valuable benefits as well. It is independent from the types of power sources, heat exchangers and fuel sources being used and it can be used for system optimization, component optimization and comparative studies between different power sources and even fuel sources. Part load conditions of the power sources are considered, which is crucial for design optimization and accurate predictions.

The design tool was developed with flexibility in mind and is not limited to the soya business unit. It could be used for other applications where heat and power are required from different power sources and where waste heat can be recovered from the power source. The flexibility of the system makes it possible to be utilized on current systems and to identify peak load conditions that may be reduced with load shedding techniques.

The design tool was developed within the Microsoft Excel environment which makes it easy to modify, external data can easily be imported and the software is readily available to run the design tool. Literature indicated that a drawback of other design tools was that the calculations could not be followed by the user and that some doubt existed in confidence in the results. All calculations can be verified within this design tool.

6.2 Recommendations

The design tool can be further developed to make it more applicable to a wider range of combined heat and power applications. It was developed with a great deal of flexibility, but some limitations where not investigated. The further development consideration for the design tool can be listed as follows:

- Consideration can be given to incorporate the use of more than one power source to supply the required energy. Smaller power sources can be operated in conjunction with one another at more efficient load conditions and when a power source is not required it can be switched off. The literature and the experimental work indicated that running a diesel engine at higher loads will result in higher efficiencies. The initial capital cost will be higher, but annualized total cost might be lower due to the possible saving in fuel, which is the largest contributor to the total cost.

- The cost of CO_2 emissions can be incorporated in calculating the total cost. The total cost of operation will be more accurate and the design tool can then be used for larger energy systems. Legislative requirements are becoming more stringent and within certain applications and countries the cost of CO_2 emissions are required before any installation is approved.

- Heat recovery from other heat sources from the power sources can be added to the design tool. This becomes more significant in bigger installations where the heat loss through oil coolers and intercoolers becomes significant.

- Other energy sources could be utilized in parallel and in series with the prime power source and this can be added to the design tool. Other energy sources would typically be alternative or renewable energy sources like the sun and wind.

In conjunction with the improvement of the design tool to broaden its application, increasing the efficiency of the business unit and its power source and the reduction of running cost can be investigated. It is suggested that the following ideas and concepts are investigated:

- Generating electricity by utilising the waste heat to generate steam and to drive a small steam turbine from small scale power sources. This is similar to bottoming CHP systems where the secondary function is to generate electricity in larger systems. The optimum power source size needs to be determined to warrant the additional capital expenses to generate the electricity from steam. This is especially applicable to stand-alone business units with no or very little thermal demands.

- Further development of intelligent, cheap and robust electronic control systems to manage the power utilization and load shedding requirements of the business unit should be investigated. Various control systems do exists, for instance programmable logic controllers (PLC), but on small scale business units the price of these controllers relative to the price of the power source does not warrant the use of these control systems. Current electrical equipment such as ovens operate on an "on or off" basis and once the device is switched on the rated electrical energy is required by the device. Supplying less energy or sequencing the switching on of equipment will reduce peak loads. Devices, like ovens can be installed with two or three smaller heaters. All the heaters are used for heating the system, but only one or two are used to maintain the heat. This will not reduce the energy required, but will reduce peak loads at certain times during the production cycle. The need for small scale power sources for domestic use is also increasing with the shortage of electrical supply in various countries and is a reality in South Africa, therefore a more cost effective control system and switchgear system is needed.

- Solar energy systems are readily available and much research has been done on this topic, but the affordability of this technology to poorer communities is still a significant challenge. The development of cheap modular solar energy systems are needed, whereby a basic system can be obtained with little money and expanded as more money is earned by the community. For these types of solar energy systems a balance between efficiency and the cost of manufacturing is required.

- Within small rural communities a need exists for electrical energy for domestic use, but due to the cost of electrical grid lines it is not a financially viable option. A stand-alone power source can be utilised to supply the electricity to these communities and the waste heat that is recovered can be utilised to supply hot water for communal kitchens, baths and washing facilities. A needs analysis is needed to determine the electrical and thermal load needs per household in these communities.

APPENDIX A: USER GUIDE

The design tool was developed within Microsoft Excel and the file can be obtained from the attached CD. Once the file is opened the user will be asked to activate the macros. A single macro is used to open the file on the introduction page. The remainder of the calculations are done within the normal Excel calculations.

The design tool makes use of different worksheets for each part of the process. Hyperlinks are used to move from one sheet to another sheet. Figure 55 shows the introduction page and the steps which have to be followed.

- Data has to be entered in the white cells.
- Blue cells indicate an option is available through a dropdown list.

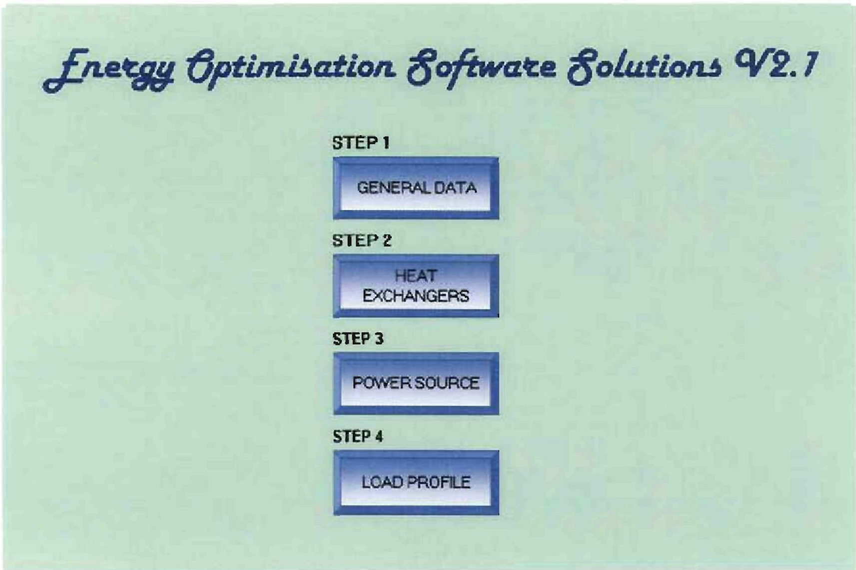
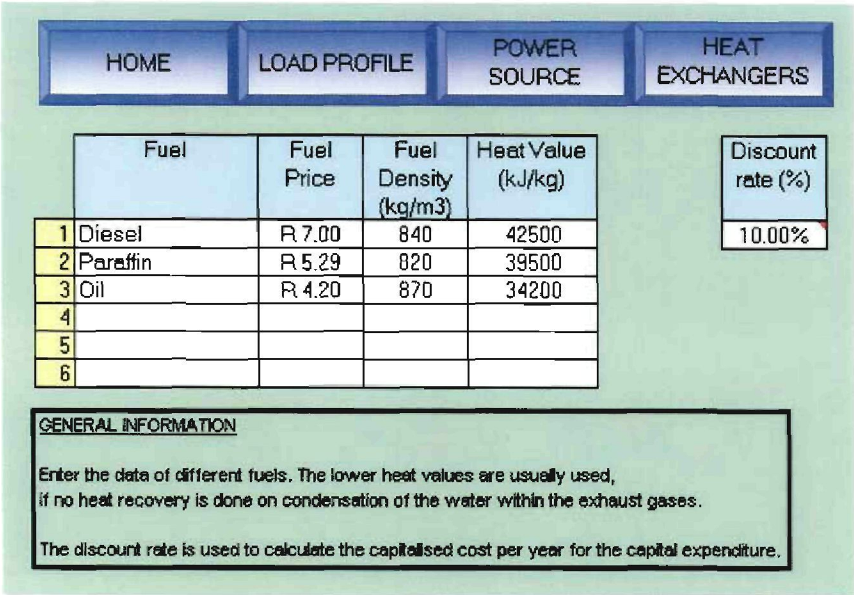


Figure 55: EOSS - Introduction page

Step 1 – General data (Figure 56)

- Enter the data of different fuels. The lower heat values are used unless heat recovery is done to an extent where condensation of the water takes place within the exhaust gases.
- The discount rate is used to calculate the capitalized cost per year for the capital expenditure.



HOME | LOAD PROFILE | POWER SOURCE | HEAT EXCHANGERS

	Fuel	Fuel Price	Fuel Density (kg/m3)	Heat Value (kJ/kg)
1	Diesel	R 7.00	840	42500
2	Paraffin	R 5.29	820	39500
3	Oil	R 4.20	870	34200
4				
5				
6				

Discount rate (%)
10.00%

GENERAL INFORMATION

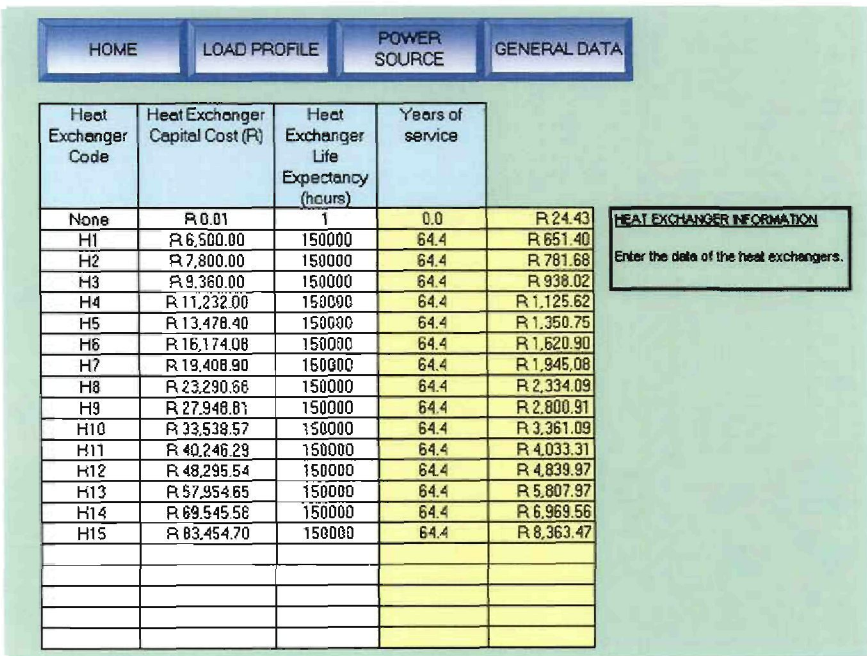
Enter the data of different fuels. The lower heat values are usually used,
if no heat recovery is done on condensation of the water within the exhaust gases.

The discount rate is used to calculate the capitalised cost per year for the capital expenditure.

Figure 56: EOSS – General data page

Step 2 – Heat exchanger data (Figure 57)

- Enter the heat exchanger data. It is preferable to have the first heat exchanger as empty. This will prevent values being divided by zero during the calculations.



HOME | LOAD PROFILE | POWER SOURCE | GENERAL DATA

Heat Exchanger Code	Heat Exchanger Capital Cost (R)	Heat Exchanger Life Expectancy (hours)	Years of service	
None	R 0.01	1	0.0	R 24.43
H1	R 6,500.00	150000	64.4	R 651.40
H2	R 7,800.00	150000	64.4	R 781.68
H3	R 9,360.00	150000	64.4	R 938.02
H4	R 11,232.00	150000	64.4	R 1,125.62
H5	R 13,478.40	150000	64.4	R 1,350.75
H6	R 16,174.08	150000	64.4	R 1,620.90
H7	R 19,408.90	150000	64.4	R 1,945.08
H8	R 23,290.68	150000	64.4	R 2,334.09
H9	R 27,948.81	150000	64.4	R 2,800.91
H10	R 33,538.57	150000	64.4	R 3,361.09
H11	R 40,246.29	150000	64.4	R 4,033.31
H12	R 48,295.54	150000	64.4	R 4,839.97
H13	R 57,954.65	150000	64.4	R 5,807.97
H14	R 69,545.58	150000	64.4	R 6,969.56
H15	R 83,454.70	150000	64.4	R 8,363.47

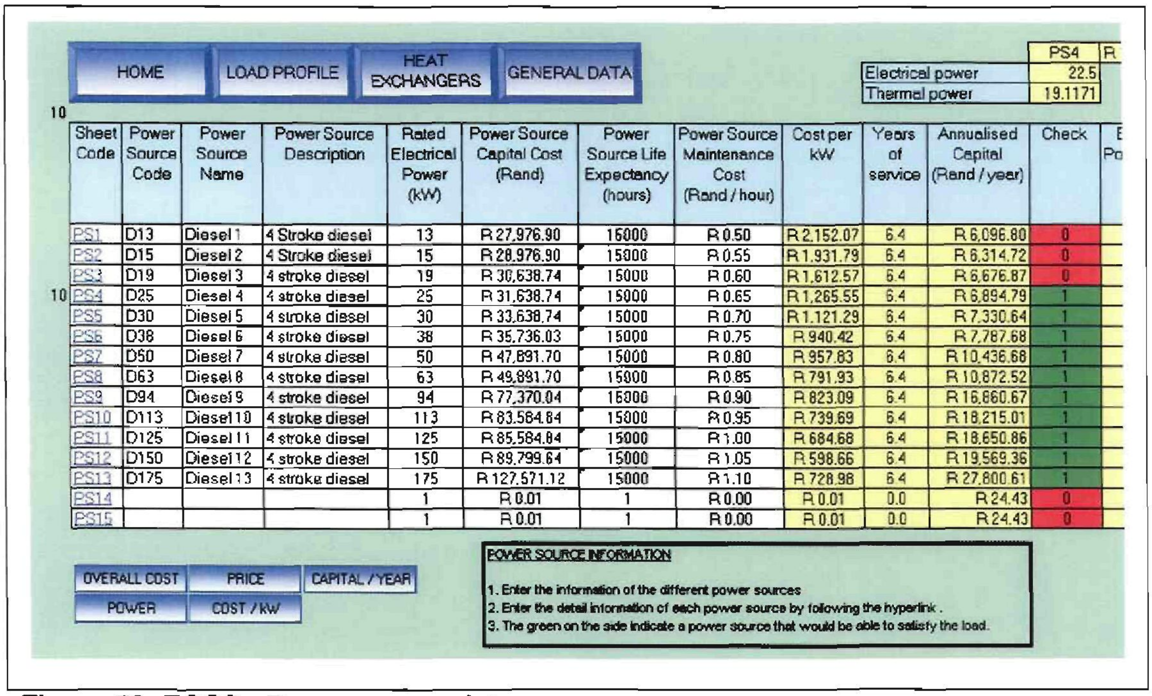
HEAT EXCHANGER INFORMATION

Enter the data of the heat exchangers.

Figure 57: EOSS – Heat exchanger data page

Step 3 – Power source data (Figure 58)

- Enter the information for the different power sources.
- Enter the detail information of each power source by following the hyperlink.
- The green on the side indicates a power source which would be able to satisfy the load.



Sheet Code	Power Source Code	Power Source Name	Power Source Description	Rated Electrical Power (kW)	Power Source Capital Cost (Rand)	Power Source Life Expectancy (hours)	Power Source Maintenance Cost (Rand / hour)	Cost per kW	Years of service	Annualised Capital (Rand / year)	Check
PS1	D13	Diesel 1	4 Stroke diesel	13	R 27,976.90	15000	R 0.50	R 2,152.07	6.4	R 6,096.80	0
PS2	D15	Diesel 2	4 Stroke diesel	15	R 28,976.90	15000	R 0.55	R 1,931.79	6.4	R 6,314.72	0
PS3	D19	Diesel 3	4 stroke diesel	19	R 30,638.74	15000	R 0.60	R 1,612.57	6.4	R 6,676.87	0
PS4	D25	Diesel 4	4 stroke diesel	25	R 31,638.74	15000	R 0.65	R 1,265.55	6.4	R 6,894.79	1
PS5	D30	Diesel 5	4 stroke diesel	30	R 33,638.74	15000	R 0.70	R 1,121.29	6.4	R 7,330.64	1
PS6	D38	Diesel 6	4 stroke diesel	38	R 35,736.03	15000	R 0.75	R 940.42	6.4	R 7,787.68	1
PS7	D50	Diesel 7	4 stroke diesel	50	R 47,891.70	15000	R 0.80	R 957.83	6.4	R 10,436.68	1
PS8	D63	Diesel 8	4 stroke diesel	63	R 49,891.70	15000	R 0.85	R 791.93	6.4	R 10,872.52	1
PS9	D94	Diesel 9	4 stroke diesel	94	R 77,370.04	15000	R 0.90	R 823.09	6.4	R 16,860.67	1
PS10	D113	Diesel 10	4 stroke diesel	113	R 83,584.84	15000	R 0.95	R 739.69	6.4	R 18,215.01	1
PS11	D125	Diesel 11	4 stroke diesel	125	R 85,584.84	15000	R 1.00	R 684.68	6.4	R 18,650.86	1
PS12	D150	Diesel 12	4 stroke diesel	150	R 89,799.64	15000	R 1.05	R 598.66	6.4	R 19,569.36	1
PS13	D175	Diesel 13	4 stroke diesel	175	R 127,571.12	15000	R 1.10	R 728.98	6.4	R 27,800.61	1
PS14				1	R 0.01	1	R 0.00	R 0.01	0.0	R 24.43	0
PS15				1	R 0.01	1	R 0.00	R 0.01	0.0	R 24.43	0

Figure 58: EOSS - Power source data page

Step 4 – Power source part-load data (Figure 59)

- Select the fuel which is used from the dropdown list.
- Select the power source load units from the dropdown list.
- Select the heat exchanger load units from the dropdown list.
- Select the heat exchanger from the dropdown list.
- Enter the available data. The maximum intervals are 5 % of maximum load.
- The left-hand column of the red and green columns indicates the possible delivery of electrical energy to the load profile. Green indicates sufficient electrical energy is available.
- The right-hand column of the red and green columns indicates the possible delivery of thermal energy to the load profile. Green indicates sufficient thermal energy is available.

Power Source Load	Fuel Consumption (kg/h)	Exhaust Heat Available	Exhaust Heat Exchanger	Exhaust Heat Exchanger Efficiency (%)	Cooling Heat Available	Cooling Heat Exchanger	Cooling Heat Exchanger Efficiency (%)	Fuel	Electrical check	Thermal check
Minimum conditions										
22.5	5.7423	25	H4	78	15	H4	58			
kW		%			%					
kW		%			%			Diesel	3	5
0	1.2828	25	H4	60	0	H4	40		-21.794	-33.47
1.25	1.53055	25	H4	61	0	H4	41		-20.544	-31.74
2.5	1.7783	25	H4	62	0	H4	42		-19.294	-29.99
3.75	2.02605	25	H4	63	0	H4	43		-18.044	-28.23
5	2.2738	25	H4	64	15	H4	44		-16.794	-24.68
6.25	2.52155	25	H4	65	15	H4	45		-15.544	-22.65
7.5	2.7693	25	H4	66	15	H4	46		-14.294	-20.59
8.75	3.01705	25	H4	67	15	H4	47		-13.044	-18.52
10	3.2648	25	H4	68	15	H4	48		-11.794	-16.42
11.25	3.51255	25	H4	69	15	H4	49		-10.544	-14.29
12.5	3.7603	25	H4	70	15	H4	50		-9.294	-12.15
13.75	4.00805	25	H4	71	15	H4	51		-8.044	-9.98
15	4.2558	25	H4	72	15	H4	52		-6.794	-7.78
16.25	4.50355	25	H4	73	15	H4	53		-5.544	-5.56
17.5	4.7513	25	H4	74	16	H4	54		-4.294	-3.32
18.75	4.99905	25	H4	75	15	H4	55		-3.044	-1.06
20	5.2468	25	H4	76	15	H4	56		-1.794	1.23
21.25	5.49455	25	H4	77	15	H4	57		-0.544	3.54
22.5	5.7423	25	H4	78	15	H4	58		0.706	5.87
23.75	5.99005	25	H4	79	15	H4	59		1.956	8.23
25	6.2378	25	H4	80	15	H4	60		3.206	10.61

Figure 59: EOSS – Power source part-load data page

Step 5 – Load profile data (Figure 60)

- Enter the number of cycles per day.
- Enter the days of operation per week.
- Enter the weeks of operation per year.
- Enter the time per time interval.
- Select the time per interval units.
- Enter the load profile in kWe and kWth.
- Select a comparative power source.
- Select reset
- Select start

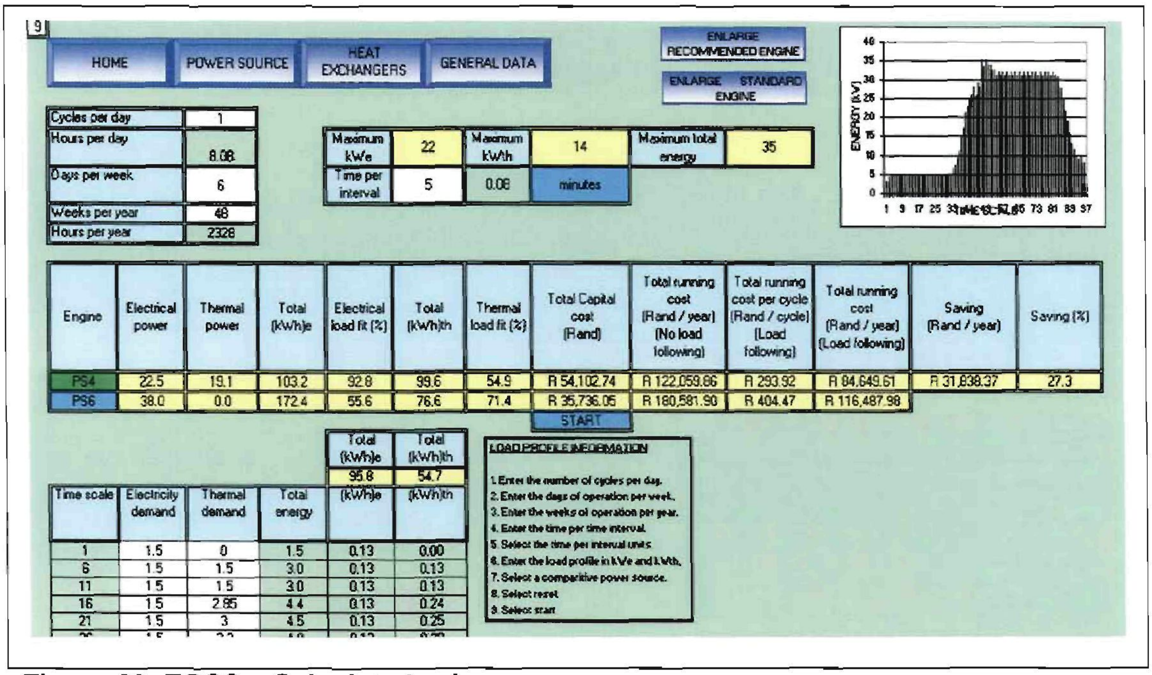


Figure 60: EOSS – Calculated values page

The recommended power source is indicated in the green block. The blue block provides a dropdown list with the other power sources which can be used for comparative analysis.

APPENDIX B: LABVIEW BLOCK DIAGRAM

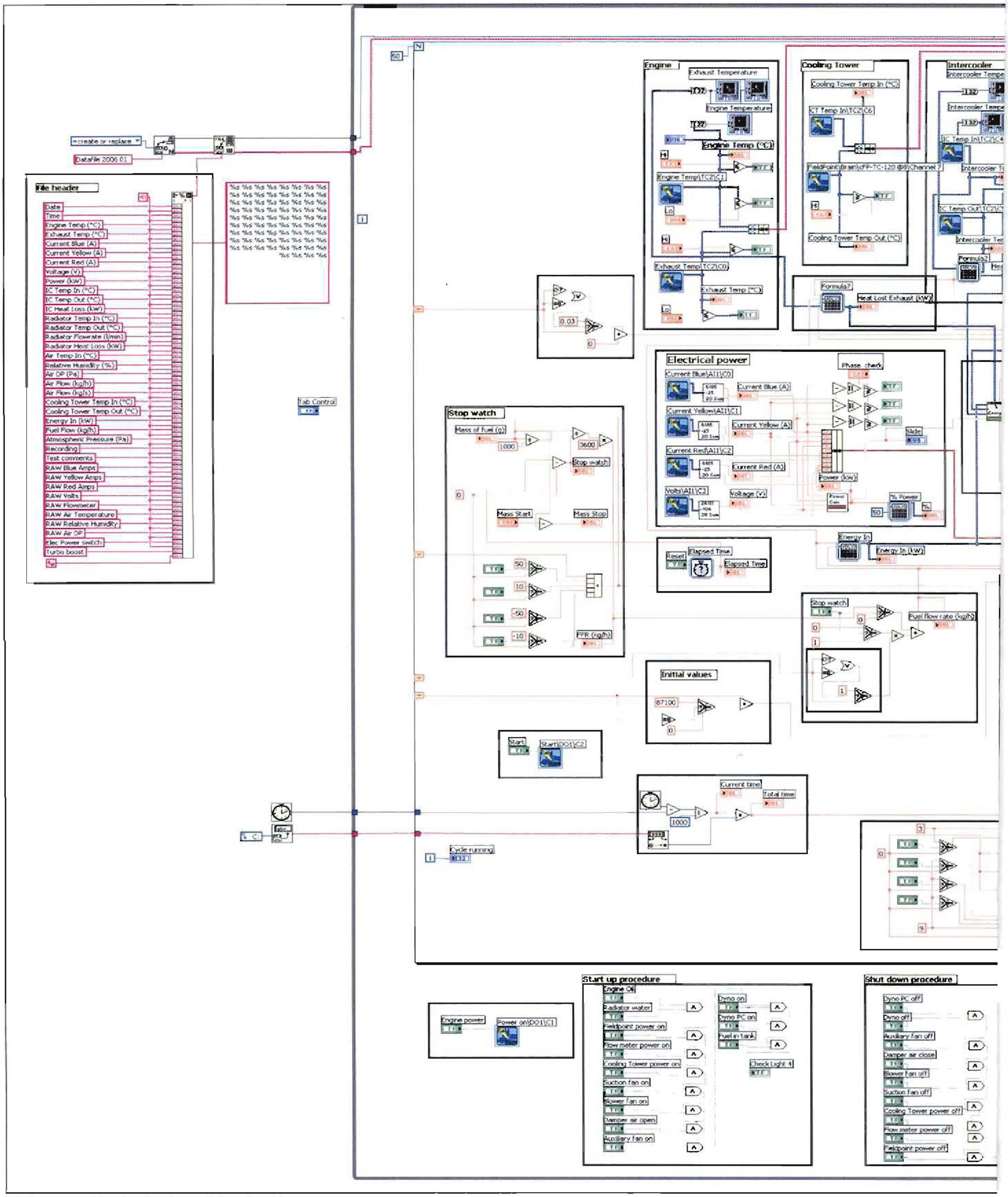
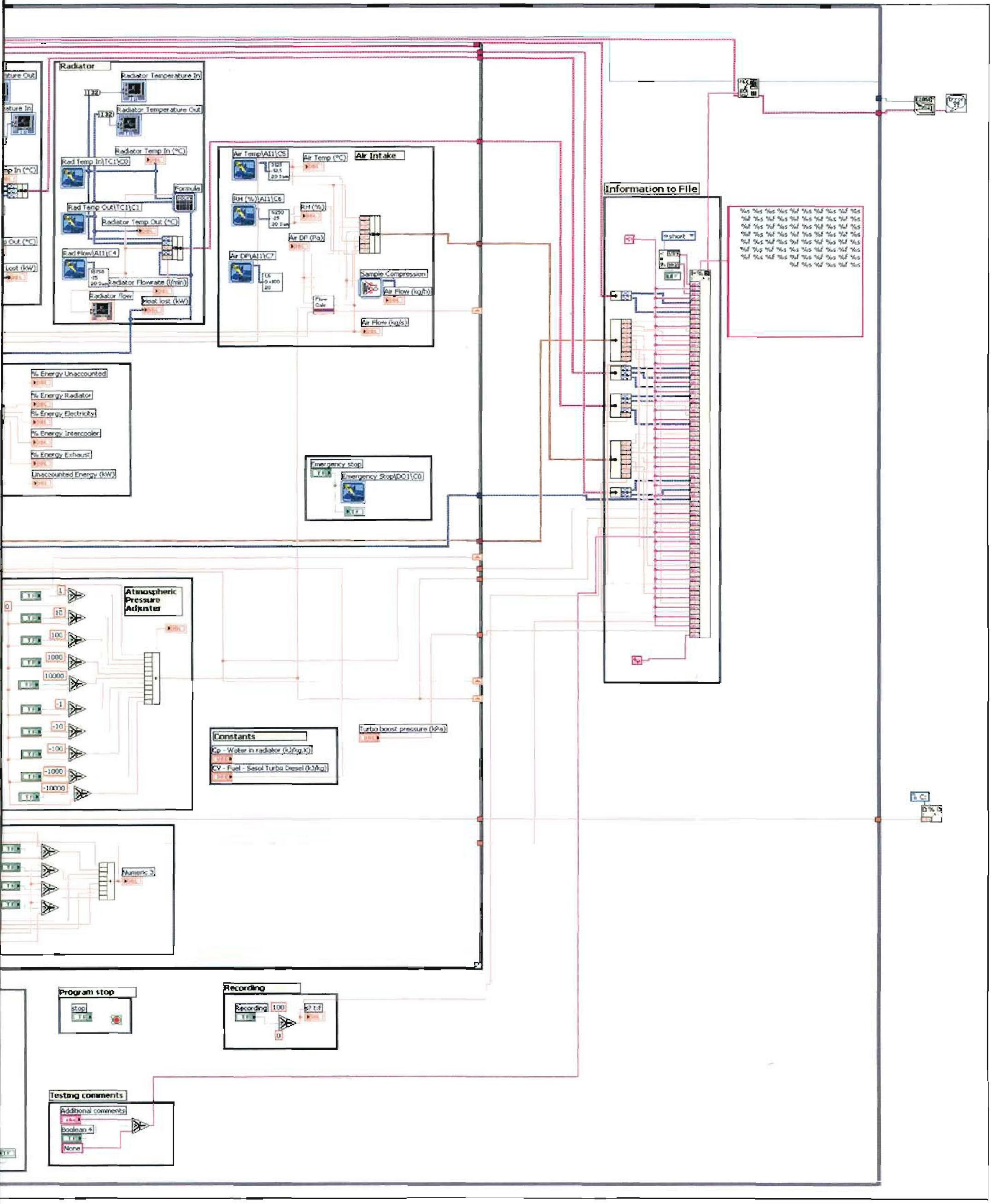


Figure 61: Labview block diagram


Radiator
Radiator Temperature In
Radiator Temperature Out
Radiator Temp In (°C)
Rad Temp In\TC1\C0
Formula
Rad Temp Out\TC1\C1
Radiator Temp Out (°C)
Rad Flow\AI1\C4
Radiator Flowrate (l/min)
Radiator flow
Heat lost (kW)
Air Temp\AI1\C5
Air Temp (°C)
Air Intake
RH (%)\AI1\C6
RH (%)
Air DP (Pa)
Air DP\AI1\C7
Sample Compression
Air Flow (kg/h)
Air Flow (kg/s)
Information to File
% Energy Unaccounted
% Energy Radiator
% Energy Electricity
% Energy Intercooler
% Energy Exhaust
Unaccounted Energy (kW)
Emergency stop
Emergency Stop\DO1\C0
Atmospheric Pressure Adjuster
Constants
Cp - Water in radiator (kJ/kg.K)
CV - Fuel - Sasol Turbo Diesel (kJ/kg)
Turbo boost pressure (kPa)
Numeric 3
Program stop
stop
Recording
Recording
Testing comments
Additional comments
Boolean 4
None