THE DEVELOPMENT AND ASSESSMENT OF A DIRECT ENERGY CALCULATOR FOR USE IN SUGARCANE PRODUCTION

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ABSTRACT

The rising cost of energy coupled with an increasing awareness of Greenhouse Gas (GHG) emissions has led to a concerted effort to reduce fossil fuel Energy Use (EU) in all sectors. Sugarcane production in South Africa is dependent on fossil fuel to provide a source of energy for production. To remain commercially and environmentally sustainable, measures need to be taken to reduce EU and increase EU efficiencies of on-farm operations. The first step toward realising this is to identify and quantify energy inputs. Following on from this, total GHG emissions, also known as carbon footprint, can be estimated.

The primary objective of this research is to develop an energy calculator to estimate EU in sugarcane production in South Africa. The results generated by the calculator highlight areas of high energy intensity and low energy efficiencies at three different levels of detail. Based on these results, changes in management practices and technological improvements can be made to reduce EU and carbon footprint. Case studies were used to test the functionality of the calculator. Results from the case studies show that, in irrigated sugarcane production, the harvest and transport process together with irrigation account for a majority of the total on-farm EU. For one of the case studies, an estimated 20 % saving in the total on-farm EU was identified and can be achieved if appropriate technology is adopted in irrigation practices. Less significant energy savings were realised when in-field tractor operations were optimised for best tractor-implement matching.

It is envisaged that the energy calculator will help farmers minimise on-farm EU and subsequently reduce input costs and carbon footprint. It will also provide a valuable tool for researchers to benchmark and profile EU in sugarcane production in South Africa. Research focussed on the sustainable production of sugar, from the agricultural to milling phase is of high priority at present. The quantification of on-farm EU in sugarcane production will form a critical component of such research.

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1. INTRODUCTION

The productivity and efficiency of intensive cropping systems such as sugarcane production is influenced by operational input costs. Baillie and Chen (2011) estimate that within highly mechanised farming systems, direct Energy Use (EU) costs can represent 40 - 50 % of the total operational costs. Direct energy refers to the energy content of fuels, lubricants, and electrical power used in production. Conversely, indirect energy accounts for the energy used in the production and transportation to and from the farm of all inputs used (Alluvione *et al.*, 2011). It is also estimated that 20 % of global annual Greenhouse Gas (GHG) emissions result from land use change and agricultural practices (IPCC, 2013). The combination of governmental pressure to reduce GHG emissions and an increasing cost of energy is likely to result in a drive towards better EU efficiency in agriculture (Baillie *et al.*, 2008).

Direct EU in field crop agriculture can be considered a function of the number and intensity of mechanical operations and pumping requirements for irrigation (Baillie and Chen, 2011). Rein (2010) apportions approximately 20 % and 19 % of the total EU in sugar production to farm diesel and electricity consumption, respectively. Renouf and Wegener (2007) considered the entire life cycle of irrigated cane sugar production in Australia and estimated on-farm fuel use as 22 % of the total EU, while electricity for irrigation consumed 41 % of the total EU. In the South African agricultural sector, on-farm diesel and electricity use account for 55 % and 20 % of total energy inputs, respectively (StatsSA, 2005).

Although alternative energy sources are available, agricultural production is largely dependent on energy sourced from non-renewable fossil reserves. Renouf *et al.* (2008) and Seabra *et al.* (2011) estimate GHG emissions from direct on-farm EU as 276 and 234 kg carbon dioxide equivalent (CO_2e) per kg monosaccharide, respectively. Typical GHG emissions in the agricultural phase of monosaccharide production from maize and sugar beet are 171 and 158 kg CO_2e per kg monosaccharide, respectively (Renouf *et al.*, 2008).

Lal (2004) identified tillage and irrigation as being the most important primary sources of CO_2 emissions in agricultural production systems. GHG emissions from direct EU can be similar, if not greater, than that from soil–fertilizer–water interactions (Baillie and Chen, 2011). Finding ways to improve direct EU efficiency, and thus reduce total energy consumed, could reduce these emissions. Results from Baillie and Chen (2009) indicate that a 55 % saving in energy for pumped irrigation and a 30 % saving in diesel for tractor operations are possible subject to design changes, regular maintenance and improved management. Energy assessments using both measurements and simulation models are used as a platform from which these savings can be estimated.

The objective of this study is to develop an energy calculator and assess its ability to estimate the direct EU and carbon footprint of sugarcane production in South Africa. This calculator will be in the form of a spreadsheet that makes use of equations developed from first principles, empirical equations and field measurements in order to estimate diesel fuel consumption and electricity use. It is expected that the results generated by the calculator should highlight areas of production where energy savings can be made

The following chapter introduces EU and carbon footprint pertaining to field crop agriculture and reviews previous studies in EU and carbon footprint. The review gives justification to the development of an energy calculator for sugarcane production in South Africa. The development, rationale and functionality of the calculator are described in Chapter 3. Chapter 4 contains the details of methods used by the calculator to quantify EU and carbon footprint in sugarcane production. The performance of the calculation methods that are considered critical to the accuracy of the calculator are assessed in Chapter 5. In addition to this validation, two case studies were conducted and are reported in Chapter 6. These case studies are necessary to assess the practicality and robustness of the calculator outside of the research environment and to identify where further research and development is necessary. Lastly, discussion, conclusions and opportunities for future research as a result of this study are covered in Chapter 7.

2. REVIEW OF DIRECT ENERGY USE AND CARBON FOOTPRINT OF SUGARCANE PRODUCTION

When assessing energy inputs for crop production it is necessary to consider mechanisation and agronomic inputs (Alluvione *et al.*, 2011). Mechanisation inputs include the energy required to manufacture the machinery used and the energy resource consumed. Agronomic inputs account for the energy required to produce and deliver fertiliser, chemicals and irrigation water to the field. Diesel fuel and electricity supplied from a network are the predominant direct energy resources used in agricultural production. Diesel is used to drive machinery and electricity typically used to power electric motors for pressurised irrigation, food processing, lighting and ventilation.

2.1 Sugarcane production in South Africa

In South Africa, the total annual sugarcane harvest ranges between 18-23 million tons (Anon, 2013). Figure 2.1 indicates the geographical location of sugarcane mills in South Africa. The majority (80 %) of the crop area falls in the rainfed KwaZulu-Natal coast and midlands with the remaining 20 %, accounting for 40 % of the industry yield, in the irrigated northern regions of Pongola and Mpumalanga (Anon, 2013).

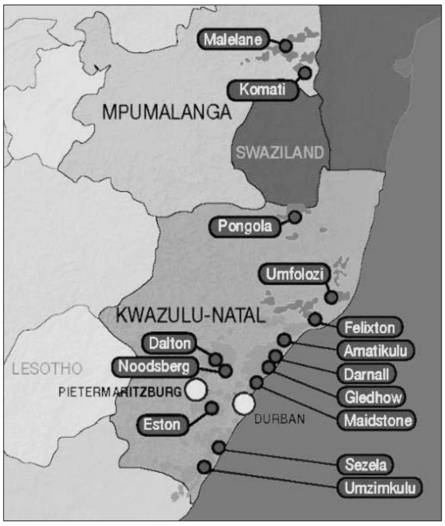

Figure 2.1 Sugarcane mill distribution in South Africa (SASA, 2010)

Due to the unfavourable topography for mechanical harvesting and the availability of relatively inexpensive labour, the majority of the sugarcane yield is harvested by hand (Meyer, 2005). For ease of cutting and efficiency in transport, 85 - 90 % of the sugarcane is burnt before harvest between the months of April and December (Meyer, 2005). The burning of cane prior to harvesting is, however, slowly decreasing due to the increasing awareness of the benefits in retaining a good trash blanket for moisture retention, increased organic matter, weed prevention and erosion control (Meyer *et al.*, 1996).

Mill regions under irrigation include, Umfolozi, Pongola, Komatipoort, Malelane and partial irrigation in Felixton (see Figure 2.1). Irrigation water is sourced from major rivers in these areas and delivered by dragline (67%), drip (18%), centre pivot (12%), flood (3%) and floppy (1%) irrigation systems (Olivier and Singels, 2004). The cost of irrigation is directly related to increases in electricity tariffs. Until recently the cost of electricity in South Africa has been among the cheapest in the world, however, recent and proposed price increases are likely to have an impact on the profitability of irrigated sugarcane production (Jumman and Lecler, 2010).

Tillage systems commonly used in sugarcane production in South Africa include conventional mechanical, reduced mechanical and minimum tillage systems (Tweddle, 2013a). The conventional system uses rippers, mouldboard and disc ploughs, tandem/offset disc harrows, and ridging equipment (Meyer, 2005). In a reduced tillage system rippers are avoided and ploughing only takes place at a shallow depth and the weight of the harrows is also reduced (Tweddle, 2013a). In a minimum tillage system and often in reduced tillage, herbicide application followed by rotary tiller operation is used for stool eradication (Meyer, 2005). An objective of minimum tillage it to retain a good plant residue or a trash blanket. For this reason tillage equipment that might incorporate plant residue into the soil is avoided.

Manual harvesting methods include cut and load, cut and windrow, as well as cut and stack methods (Meyer, 2005). The choice of method depends largely on the topographical characteristics of the land and the loading machinery available. Loading of stacked cane into infield haulage rigs is usually done by non-slewing grab loaders, or purpose designed self-loading trailers. Windrowed cane is, however, loaded by both non-slewing and slewing loaders.

Methods of transporting sugarcane from field to mill vary depending on the topography, cropping systems and lead distances. From the flat fields, harvested cane is often loaded infield and transported directly to the mill. In areas of steeper slope where direct transport is not possible, and often when fields are wet, smaller, self-loading tractor-trailers haul cane from the field to appropriate trans-loading zones. From these zones the cane is loaded into large haulage vehicles for delivery to the mill (Meyer, 2005).

2.2 Direct Energy Use in Sugarcane Production

Energy requirements for the milling phase of cane sugar production are small when compared to the agricultural phase, with co-generation and steam from bagasse providing the necessary energy to run the mill (Seabra *et al.*, 2011). The relatively small portion of direct primary energy, usually coal, required for milling is used for starting the boilers. Indirectly, energy is used in the manufacture of chemicals and is embodied in the mill's infrastructure and machinery.

Donovan (1978) used costing data to derive energy inputs for the production of sugarcane in South Africa. Results from this study show that in the rainfed mill areas, 34 % of the total energy input is accounted for by fertilizer use, 30 % for fuel and lubricants and 5 % for electricity usage. In the irrigated mill areas, the values are 15, 24 and 28 %, respectively.

For cane sugar production in the United States, Rein (2010) estimates 29 % of total energy inputs are used in fertiliser and chemical production, 29 % in mechanised operations and transport, 18 % in irrigation, and the balance used in the milling process. Renouf and Wegener (2007) considered the entire life cycle of cane sugar production in Australia and apportioned the total Energy Use (EU) as 26 % for fertilizer production, 22 % for on-farm fuel use of tractors and harvesters, 41 % for electricity in irrigation, with capital goods, milling and transport accounting for the remainder. It must be noted that sugarcane production in both the United States and Australia is highly mechanised, with mechanical harvesting accounting for the majority of the farm diesel usage.

To compare total direct energy inputs of different sugarcane production systems, a number of factors should be taken into account. These include whether or not the crop is irrigated, plant or ratoon crop, and the degree of mechanisation employed. Table 2.1 contains a comparison the total direct energy inputs from studies conducted in major sugarcane producing countries. A limitation of most of these studies is that they did not account for transportation EU.

Table 2.1 Direct energy inputs for sugarcane production from studies conducted in major sugarcane producing countries

Country	**Ratoon/ plant**	**Irrigated/ rainfed**	**Transport accounted for**	**Mechanised/ manual harvest**	**Direct energy input [GJ.ha^{-1}]**	**Reference**
Australia	Plant	Irrigated	No	Mechanised	20.03	Baillie and Chen (2012)
Australia	Ratoon	Irrigated	No	Mechanised	10.52	Baillie and Chen (2009)
Brazil	Ratoon	Rainfed	Yes	20% Mechanised	5.16	Macedo (1998)
Mexico	Ratoon	Rainfed	No	Manual	3.36	Garcia *et al.* (2011)
Morocco	Ratoon	Irrigated	No	Manual	28.76	Mrini *et al.* (2001)
South Africa	Plant	Irrigated	No	Manual	27.34	Donovan (1978)
South Africa	Plant	Rainfed	No	Manual	9.04	Donovan (1978)
Thailand	Ratoon	Irrigated	No	Manual	9.36	Yuttitham *et al.* (2011)
United States	Plant	Irrigated	No	Mechanised	18.88	Rein (2010)

Table 2.1 shows a large range in energy input of between 3.36 and 28.76 GJ.ha^{-1}. In most cases, the energy input for irrigated production almost doubles that of the dryland equivalent. Other important factors such as yield, type of irrigation systems, and topography need to be considered before comparisons and conclusions drawn from the literature.

2.3 Carbon Footprint of Sugarcane Production from Direct Energy Use

The term "carbon footprint" is used to quantify the GHG emissions of an isolated study. GHG's, as defined in the Kyoto Protocol (1998), include CO_2, N_2O, CH_4, SF_6, hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). To normalise the global warming potential of these gasses, coefficients have been formulated to equate them to a carbon dioxide emission equivalent (Rein, 2010). Different sources of fossil energy emit unique quantities and combinations of these GHGs.

The source of energy and production methods of diesel and electricity determine the magnitude of the carbon dioxide coefficient assigned to them (Letete *et al.*, 2009). In South Africa, diesel is distilled in local refineries from imported crude oil (Letete *et al.*, 2009). To account for transportation of the crude oil, the CO_2e coefficient for diesel available in South Africa is higher than in a country that has its own oil reserves. Similarly, grid electricity in South Africa is produced predominantly from coal powered stations, which results in a higher CO_2e coefficient than electricity produced from a renewable resource. Table 2.2 contains a summary of the coefficients for South Africa and other sugarcane producing countries. The low CO_2e coefficients for electricity production in Mauritius and the United States can be explained by their use of renewable energy sources. Sixty percent of the electrical energy produced in Mauritius is generated in sugar mills using cogeneration processes (Soobadar *et al.*, 2010).

Table 2.2 Carbon dioxide equivalent (CO_2e) coefficients for electricity and diesel in selected sugarcane producing countries

Country	**Electricity coefficient [kg CO_2e .kW^{-1}.h^{-1}]**	**Reference**	**Diesel coefficient [kg CO_2e .L^{-1}]**	**Reference**
Australia	1.051	Baillie and Chen (2007)	2.890	Baillie and Chen (2007)
Mauritius	0.550	Panray Beeharry (2001)	2.110	Panray Beeharry (2001)
South Africa	1.015	Letete *et al.* (2009)	2.681	EIA (2011)
United States	0.676	EIA (2007)	2.681	EIA (2011)

CO_2e coefficients are commonly used in Life Cycle Assessments (LCAs) of industrial products and processes. LCAs assess the environmental impacts of resources consumed as well as wastes and emissions generated throughout the life cycle of a product or process. LCAs in sugar producing countries are now commonly used to evaluate and validate the "cleanliness" of alternative sources of energy. Mashoko *et al.* (2010), in a LCA of the South African sugar industry, estimated that 0.164 kg CO_2 per kilogram of raw sugar is emitted from farming and transportation operations. Similar studies by Renouf and Wegner (2007), Renouf *et al.* (2008), Rein (2010) and Seabra *et al.* (2011) highlight the carbon emission from energy intensive operations and possible greenhouse gas mitigation strategies. Table 2.3 contains calculated CO_2e emissions from these studies (excluding carbon credits) for sugarcane, corn and sugar beet. Results from the study conducted by Mashoko *et al.*(2010) are omitted from Table 2.3 as these results consider only CO_2 and no other gasses included in the GHG inventory. Results in Table 2.3 are inclusive of all emission sources other than those associated with the energy embodied in equipment, infrastructure and land use change.

Table 2.3 Total on-farm GHG emissions from the production of selected field crops

Crop	Country	Agricultural phase GHG emissions per kg sugar produced [kg CO_2e]	Reference
Sugarcane	Australia	0.276	Renouf *et al.* (2008)
	Australia	0.226	Renouf and Wegener (2007)
	Brazil	0.234	Seabra *et al.* (2011)
	USA	0.275	Rein (2010)
	Thailand	0.490	Yuttitham *et al.*(2011)
Corn	Australia	0.171	Renouf *et al.* (2008)
Sugar beet	Australia	0.158	Renouf *et al.* (2008)

Table 2.3 shows considerably higher GHG emissions for the sugarcane crop over corn and sugar beet. The difference could be as a result of the comparatively large yields of the sugarcane crop and the subsequent additional energy required for harvesting and transportation. In addition, the typically high irrigation requirements of sugarcane and the impact of burning sugarcane leaves prior to harvest could be major contributing factors.

2.4 Energy Assessments and Calculators

Energy assessments, also referred to as energy audits, are conducted in farming enterprises to determine and document the current EU and the potential for energy savings (ASABE, 2009). This involves a systematic examination of the energy intense processes and operations to highlight inefficiencies, potential cost saving opportunities, and the potential to improve quality and productivity (Baillie and Chen, 2011).

On a farm level, energy intense processes can be identified by examining fuel and utility bills. To further quantify EU per process or operation may require theoretical calculation, specialised instrumentation, and analyses performed by specialists. To aid in the estimation of EU, calculator tools have been developed and are used in many industries, be that in the form of customised computer programs or a set of spreadsheets.

The adoption of energy calculators as tools to estimate and evaluate the efficiency of EU in agriculture has been slow in comparison to other industries (Morris, 2009). However, with pressure from government and the rising cost of energy this trend is changing. There are numerous web-based calculators freely available for public use which range in accuracy and comprehensiveness (e.g. *USDA Energy Estimator*, 2006; *EnergyCalc* 2011; and *Comet-Farm*, 2013). Reviews emphasise that the choice of calculator and interpretation of results needs careful consideration depending on the type and complexity of the farming enterprise and the accuracy required (Morris, 2009; McHugh *et al.*, 2010). It must also be considered that the operations and management practices of certain processes as well as their associated energy intensities vary between countries and regions. For this reason the database and input variables used by the calculator needs to be continually updated to suit varying production practices, socio-economic, geographic and climatic conditions.

During a home or business energy assessment, an energy professional will visit the site, measure energy consumptions and write a report highlighting inefficiencies and opportunities to reduce costs. In the United States, Morris (2009) attributes the lack of adoption of energy assessments in agriculture to a number of factors, the most influential of which is cost. The introduction of free web-based energy calculators makes it possible for farm managers to perform the assessment and obtain estimates of energy consumption. Depending on the complexity of the calculator, areas of high and inefficient EU can be identified and corrective measures implemented (Baillie and Chen, 2007). Farm managers will then be in a position to decide whether to further consult with energy professionals.

2.4.1 Classification of Calculators

Morris (2009) separates energy calculators by their degree of complexity and detail of user input. A high level, simple calculator will require the user to select or check multiple choice options given on a web-based form. Most of this input data will be drawn from user knowledge, such as approximate electricity tariffs, liquid fuel prices, size of land, and machinery in use. The final output will often be a monetary value that highlights areas of greatest cost to the producer. An example of such a calculator is the *USDA Energy Estimator* (USDA, 2006).

The next level of calculator requires further insight from the user. The form may automatically populate certain values depending on, for example, the geographical location of the farm. The user will be required to do some background research into details such as mechanical and electrical specifications, timing and intensity of operations, as well as specifics pertaining to management practices. Results are generally presented in a number of reports highlighting inefficiencies and where opportunities may exist to reduce EU. The carbon foot print for defined operations, usually expressed as a unit mass of CO_2e, is also a common output added to the final report. *EnergyCalc* (NCEA, 2011), developed by the National Centre for Engineering in Agriculture (NCEA) in Australia, is a good example of a calculator of this level.

2.4.2 Currently available Web-based Energy Calculators

McHugh *et al.* (2010) conducted a literature review and industry interviews and identified two energy calculation software tools for possible use in developing a framework for energy audits. The *USDA Energy Estimator* (USDA, 2006), developed by the United States Department of Agriculture (USDA), consists of four separate calculators which estimate EU in tillage, nutrient application, animal housing and irrigation. The tools are intended to give an estimate of the magnitude and potential energy savings that could be realised under different management systems (USDA, 2011).

Another web-based calculator, *EnergyCalc* (NCEA, 2011), is described by Baillie and Chen (2007) as a software tool to assess on-farm EU, EU costs and greenhouse gas emissions. Initially developed for use in cotton production, later versions make it possible to assess various production systems ranging from the field crop, nursery, aquaculture and turf industries.

McHugh *et al.* (2010) reviewed the *USDA Energy Estimator* (USDA, 2006) and found that the calculator did not relate energy estimates to specific operations, as calculations are based on simple high level user input. The calculator provides a rough estimate of energy use in animal housing, irrigation, nitrogen and tillage utilised averages obtained from regions which are limited to the USA.

The calculations in *EnergyCalc* (NCEA, 2011) were initially based on generalised performance data. This database is continually being refined to better represent conditions unique to the Australian agricultural systems, thus further increasing the accuracy of the model (Baillie and Chen, 2007). The tool evaluates the EU of key processes in a field crop production system, including preparation, establishment, in-season operations, irrigation, harvest, post-harvest and general processes. Within one assessment it is possible to evaluate multiple crops and operations to obtain a holistic view of the entire farming enterprise (Baillie and Chen, 2007). Each analysis can be saved as a Level 1, 2 or 3 assessment so as to differentiate between the accuracy of input data. The choice of level, however, does not change the required user inputs or method of calculation. The results are presented in reports that list energy inputs for different machinery used and categorises EU by the key processes mentioned above. User defined, site specific data can be added while populating the calculator, and this together with the output format of the reports enables benchmarking against peer farmers and best practices (Baillie and Chen, 2007).

Although the calculators themselves do not suggest energy saving opportunities as an output, reports and papers by the developers discuss potential areas for improvements in EU efficiency and consequent reductions in the carbon footprint of the production operation or system analysed. These potential areas of improvement in EU are covered in Section 2.4 below.

2.5 Opportunities to Reduce Direct Energy Use and Carbon Footprint

Recently, much research has been conducted to identify methods to reduce EU and carbon footprint in farming operations. These methods range from changes in management practice to the adoption of new and appropriate technologies.

The methods that are applicable to sugarcane production are summarised in Tables 2.4 and 2.5. Table 2.4 contains information on the possible methods to reduce EU in operations that require diesel as an energy source and, similarly, Table 2.5 contains information for electricity use in irrigation. In both tables, the methods are grouped according to the objective they are trying to achieve. The objectives which contribute towards a reduction in EU and carbon footprint include decreasing operating hours, increasing efficiency, and reducing the load on the power unit.

Table 2.4 Objectives and methods to reduce EU in diesel dependent operations

Objective	**Method**
Decrease operating hours	• Minimum and/or combination tillage to reduce the number of field operations (Mrini *et al.*, 2001; Karimi *et al.*, 2008; Baillie and Chen, 2011; Baillie and Chen, 2012) • Appropriate tractor-implement matching for increased field efficiencies (Dyer and Desjardins, 2003) • Precision application of agronomic products to reduce hopper and tank refills and increase field efficiencies (Sandell *et al.*, 2013) • Increase transport vehicle payloads to reduce trips to the mill (Mrini *et al.*, 2001; Karimi *et al.*, 2008)
Increase EU efficiency	• Scheduled tractor and transport vehicle maintenance for increased fuel efficiency (Mrini *et al.*, 2001; Karimi *et al.*, 2008) • Appropriate tractor-implement matching for most efficient use of available tractor power (Dyer and Desjardins, 2003) • Tractor operator training for most efficient operation of tractor engines (Smith, 1993; Baillie and Chen, 2009; Kichler *et al.*, 2011) • Tractor operator training to setup implements for the most effective and efficient operations (Mrini *et al.*, 2001; Serrano *et al.*, 2003; Karimi *et al.*, 2008)
Decrease load on power unit	• Timing tillage operations to coincide with appropriate soil moisture conditions for reduced draft requirements (Mrini *et al.*, 2001; Karimi *et al.*, 2008) • Tractor operator training to setup an implement for the lowest draft while maintaining the efficacy of the operation (Serrano *et al.*, 2003) • Controlled traffic systems to increase tractive efficiency in the inter-

	row and reduce the draft of soil engaging equipment (Jenane *et al.*, 1996; Gasso *et al.*, 2013)

Table 2.5 Objective and methods to reduce EU in electrically powered irrigation systems

Objective	**Method**
Decrease operating hours	Change in irrigation regulation or scheduling to limit over-irrigation (Moreno *et al.*, 2007)
Increase EU efficiency	• Electric motor load matching for most efficient use of available power (Kaya *et al.*, 2008) • Installation of Variable Speed Drives (VSDs) to match the power supply with the system's demand (Hanson *et al.*, 1996; Saidur, 2010; Lamaddalena and Khila, 2011; Saidur *et al.*, 2012)
Decrease load on power unit	• Maintenance and repairs to irrigation networks to reduce friction losses and reduce the system pressure requirements (Kaya *et al.*, 2008) • Where possible, conversion to a system with low operating pressure requirements, such as drip or furrow systems (Mrini *et al.*, 2001; Karimi *et al.*, 2008)

As reported in Chapter 6, case studies using the energy calculator developed in this study make use of some of the above methods to compare possible reductions in EU with their current EU. The development and structure of the calculator follow in Chapter 3.

3. ENERGY CALCULATOR DEVELOPMENT AND STRUCTURE

The primary aim of this project is to develop an energy calculator for sugarcane production in South Africa. It must be emphasised that the energy under consideration is only direct energy. Direct energy is the energy content of fuels, lubricants, and electrical power used in sugarcane production. Hence, no indirect energy used in processing agronomic inputs or that which is embedded in farm structures and machinery are considered. For the remainder of this document any reference to "Energy Use" (EU) implies "direct" EU, unless otherwise specified. This chapter contains a description of the concept, structure and functionality of the energy calculator.

3.1 Conceptualisation and Requirements

The concept of an energy calculator is not new. However, the calculators (USDA, 2006; NCEA, 2011) that were reviewed in Chapter 2 do not capture all the processes and operations involved in sugarcane production in South Africa. The harvest and transport systems that are used in South Africa differ to those used in the more mechanised industries in Australia and United States of America. Further to this, certain aspects in the calculation of EU were also seen to be over-simplified, neglecting changes in variables which may lead to a more accurate estimation of EU. For example, the calculation in both the *USDA Energy Estimator* and *EnergyCalc* of fuel consumption in tractor tillage operations does not take into account the working depth, soil conditions and operation speed.

The value of a decision support tool is only realised if it is designed to suit the needs of the target user. In this case there were a number of potential users of the calculator, including growers, extension specialists, and researchers.

It would be useful to have an energy calculator capable of quantifying and benchmarking EU and carbon footprint in sugarcane production. The development of the calculator into a web-based application that is available to growers and extension specialists should also be considered. Thus, not only will the calculator be used as a research tool, but also as a decision support tool for extension and growers. For the remainder of this document, the researcher, extension specialist and grower will collectively be referred to as the "user".

MS Excel ® was used as a platform for the development of the calculator, from which it can be converted to a web-based application. It was decided to focus on, and complete only the Excel ® version for the purpose of this dissertation, with the web-based application being completed at a later stage.

3.2 Functional Units

In order to compare the results of energy assessments within a farming enterprise and against other enterprises, it is necessary to decide on a functional unit that normalises EU (Alluvione *et al.*, 2011; García *et al.*, 2011). This is also necessary when assessing potential EU savings of alternative production systems.

Mrini *et al.* (2001) and Alluvione *et al.* (2011) used energy intensity as an energy indicator for their studies in EU in agriculture. Karimi *et al.* (2008) used similar terminology, "energy productivity", to define the same unit of measurement. Energy intensity was chosen as the functional unit for this study so that different farming operations and systems could be compared. The functional unit of energy intensity can either be expressed as a ratio of energy used to the mass of crop yielded [e.g. $MJ.t^{-1}$] or alternatively as energy used relative to the area cultivated [e.g. $MJ.ha^{-1}$]. Although EU per ton is a better indicator of efficiency of converting energy into useful product, EU per area cultivated is potentially useful when assessing the EU in agronomic homogenous regions. Both functional units are used in the output of the results from the calculator.

3.3 Structure and Functionality

For the purpose of the energy calculator, total EU and carbon footprint are apportioned to different process in sugarcane agriculture. These processes are:

i) re-establishment,
ii) ratoon management,
iii) harvest and transport,
iv) general tractor use,
v) break cropping, and

vi) irrigation

The function of the energy calculator is to quantify EU in these processes at different levels of detail. Often more input detail is required by the user when a more precise and descriptive method is used to quantify EU. This results in a greater potential to identify opportunities to improve energy efficiency and subsequently reduce EU. For example, calculating the EU of a tillage operation using empirical equations provides move evidence as to where inefficiencies may lie as opposed to EU calculations based on an average fuel consumption rates.

The level of detail to which EU is quantified is categorised in a similar way to that defined by the ASABE (2009) and used by Bailie and Chen (2007). Table 3.1 contains a summary of the structure of the energy calculator developed in this study. The calculator is divided into three levels of assessment, each having their own data requirements. Table 3.1 also details the means by which data can be obtained for each level of assessment.

Table 3.1 Structure of the energy calculator (shaded cells pertain to electrical EU in irrigation, and the un-shaded cells refer to diesel use in mechanisation operations)

Level	Data Requirements	How data is obtained
1. Accounts	• Electricity cost, or • Active energy used	• Electricity accounts, or • Meter readings
	• Fuel cost, or • Bulk volume used	• Diesel accounts or • Farm records
2. Operational time; or Simulated	• Irrigation system details	• Owner / managers
	• Machinery engine hours and odometer readings, or • Details of operations and management practices	• Owner / managers
3. Measured	• Detailed system specifics, and • Continuous / instantaneous system measurements	• Owner / managers • Recorded and direct measurement
	• Detailed system specifics, and • Continuous / instantaneous system measurements	• Owner / managers • Recorded and direct measurement

The structure of the energy calculator is further illustrated in the flow diagram in Figure 3.1. It is intended that the user moves from a Level 1 to a Level 3 assessment. At the completion of a Level 1 assessment, results can be viewed, analysed and a decision can be made as whether to end the assessment, or progress to a Level 2 or 3 assessment. At the completion of a Level 2 or 3 assessment, the user has three options; (i) the assessment can be ended with no further action, (ii) simulated energy saving changes can be re-run through a Level 2 assessment, and (iii) energy saving practices or technologies can be implemented and any level of assessment can be re-run.

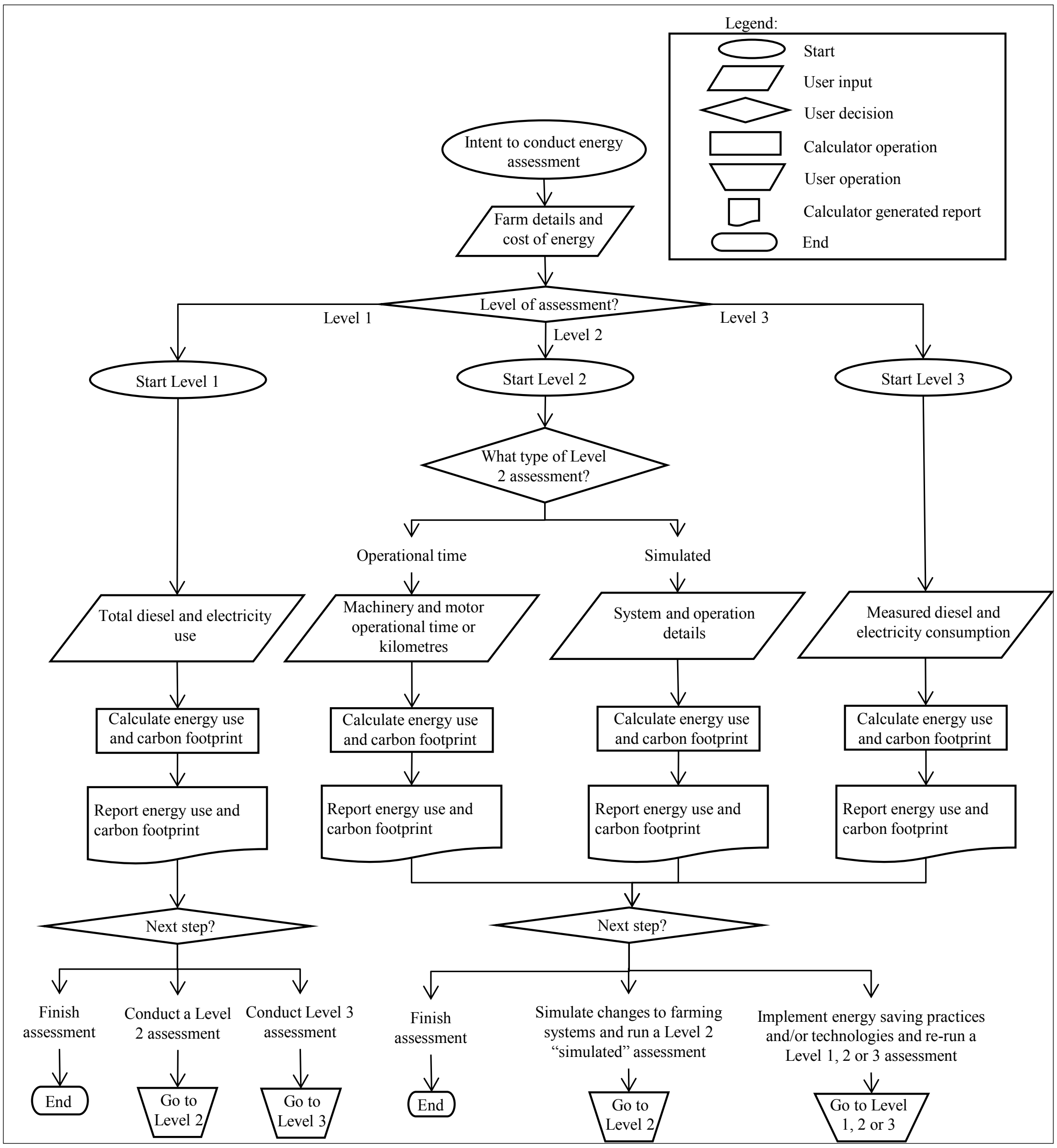

Figure 3.1 Simplified flow diagram of the energy calculator

The Excel workbook used for the calculator is structured such that the user moves sequentially through worksheets addressing the input requirements for each level of assessment. The last tab is a summary of the results for each level of assessment completed. An explanation of each tab and subsequently the functionality of the calculator follow in the following subsections. Reference should be made to Appendix 1 to supplement the following subsections. Appendix 1 is a detailed diagrammatic version of Figure 3.1 and expands on the input requirements for each level of assessments and gives examples of the results that are generated. The reader can also refer to the MS Excel ®, spreadsheet version, of the energy calculator. A copy of this can be found on the CD that accompanies this document.

3.3.1 Assessment results

In practice, the results of an assessment would only be obtained once the input fields of the different levels of assessment have been populated. However, for the purposes of this document, discussing the assessment results first provides a holistic idea of the structure and functioning of the energy calculator.

For a Level 1 "accounts" assessment, total EU is apportioned to total diesel and electrical consumption and reported in a summary table (see Appendix 1) using the following units of measurement:

- energy intensity [$GJ.ha^{-1}$] or [$MJ.t^{-1}$],
- GHG emission intensity [kg CO_2e ha^{-1}] or [kg CO_2e t^{-1}], and
- cost of EU [$R.ha^{-1}$] or [$R.t^{-1}$].

For a Level 2 assessment, both "operational hours" and "simulated" assessments produce the same summary table. Although, diesel and electricity is divided into the six processes mentioned in Section 3.3.

To reconcile Level 2 assessments against Level 1 assessments, a stacked bar chart is produced. An example of this is shown in Appendix 1. From this reconciliation process, if discrepancies exist, the decision can be made to proceed to a Level 3 "measured" assessment.

3.3.2 Assessment specifications

The "Assessment specifications" defines the time period that the assessment will cover, the farming enterprise and the cost per unit of diesel and electricity. The assessment time period will likely be historical so that results can be compared against farm records or accounts. Alternatively, an assessment might be conducted to forecast EU if, for example, management practices are changed.

The farming enterprise input form requires the following information:

- mill area (e.g. Pongola),
- total arable area [ha],
- area under sugarcane [ha],
- portion of arable area break cropped [%],
- portion of arable area fallowed [%],
- average seasonal harvest [t], and
- percentage of total arable area replanted [%].

3.3.3 Level 1 “Accounts”

If the farm’s records and accounting is accurate, this level of assessment is the most simple and accurate means of quantifying EU over a given period of time. The term “accounts” is used to encompass farm records and/or financial accounts and receipts from the energy suppliers.

For diesel use, the beginning of an assessment period might not coincide with the purchase and refilling of a diesel bowser, and hence fuel not used during the assessment period will not be accounted for. It is expected that the total metered volume of diesel pumped from a farm bowser during an assessment period will be more accurate than the sum of the purchase receipts from a supplier.

Similar issues related to differences in the metered and use periods of electricity may arise. As a result, the total active energy [kWh] component can be read from the electricity account and prorated if appropriate. In some cases, the electricity supplier records half-hourly power consumption at the transformers, which, by request, is available to the customer. This detailed information would be useful for both Level 2 as well as Level 3 assessments, as discussed in Section 3.3.6.

3.3.4 Level 2 "Operational time"

This level of assessment is the first partitioning of EU into the six different processes defined in Section 3.3. It is necessary for this, as well as the Level 2 "simulated" and Level 3 "measured" assessments to create a power unit inventory for the farming enterprise. In addition to operating hours or kilometres, details necessary for the calculation of EU are listed for each power unit. The power units are classified by the following convention:

- type (e.g. tractor, electrical pump, farm vehicle etc.)
- manufacturer name,
- model name or number,
- bin or trailer payload if used for haulage,
- rated power,
- drive system (E.g. 4WD, 2WD etc.), and
- operational hours or kilometres for the assessment period.

Optional input fields exist for information regarding average fuel consumption and work rates. These can be populated if the performance and efficiencies of the machinery have been assessed. If available, these values will be used as opposed to calculated values in Level 2 and 3 assessments.

Operating hours, or distance travelled, together with the power unit's rated power is used to calculate EU. Typically operating hours and kilometres are readily available from farm records, as servicing and maintenance of machinery is normally scheduled according to use. The only power units that use kilometres as an indication of operational time are transport vehicles. In sugarcane production these would include haulage trucks, light motor vehicles and motorcycles. For all other power units, operational hours would be the unit of measurement.

It is required that, for all tractors defined in the power unit inventory, an estimated percentage of their use in the different processes be specified as a percentage of the annual running hours. The calculator assumes a typical engine load for the process and calculates fuel consumption accordingly. These default engine loads can be changed by a user who has some experience of how loaded the tractor typically is for a given operation. Details of the calculation methods follow in Chapter 4.

3.3.5 Level 2 “Simulated”

Simulated assessments are desktop based and rely on the owner or manager’s knowledge and records of operations to populate input fields. If a Level 2 “operational time” assessment has not been conducted prior to starting this level of assessment, the user is required to create a power unit inventory for the farming enterprise. Agricultural tractors are used in the majority of the processes on the farm. As such, one worksheet is dedicated to the simulation and calculation of EU from tractor operations. The harvest and transport operations and irrigation process also have their own worksheets, all of which are discussed below.

3.3.5.1 Tractor operations

The intention of this level of assessment is to simulate tractor operations to calculate fuel consumption accurately with as much detail as possible. The input variables, having the biggest impact on fuel efficiency, can then be identified. Only in-field operations are covered here, where the tractor is used as a power source for soil engaging operations and agronomic production operations. These operations make up the bulk of fuel consumption in re-establishment, ratoon management and break crop processes. Tractor fuel consumption in the harvest and transport process is accounted for in the Level 2 “Simulated harvest and transport” sheet (Section 3.3.5.2). Details of how fuel consumption is calculated for “general tractor use” operations are covered in Chapter 4. “General tractor use” includes operations that are not directly related to sugarcane husbandry such as carting, slashing, road maintenance and maintenance of structures.

Each operation is defined by an operation name (e.g. Crop eradication), task name (e.g. Spray), the power unit (e.g. New Holland DT90), and the implement or machine used (e.g. boom sprayer). Thereafter, each task requires input variables which are selected from drop-down lists as well as user defined fields. The input variables required for the calculation of fuel consumption rate include the following:

- implement or machine description,
- application rate,
- depth of operation (if soil engaging),
- estimated clay percentage of soil,
- tractive conditions,
- travel speed, and
- field efficiency.

If different combinations of tractor operations are used for different fields, the user can define these as a percentage of the total area under sugarcane. This could be the case where slopes are too steep for mechanical operations, or if climatic conditions negate a certain management practice.

Further to fuel consumption, an Overall Energy Efficiency (OEE) ratio is calculated for each operation. The OEE ratio shows the percentage of chemical energy embedded in diesel fuel that is converted for useful work (Bowers Jr, 1985). Bowers Jr (1985) reported that a well matched tractor-implement combination should have an OEE ratio of between 10 % and 20 %. An OEE ratio less than 10 % indicates either poor load matching and/or tractive efficiency (Kheiralla *et al.*, 2004).

3.3.5.2 Harvest and transport

As with the tractor operations, the user can define the percentage of the total sugarcane production area where different extraction systems are used. For each system, the user is required to select from the power unit inventory, the in-field loader, field-to-zone haulage vehicle, the trans-loader, and zone to mill haulage vehicle. In addition, information pertaining to average field to zone distance and speed, as well as zone to mill distance is required. If the system is a direct, field to mill type, the field to zone transport and trans-loading will be omitted from the calculations. Details on how fuel consumption is calculated are covered in Chapter 4.

3.3.5.3 Irrigation

Simulated irrigation EU is based on the difference between evapotranspiration and effective rainfall. The user is required to specify the area under irrigation for each pump itemised in the power unit inventory. Thereafter, input fields for details of the type of system, pressure requirements and efficiencies are populated. Flow requirements are calculated using simulated gross irrigation requirements of the crop.

3.3.6 Level 3 "Measured"

It is advisable that a Level 3 assessment only be conducted once a Level 2 assessment is complete. The Level 2 assessment highlights areas where energy savings are possible. A Level 3 assessment will reaffirm these areas and justify the implementation of any energy saving management practices and/or technologies.

3.3.6.1 Diesel consumption

Measuring the fuel consumption rate for any diesel powered machinery can either be done by on-board engine management systems or direct, bulk volumetric measurement. Due to the nature of the machinery used in the sugarcane industry in South Africa, the latter is likely to be the most feasible means of measurement.

For tractor operations, the user is required to input a description of the operation, field efficiency, time of entry to the field, time of exit from the field, and diesel consumed during the operation. From this a fuel consumption rate [$l.ha^{-1}$] is calculated.

Fuel consumption rates for loading machinery requires information regarding the payload of the trailer being loaded, the number of trailers loaded and the volume of fuel consumed during that time. A fuel consumption rate [$l.t^{-1}$] is then calculated.

For computing haulage vehicle fuel consumption, the following measured input parameters are required: payload [t], cycle (return) distance, and the volume of fuel consumed per cycle. A fuel consumption rate per ton-kilometre [$l.t^{-1}.km^{-1}$] is subsequently calculated.

3.3.6.2 Electricity use in irrigation

Generally for transformers in rural areas, a thirty minute average measurement of electricity use is available from the energy provider. However, for some older installations, this resolution of metering is not possible (Moynihan, 2013). Furthermore, there is the likelihood of multiple pump motors being run off the same transformer which would make the metered data difficult to interpret. Therefore, in such situations and if more detailed data is necessary, electricity metering devices can be installed at the control panel or at the switch gear of individual motors.

To add value to electrical data, suction and delivery pressures as well as flow rate should be measured and recorded. In light of this, an instrumentation kit was designed and constructed for this level of assessment. The kit, referred to as a Pump Evaluation Kit (PEK), comprises of an electricity metering device, three pressure sensors, an ultra-sonic flow meter, multi-channel data logger, and a GSM modem. Further details of the components and costs thereof are contained in a table in Appendix 2. The electricity metering device measures apparent and reactive current and voltage, from which phase angle, frequency and power can be calculated. Figure 3.2 shows the complete kit, housed in an electrical box for protection and ease of transport. A description of how the PEK is installed is covered in Chapter 6, where it is used in a Level 3 assessment case study.

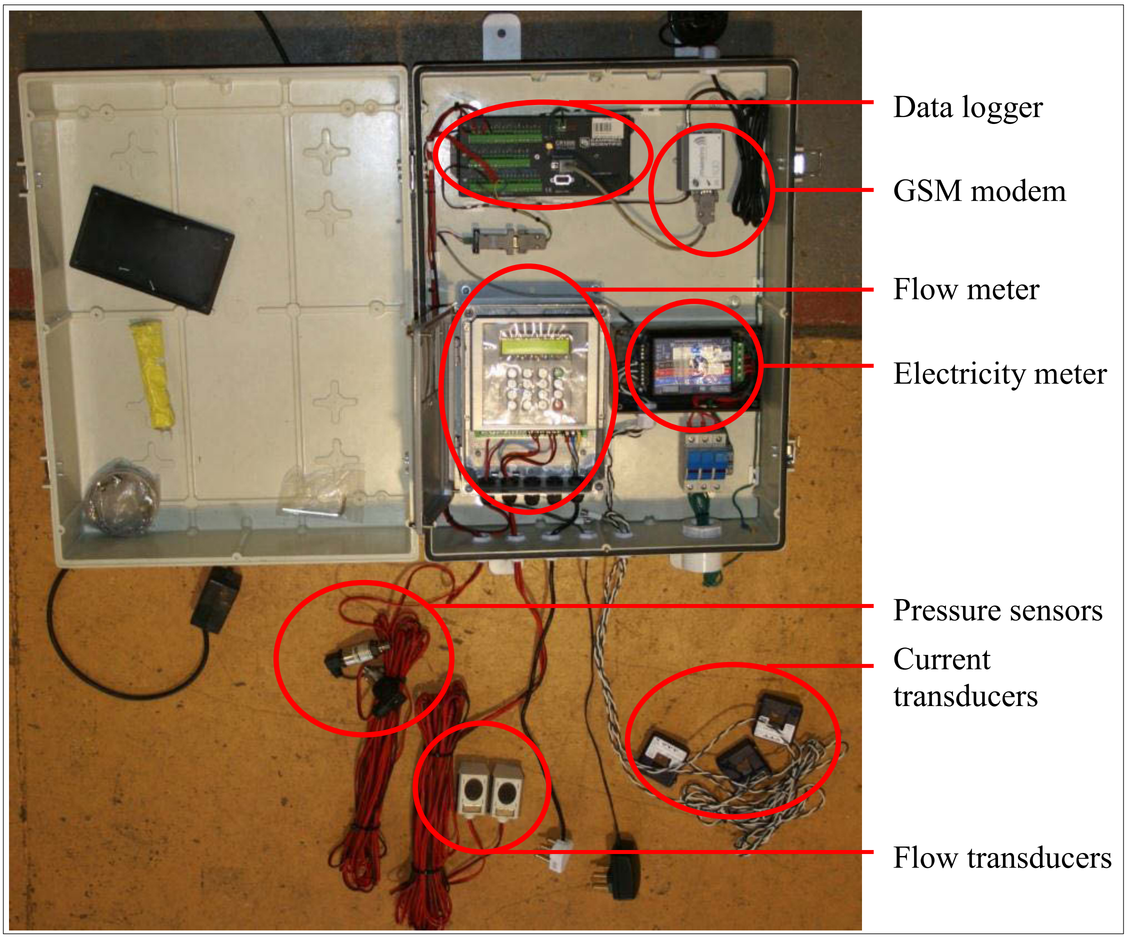

Figure 3.2 Final assembly of the Pump Evaluation Kit (PEK)

4. CALCULATION METHODS

The methods used to calculate diesel fuel consumption and electricity use for each level of assessment are detailed in this chapter. The order in which the equations are presented is according to the logical progression through an energy assessment.

4.1 Level 1 "Accounts"

At an accounts level, the user can either input a cost for electricity and diesel consumed during the assessment period, or alternatively the quantities consumed if they were recorded. Converting the cost of Energy Use (EU) into litres and kilowatt hours is achieved by dividing the total cost by the unit cost of diesel and electrical energy.

The quantity of electricity and diesel consumed can be converted into an equivalent energy intensity value using Equation 4.1.

$$EI = e\ C_E\ \frac{1}{A_{SC}} \quad \text{..........} (4.1)$$

where EI = energy intensity [$MJ.ha^{-1}$],

e = quantity of active electrical energy or diesel consumed [kWh or l respectively],

C_e = calorific value of diesel or conversion factor for electricity [$MJ.l^{-1}$ or $MJ.kWh^{-1}$], and

A_{SC} = area under sugarcane [ha].

For diesel fuel, the calorific value used is 37 $MJ.l^{-1}$ (FAO, 1991), and the conversion factor for electrical EU is 3.6 (FAO, 1991).

Greenhouse Gas (GHG) emissions are calculated by multiplying the quantity of electrical energy or diesel consumed by its carbon dioxide equivalent coefficient (Equation 4.2).

$$GHG = e \times C_{GHG} \quad \text{..........} (4.2)$$

where GHG = carbon dioxide equivalent (CO_2e) emissions [kg], and

C_{GHG} = CO_2e coefficient (mass of CO_2e emitted per litre of diesel or kilowatt-hour electricity) [$kg.l^{-1}$ or $kg.kWh^{-1}$] (refer to Table 2.2 for values specific to South Africa)

Equations 4.1 and 4.2 are used in every level of assessment once the quantity of active electrical energy and volume of diesel are calculated.

4.2 Level 2 "Operational time"

In a Level 2, "Operational time" assessment, the user is required to estimate the percentage of the total engine hours of a specific tractor that are spent on each of the six processes defined in Section 3.3. A default average engine loading factor for tractor operations within each process is used. This is, however, dependant on the rated power of the tractor and the details of the implement and operation, all of which are farm and operation specific. As such, the user has the ability to increase or decrease the load factor. As a guide, and based on EU estimates from Ortiz-Canavate and Hernanz (1999), the defaulted engine loading factors for the different processes are:

- re-establishment: 60 %,
- ratoon management: 40 %,
- sugarcane haulage: 30 %,
- general tractor use: 30 %, and
- break crop: 60 %.

Having input the rated engine power and total engine hours in the assessment specifications, and specifying the percentage of time spent on each process, the total fuel consumption for each process is calculated using Equation 4.3 (Grisso *et al.*, 2004).

$$FC = SFC \times P \times f \times t \quad (4.3)$$

where FC = total fuel consumption [l],

SFC = specific fuel consumption [$l.kWh^{-1}$] (see Equation 4.5),

L = engine loading [%],
P = rated tractor power [kW],
f = percentage of engine hours spent on a process [%], and
t = total engine hours of the tractor for the assessment period [h].

4.3 Level 2 “Simulated” - Tractor Operations

ASABE standards (ASABE, 2011) were used to calculate fuel consumption for soil engaging and Power Take-off (PTO) operations. Total fuel consumption for all operations is calculated using Equation 4.4 (ASABE, 2011).

$$\mathrm{FC} = \frac{\mathrm{SFC} \times \mathrm{P}}{\mathrm{C_{ha}}} \times \mathrm{A} \qquad (4.4)$$

where $\mathrm{C_{ha}}$ = work rate [ha.h^{-1}], and
A = area worked [ha].

The specific fuel consumption at full throttle is calculated using an empirical equation (Equation 4.5) developed by Grisso *et al.* (2004).

$$\mathrm{SFC} = 0.22\mathrm{L} + 0.096 \qquad (4.5)$$

where L = engine loading [fraction].

Engine loading is defined by ASABE (2011) as the fraction of equivalent PTO power available (Equation 4.6).

$$\mathrm{L} = \frac{\mathrm{P_T}}{\mathrm{P}} \times 100 \qquad (4.6)$$

where $\mathrm{P_T}$ = the total power requirements for an operation [kW].

Work rate, often referred to as field capacity, is calculated using Equation 4.7 (ASABE, 2011). This is dependent on the speed, effective working width and field efficiency of the operation. Field efficiencies vary depending on the type of operation, although typically for tillage operations this ranges from 0.7 to 0.9 and 0.5 to 0.7 for chemical and fertiliser type applications, respectively, where refilling is necessary (DAFF, 2013).

$$C_{ha} = \frac{s \times w \times E_f}{10} \quad (4.7)$$

where s = field speed [km.h^{-1}],
w = implement working width [m], and
E_f = field efficiency [fraction].

The total power requirement (P_T) for an operation is calculated by Equation 4.8. This is the sum of the drawbar, PTO, hydraulic and electrical power requirements of the operation (ASABE, 2011). Since tractor operations carried out in sugarcane agriculture rely predominantly on drawbar and PTO power, only these two components of the total power requirements are detailed in Equations 4.9, 4.10 and 4.11.

$$P_T = \frac{P_{db}}{E_m \times E_t} + P_{pto} + P_{hyd} + P_{el} \quad (4.8)$$

where P_{db} = drawbar power requirement [kW],
P_{pto} = power-takeoff (PTO) power requirement [kW],
P_{hyd} = hydraulic power requirement [kW],
P_{el} = electrical power requirement [kW],
E_m = overall mechanical efficiency of tractor [fraction], and
E_t = tractive efficiency [fraction].

Typical tractive efficiency values are published by the American Society for Agricultural and Biological Engineering (ASABE, 2011). These tractive efficiencies are presented in Table 4.1 for different tractor types and tractive conditions and are used in the calculator.

Table 4.1 Typical tractive efficiencies for different tractor types and tractive conditions (after ASABE, 2011)

Tractor Drive Type	**Tractive Condition**			
	Concrete	**Firm**	**Tilled**	**Soft**
2WD	0.87	0.72	0.67	0.55
MFWD	0.87	0.77	0.73	0.65
4WD	0.88	0.78	0.75	0.70
Track	0.88	0.82	0.80	0.78

ASABE (2011) use horizontal draft and travel speed to calculate the drawbar power required for an operation (Equation 4.9).

$$P_{db} = D \times s \qquad (4.9)$$

where D = horizontal draft of implement [kN].

ASABE (2011) contain empirical equations to calculate draft requirements for a range of soil engaging implements. The draft can be calculated using Equation 4.10.

$$D = F_i \times [A + B(s) + C(s)^2] \times w \times T \qquad (4.10)$$

where F_i = soil adjustment parameter [dimensionless],

A, B, C = implement specific parameters [dimensionless], and

T = depth of operation [cm].

Similarly, ASABE (2011) contain empirical equations to estimate PTO power requirements for typical operations (Equation 4.11).

$$P_{pto} = a + (b \times w) + (c \times F) \qquad (4.11)$$

where a, b, c = machine specific parameters, and

F = material feed rate [$t.h^{-1}$].

The Overall Energy Efficiency (OEE) of a tractor operation is calculated using Equation 4.12 (Bowers Jr, 1985).

$$\text{OEE} = \frac{3.6\times(L\times P)}{38.7\times\frac{FC}{A}\times C_{ha}}\times 100 \qquad (4.12)$$

where OEE = overall energy efficiency [%].

4.4 Level 2 “Simulated” - Harvest and Transport

Harvest and transport fuel consumption consists of loading and trans-loading operations, as well as zone and mill haulage. It is assumed that the most accurate means of estimating total fuel consumption is if typical consumption and work rates are known by the user. The default option is for these input values to be used to calculate total fuel use for the operation. Alternatively, if these values are not known, manufacturer specified rates or industry norms contained in the calculator database are used for calculations. Fuel consumption rates and methods of calculating total fuel use for each operation in the harvest and transport process are discussed below.

4.4.1 Mechanical loading and trans-loading

Total fuel use for mechanical loading and trans-loading is calculated using Equation 4.13.

$$FC = Q_h \times C_t \times Y \qquad (4.13)$$

where Q_h = fuel consumption rate [$l.h^{-1}$],
C_t = average work rate [$t.h^{-1}$], and
Y = tons cane harvested [t].

4.4.2 Field to zone haulage

Field to zone haulage is typically carried out by agricultural or haulage tractors. Typical fuel consumption rates for sugarcane transported by haulage tractors are extracted from the SASRI mechanisation cost guides (Tweddle, 2013b) and are used to calculate (Equation 4.14) total fuel consumption, unless otherwise defined by the user.

$$FC = (\frac{Y}{PL}) \times Q_h \times \frac{t_{min}}{60} \qquad (4.14)$$

where PL = payload of trailer [t], and

t_{min} = field to zone to field time [min].

4.4.3 Mill haulage

If a tractor is used for mill haulage, from a zone or directly from the field, fuel consumption is calculated by Equation (4.14) as in zone haulage. For haulage by truck, Equation 4.15 is used. Again, typical fuel consumption rates for truck cane haulage are extracted from SASRI mechanisation cost guides (Tweddle, 2013b) and are used to calculate (Equation 4.15) total fuel consumption, unless otherwise defined by the user.

$$FC = (\frac{Y}{PL}) \times \frac{Q_{km}}{100} \times (d \times 2) \qquad (4.15)$$

where Q_{km} = fuel consumption [$l.100km^{-1}$], and

d = distance to mill [km].

4.5 Level 2 "Simulated" - Irrigation

Due to the potential inconsistency of defining irrigation system duty points and management regimes, it was decided to estimate the EU of the system according to the Gross Irrigation Requirements (GIR) of a typical crop in the region and for the timeframe the assessment is being conducted. In doing so, a comparison can be made between billed energy consumption and a theoretical EU calculated from crop water requirements.

The electrical energy requirement for irrigation systems is calculated using hydraulic principles as contained in Equation 4.16 (Moreno *et al.*, 2007).

$$e = \frac{\rho \times g \times Q \times (H_2 - H_1)}{n_p \times n_c \times n_m \times n_s \times 3600} \times t_p \qquad (4.16)$$

where e = annual active energy requirement [kWh],

ρ = density of water [kg.m^{-3}],
g = gravitational constant [m.s^{-2}],
Q = flow rate [m^{3}.h^{-1}],
H_2 = delivery side pressure requirement [m],
H_1 = suction side pressure [m],
n_p = efficiency of pump at duty point [%],
n_c = efficiency of motor-pump coupling [%],
n_m = efficiency of motor [%],
n_s = efficiency of switchgear [%], and
t_p = pumping time [h].

For comparison with measured active electrical EU from service provider accounts, it is logical to assess this energy requirement for a monthly or annual period. For an annual energy estimate, the Gross Irrigation Requirement (GIR) for the time period of one year would be used for the calculation of EU in Equation 4.17.

$$e = \frac{\rho \times g \times \left[\frac{GIR \times 10 \times A_{sc}}{3600 \times 24 \times 365}\right] \times (H_2 - H_1)}{n_p \times n_c \times n_m \times n_s} \quad \text{........} (4.17)$$

where GIR = annual gross irrigation requirement [mm.annum^{-1}].

GIR is calculated (Equation 4.18) as the difference between the crop evapotranspiration and effective rainfall for an area, taking into account the irrigation system efficiency. The multipliers, 3600, 24, 365 and 10 are necessary to convert GIR [mm.annum^{-1}] into a flow rate [m^{3}.s^{-1}].

$$GIR = \frac{ET_c - R_e}{n_i} \quad \text{........} (4.18)$$

where ET_c = annual evapotranspiration of the crop [mm.annum^{-1}],
R_e = annual effective rainfall [mm.annum^{-1}], and
n_i = system irrigation application efficiency [%].

The annual evapotranspiration for the entire crop, taking into account all stages of growth for an entire farm was obtained from simulations done using the *CaneSim* model (Singels, 2011). Simulations were run for all the automatic weather stations in the South African sugarcane industry from which the user is able to select the nearest to the farm being assessed.

The effective rainfall is the portion of rainfall that is used for the evapotranspiration requirements of a crop. Effective rainfall was obtained from the results of the *CaneSim* (Singels, 2011) simulations conducted to determine annual evapotranspiration.

In Equation 4.19, the delivery side pressure head requirements, H_2, are estimated as the sum of the system operating pressure, elevation difference between the pump and the highest emitter, and the friction losses incurred from the pump to the furthermost emitter. The friction losses are estimated as 1.5 % of this distance (Koegelenberg and Breedt, 2003).

$$H_2 = H_e + H_s + (d_e \times 0.015) \quad (4.19)$$

where H_e = system operating pressure [m],
H_s = static head [m], and
d_e = distance from the pump to the furthermost emitter [m].

The suction side pressure head requirements (H_1) are, in most cases, negligible in comparison to the delivery side. This is due to the close proximity of the pump to the water source. Alternatively this can be calculated using Equation 4.20 (Mulder *et al.*, 1997b).

$$H_1 = \frac{-v^2}{2g} - h_2 - h_f \quad (4.20)$$

where v = velocity of fluid entering the pump [$m^3.s^{-1}$],
h_2 = elevation of pump relative to the reservoir [m], and
h_f = sum of losses between the foot valve and pump [m].

The efficiencies of the pump station n_c, n_m and n_s are all constant for a given system whereas, the pump efficiency, n_p, is dependent on the pump characteristics and operating or duty point. If the duty point flow rate and pressure are known by the user, it is expected that the relevant pump curves are used in order to obtain the pump efficiency. Alternatively a default value of 75 % is used.

4.6 Level 3 "Measured"

Calculations of diesel consumption in this level of assessment are simple and are based on volumes, work rates and time and are thus not detailed in this section. However, the calculation of electrical energy in irrigation requires definition. Electrical EU can be calculated using Equation 4.21 (Hambley, 2005).

$$e = \sqrt{3} \times V_{LL} \times I_{\emptyset} \times PF \times t_p \qquad (4.21)$$

where V_{LL} = line-to-line supply voltage [V],
$I_{\emptyset}$ = phase current [A], and
PF = power factor [fraction].

The line-to-line voltage and phase currents can be measured using a multi-meter or an electrical energy meter and logger as used in the pump evaluation kit developed in this study. The power factor is specified on the motor nameplate for full load applications. Alternatively, this is a calculated output of most electrical energy meters.

The total pumping efficiency, which is the efficiency by which electrical energy is converted to hydraulic energy is calculated using Equation 4.22 (Moreno *et al.*, 2007). This will be referred to as total pump station efficiency (n).

$$n = \frac{\rho \times g \times Q \times (H_2 - H_1)}{\sqrt{3} \times V_{LL} \times I_{\emptyset} \times PF} \qquad (4.22)$$

The efficiency of the pump is useful to know, especially for maintenance and upgrade purposes. This can be calculated by Equation 4.23 (Moreno *et al.*, 2007).

$$n_p = \frac{n}{n_c \times n_m \times n_s} \qquad (4.23)$$

A default value of 98 % is used for a combined coupling and switchgear efficiency. Usually, minimal power losses occur in the coupling and switchgear, especially if a direct coupling system is used (Mulder *et al.*, 1997a). The efficiency of the motor can be obtained from the motor nameplate. All three of these efficiencies can, however, be defined by the user.

A typical pump-throttle assembly used to regulate pressure and flow in irrigation systems is shown in Figure 4.1. Points 1, 2 and 3 are positions where pressure sensors/gauges are essential for system control and performance monitoring.

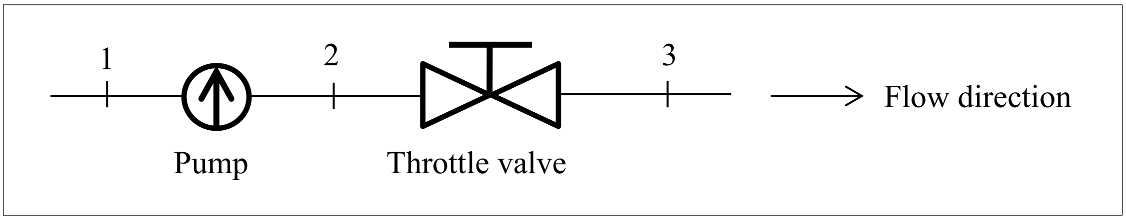

Figure 4.1 A simplified schematic of a pump-throttle assembly to control flow and pressure in irrigation systems

The power dissipated across a throttle valve ($P_{2\text{-}3}$) can be calculated using Equation 4.24, which is similar to Equation 4.16 (Moreno *et al.*, 2007).

$$P_{2\text{-}3} = \rho g(H_3 - H_2)Q \qquad (4.24)$$

where H_3 = pressure downstream of the throttle valve [m].

The percentage of hydraulic power produced by the pump that is dissipated across the throttling valve (e_{loss}) can be calculated by the ratio of $P_{2\text{-}3}$ to the power generated by the pump, $P_{1\text{-}2}$ (Equation 4.25).

$$e_{loss} = \frac{\rho g(H_3 - H_2)Q}{\rho g(H_2 - H_1)Q} \times 100 \qquad (4.25)$$

As ρ, g and Q are constant, Equation 4.25 can be simplified to Equation 4.26.

$$e_{loss} = \frac{H_3 - H_1}{H_2 - H_1} \times 100 \qquad (4.26)$$

This chapter has summarised the methods that were chosen to calculate EU in sugarcane production. The following chapter details the process of selecting a suitable method to calculate fuel consumption in tractor tillage operations. Using data from literature, three methods were compared and assessed based on their accuracy in predicting fuel consumption.

5. SELECTION OF THE METHOD USED FOR ESTIMATING FUEL CONSUMPTION IN TILLAGE OPERATIONS

As a consequence of the approximately 10 % seasonal replant rate typical to sugarcane production in South Africa, tractor hours spent on tillage operations are less than for the production of annual crops. They remain, however, energy intense operations with highly variable fuel consumption rates. It is therefore necessary to calculate fuel consumption rates and define the operations as accurately as possible in order to identify where fuel savings can be realised. Other tractor operations typical to sugarcane agriculture include product application, transport and farm maintenance. The fuel consumption rates for these operations are generally lower and more predictable than for tillage operations. It was thus decided to assess the performance of available methods to calculate fuel consumption in tillage operations.

5.1 Available Methods

The calculation of diesel use in tractor operations is a function of engine loading and rated power. Rated power of a tractor is available from the manufacturer or certified tractor test laboratories. Engine loading is, however, variable and dependant on the nature of the operation being carried out. Three methods used in South Africa for calculating engine loading were identified for possible use in the energy calculator. These include two locally developed methods and one based on standards published by the ASABE (2011) and are described in Section 5.1.1 to 5.1.3.

5.1.1 The Department of Agriculture, Forestry and Fisheries method (DAFF)

DAFF (2013) annually publish tables of power requirements compiled from field measurements, calculations and interpolations for a range of tractor drawn or mounted implements and machinery. Appendix 3 contains a sample page from this set of tables. For each implement or machine, the recommended power requirements vary depending on the width and depth of operation, and soil classification. Tractor engine loading can be calculated (Equation 5.1) by the ratio of the recommended power requirement to the rated power of the selected tractor.

$$L = \frac{P_T}{P} \times 100 \quad (5.1)$$

5.1.2 The Pretorius method

Pretorius (1986) developed a mechanisation planning model for effective tractor - implement matching. An important outcome of this is a method to estimate engine loading and subsequently fuel consumption.

The specific energy input requirements [kWh.ha^{-1}] for field operations form the basis of this method. Through experimentation, calculations and interpolations, optimum specific energy requirements for implements were determined for common working depths and soil conditions. Pretorius (1986) defines the point of optimum specific energy input as operating conditions where the tractor engine is fully loaded and work rate is at a maximum (Equation 5.2).

$$K = P \times \left(\frac{10}{s \times w}\right) \quad (5.2)$$

where K = energy input requirement [kWh.ha^{-1}].

From Equation 5.2, the optimum, or lowest specific energy input, occurs when the width and speed are at a maximum and rated engine power at a minimum. In practice, rated power and width are constant and only travel speed can be increased until optimum energy input and hence maximum engine loading is attained.

To calculate engine loading of a specific operation, a “K” value (as in Equation 5.2) is obtained from tables published by Pretorius (1986), an example of which can be viewed in Appendix 4. With a known rated tractor power and implement width, Equation 5.2 can then be solved for speed. This is the theoretical maximum speed for the given tractor-implement combination. Equation 5.3, the ratio of actual travel speed to theoretical maximum speed, is used to estimate engine loading for the operation.

$$L = \frac{s_a}{s} \times 100 \quad (5.3)$$

where s_a = actual travel speed [km.h^{-1}].

5.1.3 The American Society for Agricultural and Biological Engineering method (ASABE)

ASABE (2011) use implement specific parameters, soil factors, depth of operation and travel speed to calculate horizontal draft [kN] requirements of an implement. Knowing the horizontal draft, travel speed, tractive efficiency and rated engine power, engine loading can be calculated using Equation 5.4 (ASABE, 2011).

$$L = \frac{\frac{(D \times s)}{E_t}}{P} \times 100 \quad (5.4)$$

Tractive efficiency is defined by ASABE (2011) as the ratio between PTO power and drawbar power. As shown in Table 4.1, typical values of tractive efficiency range between 0.55 and 0.88 depending on the soil's tractive condition and tractor drive type.

5.2 Materials and Method of Evaluation

Literature sources were used to obtain engine loading data from tractor drawbar tests. Using statistical methods, these data were used to compare the accuracy of each method in predicting loading against actual field measurements. The literature sources included drawbar tests conducted by the South African Agricultural Research Council – Institute for Agricultural Engineering (van Biljon and Mavundza, 2011) as well as from various international authors (Karlen *et al.*, 1991; Ismail *et al.*, 1993; Smith, 1993; Al-Suhaibani and Al-Janobi, 1997; Serrano *et al.*, 2003; Kheiralla *et al.*, 2004; Abbaspour-Gilandeh *et al.*, 2006; Kichler *et al.*, 2011).

Mouldboard plough, disk harrow and sub-soiler operations were chosen to compare the accuracy of the methods in predicting engine loading. These implements are common to conventional land preparation operations for sugarcane production in South Africa.

The database compiled consists of measurements from 41 mouldboard plough, 37 disk harrow and 39 sub-soiling trial measurements. Each source of data differed in clay content, tractive conditions, tractor type, as well as implement dimensions and settings. Average draft, engine speed, travel speed, wheel slip, operating depth and fuel consumption were recorded over each trial plot, which typically was between 50 and 100 m in length.

5.3 Results

The calculated engine loading is analysed per tillage operation. Figures 5.1, 5.2 and 5.3 show the results for disk harrow, mouldboard plough and sub-soiling operations, respectively. In each figure, the calculated engine loading is plotted against measured engine loading to give an indication of the accuracy of each method.

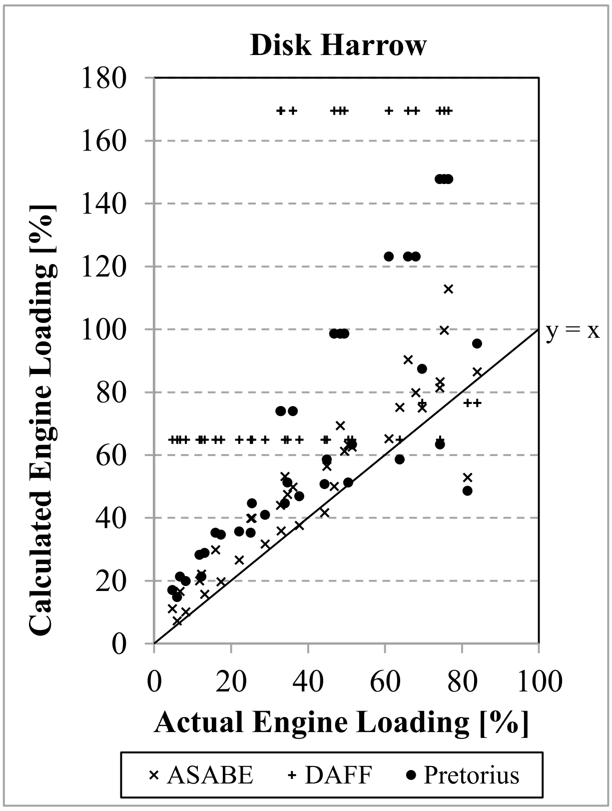

Figure 5.1 Scatter plot of calculated versus measured engine loading for disk harrow operations

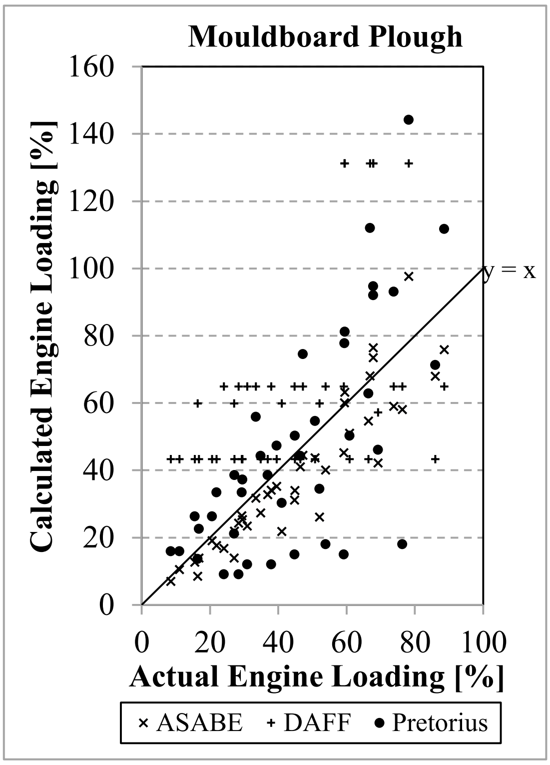

Figure 5.2 Scatter plot of calculated versus measured engine loading for mouldboard plough operations

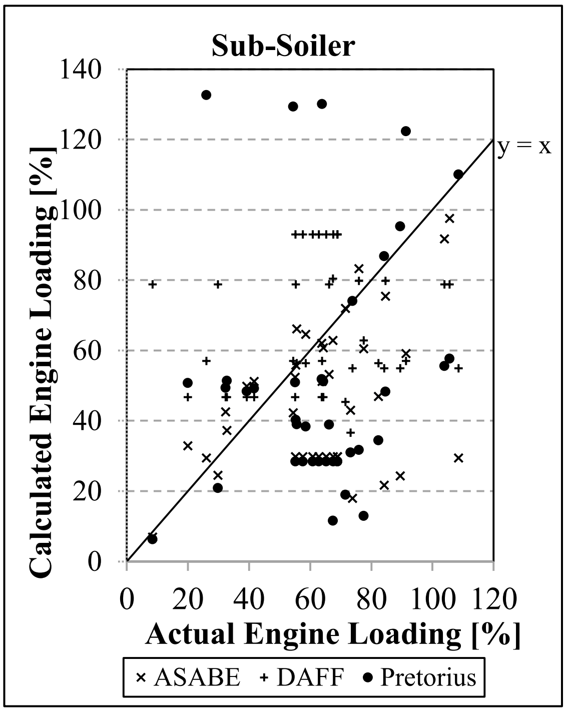

Figure 5.3 Scatter plot of calculated versus measured engine loading for sub-soiling operations

A linear equation was fitted to each method-operation combination. The offset, slope and the coefficient of determination (R^2) of the regression line are used to compare the accuracy of the methods, as summarised in Table 5.2.

Table 5.1 A summary of the linear regression coefficients and coefficients of determination to assess the accuracy of the three load estimation methods

Calculation Method	**Disk Harrow**		**MB Plough**		**Sub-Soiler**	
	Equation	R^2	Equation	R^2	Equation	R^2
Pretorius	$y = 1.28x + 12.3$	0.63	$y = 1.08x - 2.3$	0.50	$y = 0.10x + 60.3$	0.01
DAFF	$y = 0.89x + 62.2$	0.20	$y = 0.65x + 34.9$	0.23	$y = 0.29x + 33.0$	0.04
ASABE	$y = 1.04x + 7.3$	0.86	$y = 0.94x - 3.8$	0.85	$y = 0.39x + 21.2$	0.18

For disk harrow operations as shown in Figure 5.1, the ASABE method has a slope close to 1.0 and a coefficient of determination (R^2) of 0.86. Although, the slopes for the DAFF and Pretorius methods indicate good accuracy in their calculations, the scatter and fit of the linear regressions are poor, suggesting that the ASABE method performs best for this operation.

For the ploughing operation as shown in Figure 5.2, based on the slope of the regression line, the Pretorius and ASABE methods are the most accurate. The correlation of the Pretorius method is, however, not as good when compared to the ASABE method. Again this indicates a higher accuracy of the ASABE over the Pretorius and DAFF methods.

Of the three operations, sub-soiling is the least accurately estimated. The data shown in Figure 5.3 reveals no clarity as to which method performs best. This inaccuracy could be associated with the variability in the implement's design. Many different tine and tool designs are commercially available, specifics of which were either poorly defined in the source data, or the method's input parameters may not account for these variations.

For all three operations it is noticed that the calculated loading of the DAFF method stays constant for a number of data points, then changes in a step-wise manner. This can be attributed to the method's limitations with regards to varied travel speed and depth of operation. Most of the literature sources used in this study investigate the effects of varied depth and speed on power requirements, while rated power, implement width, soil texture and tractive conditions remain constant. DAFF loading is a function of rated power, implement width, and soil texture. Thus, for each data source, no matter how much the speed or depth varies, the recommended power and subsequently engine loading stays constant based on the implement width and soil texture.

5.4 Summary of Chapter

Regression analysis of the calculated versus measured engine loading suggests that the ASABE is more accurate than the DAFF and Pretorius methods for disking and ploughing operations. However, for sub-soiling, a further analysis of the relative errors in calculated engine loading is required due to the poor results achieved by all three methods evaluated.

From the above analysis and subject to further testing, the ASABE method was selected to be used to calculate tractor engine loading in the energy calculator.

The following chapter contains details of the two case studies that were conducted to evaluate the energy calculator. The case study the input data are described, followed by the calculated results and recommendations for potential energy savings.

6. CASE STUDIES

Two case studies using the energy calculator were conducted on irrigated farms in different mill areas under sugarcane production in South Africa. The geographic location of each, relative to the rest of the industry, is shown in Figure 6.1. The first assessment took place at a private grower's farm in Umfolozi supplying the Umfolozi Sugar Mill. In this region, sugarcane is harvested on a twelve month cycle, and supplementary irrigation is practiced. The second assessment was conducted in Pongola at the SASRI research station. Pongola falls in, what is termed the "fully irrigated" north, where it is common to irrigate throughout the year. This crop is also harvested on a twelve month cycle.

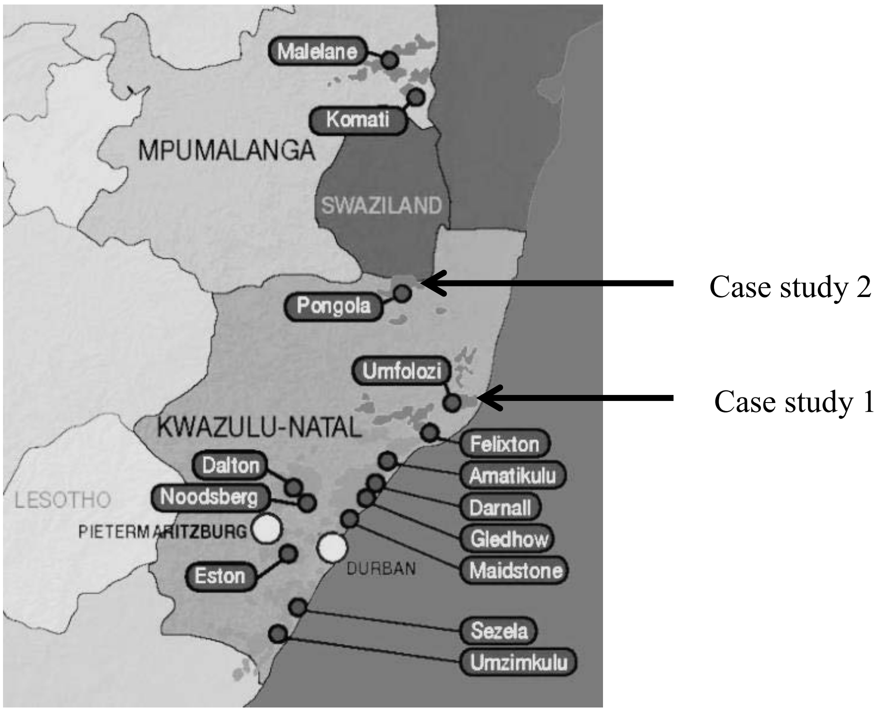

Figure 6.1 Geographic location of the case studies relative to the South African sugarcane industry, after SASA (2010)

Summaries and results of the assessments are detailed below. Energy Use (EU), cost and carbon footprint are analysed to identify areas of potential energy savings.

6.1 Case Study 1: Umfolozi

The specifications for the farm are summarised in Table 6.1. Section 6.1.1 contains an explanation of the farming enterprise considered influential on the final assessment results. The processes and details of each mechanised operation assessed for the Umfolozi case study are summarised in Appendix 6.

Table 6.1 The farm specifications that describe the Umfolozi case study

Detail	Value
Mill area	Umfolozi
Total arable area [ha]	180
Area under sugarcane [ha]	172
Break crop area [ha]	0
Fallow area [ha]	8
Average cane yield [$t.ha^{-1}$]	78.25
Average seasonal cane harvest [t]	13459
Area replanted per year [%]	10

6.1.1 Details of the farming enterprise

The assessment was conducted for the 2012/13 financial year (1st March 2012 until 28th February 2013). For this year, total fuel and electricity accounts were available and thus useful to compare against calculated EU. A Level 1 “accounts” as well as a Level 2 “operational time” and “simulated” assessments were carried out for this case study. No instrumentation was available to conduct a Level 3 “measured” assessment.

As defined by the system boundaries of the calculator, energy used in production was accounted for until the offloading of sugarcane at the mill yard. This case study is unique in the fact that a diesel locomotive tram system is used to deliver sugarcane from sidings at the field edge to the mill. The diesel used for this transportation system is included in the assessment.

6.1.1.1 Topography and ratoon management practices

Ninety per cent of the farm is situated on the flood plains (referred to as the “flats”) of the Umfolozi River and the remainder on an adjacent hillside. The hillside fields are managed in a similar way to the flats except for some ratoon management practices. On the flats three operations take place before the regrowth of a ratoon crop. The inter-rows are ripped, fertiliser incorporated, and pre-emergence herbicide is applied. The slopes, however, only receive the pre-emergence herbicide application.

6.1.1.2 Soil

The farm has deep and well drained alluvial soils, which are typical for the flood plains of this area. The hillside fields are generally sandy soils with a lower production potential. Clay percentages range from 15 % on the hillside to 25 % on the flats.

6.1.1.3 Irrigation

Water is transferred from an irrigation canal to a holding reservoir from which it is pumped to the fields. A dragline sprinkler system is used on the hillside fields, and the flats are irrigated by both centre pivot and dragline sprinkler systems. Irrigation was scheduled using four soil moisture probes and the *CaneSim* (Singels, 2011) crop modelling software.

6.1.1.4 Production system

The grower was in the process of converting the entire farm from a conventional single line layout to a controlled traffic “tram-line” system. As such, some of the ratoon management tractor mounted equipment does vary, depending on the cane row configuration.

6.1.1.5 Harvest and transport

The harvest system is a manual, cut and bundle type, where a three-wheeled loader loads the bundled cane onto tractor-trailer rigs. The trailer bins are then trans-loaded at railway sidings onto the mill’s locomotive tram system for delivery to the mill yard. The railway sidings are at an average distance of 1.5 km from the field, and the siding-to-mill distance is 20 km.

Diesel consumption rates for the locomotive were obtained from the mill group board and a default litre per ton-km value was input to the calculator.

6.1.2 Results and discussion

A Level 1 "accounts" assessment which does not distinguish between in-field operational EU and domestic EU was performed. The total electrical and diesel EU, as well as the associated carbon footprint for the Level 1 assessment are shown in Figure 6.2 as a percentage of the overall farm consumption.

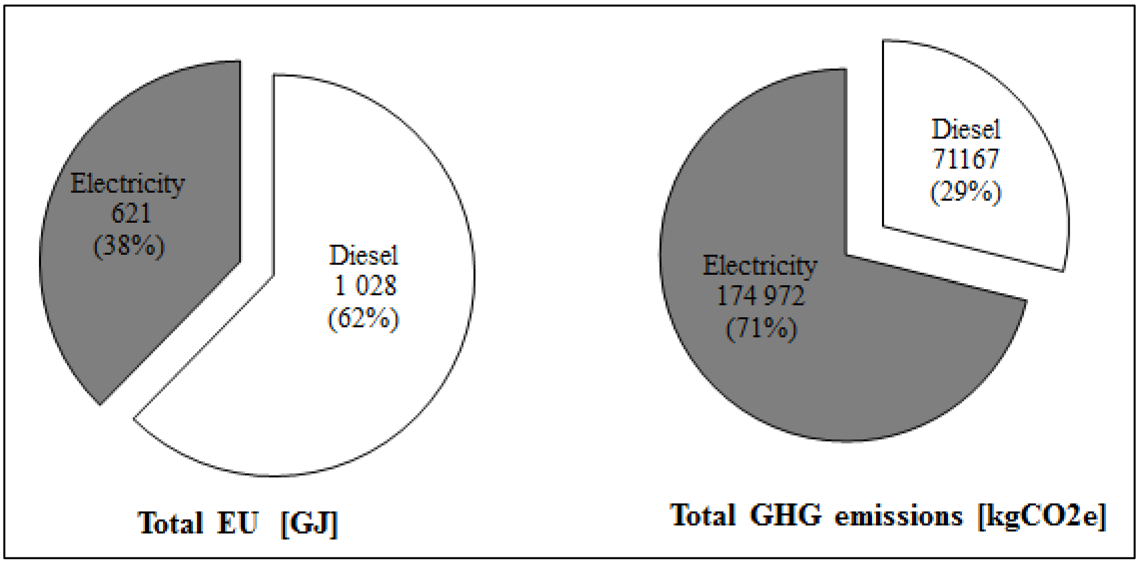

Figure 6.2 Energy use and associated greenhouse gas emissions from Level 1 "accounts" assessment

The results of the three assessments that were conducted, i.e. a Level 1 "accounts", Level 2 "operational time" and Level 2 "simulated", are compared in Figure 6.3. It is apparent that for both electricity and diesel consumption there is a discrepancy between what was accounted for in the Level 1 assessment, and the simulated use in the Level 2 assessments. For the diesel component, the difference can possibly be attributed to the use of diesel in non-farming related vehicles. Furthermore, the farm's diesel bowser is not equipped with a flow meter. Therefore, total diesel consumption was based purely on bulk volumes purchased from the supplier during the assessment period. As a result, errors would exist due to any difference in the volume of diesel in the bowser at the start of the assessment period and at the end of the period.

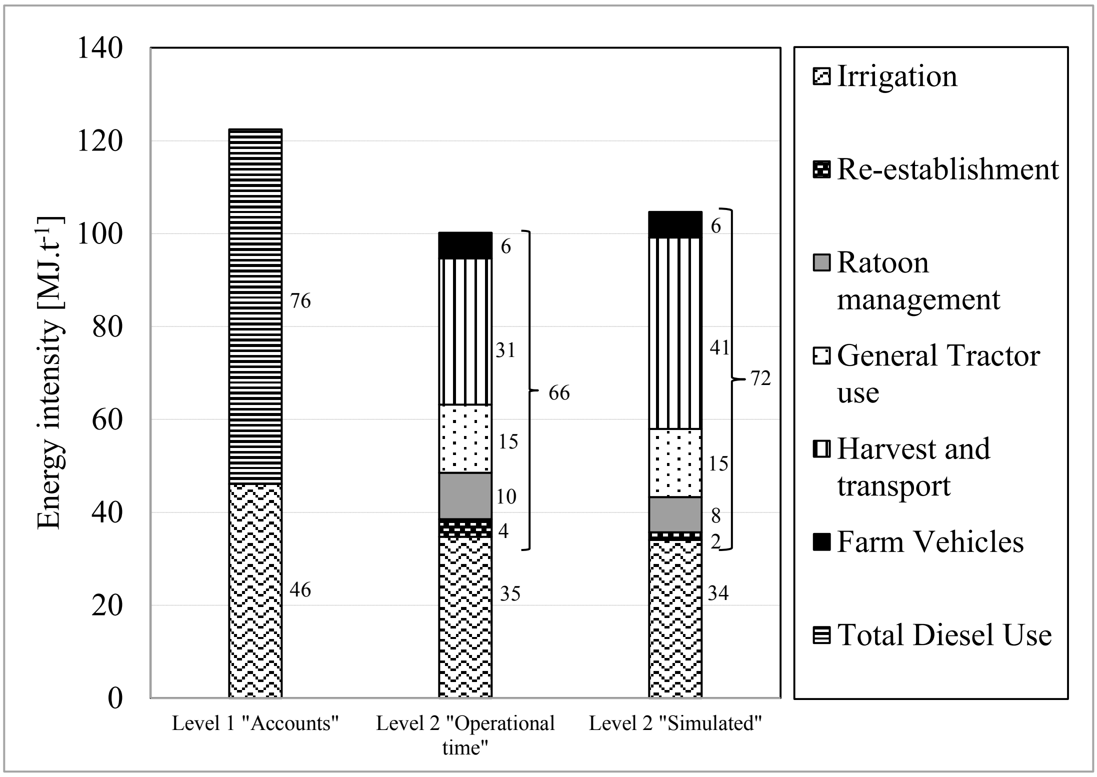

Figure 6.3 Stacked bar chart to compare the results of the Level 1 and 2 assessments for the Umfolozi case study

The grower schedules irrigation events using the *CaneSim* (Singels, 2011) model and soil moisture probes. Since the energy calculator estimates irrigation EU using *CaneSim* (Singels, 2011) simulations, the Level 2 assessments should be similar to the Level 1 assessment for this case study. Any disparity between the Level 1 and Level 2 assessments can thus be related to the layout of the electrical supply on the farm, and where electricity is metered from. In this case, one of the meters measures the energy of the transformer supplying power to an irrigation pump station, the farm house, workshop, and labourer accommodation. Thus, domestic and workshop electricity use are assumed to account for the difference between the Level 1 and 2 assessments.

The running hours of the machinery, required as input for the Level 2 "operational time" assessment, were calculated as accurately as possible or obtained from farm records. This accuracy, together with the fact that the same energy equations were used for the Level 2 "operational time" and "simulated" assessments would suggest that the results of the two Level 2 assessments should be similar.

The small percentage of the total EU that re-establishment and ratoon management consumes is noteworthy, but not unexpected. For re-establishment, this is expected in sugarcane production as a consequence of the small area percentage that is re-established annually. In this case approximately 10 % of the farm's productive area is re-established each year. The grower also keeps tillage operations to a minimum, thus avoiding unnecessary soil disturbance for soil-health and energy saving purposes.

The calculator estimates engine loading for all in-field tractor operations defined in the Level 2 "simulated" assessments. In addition, the Overall Energy Efficiency (OEE) for each tractor can be calculated. As discussed in Section 3.3, an acceptable range for this is 10 - 20 %. Efficiencies below 10 % indicate poor tractor-implement matching, and above 20 % suggest good matching. Table 6.2 summarises the OEE for each tractor for all production related field operations. Although the minimum OEE is 7 % for the New Holland tractor, on average, the operations carried out by this tractor fall into the acceptable range, but are relatively low. For the Case IH tractor, only two in-field operations were carried out, of which the OEE average is also relatively low.

Table 6.2 Overall Energy Efficiency (OEE) statistics for tractors used in re-establishment, ratoon management and break crop operations

Statistic	**New Holland dt90 (63 kW)**	**Case IH jx90-07 (63 kW)**
Number of operations	8	2
Minimum	7%	12%
Maximum	16%	12%
Average	12%	12%

6.1.3 Recommendations and potential savings

Although the tractor OEEs are low, they fall within acceptable ranges. Tractor OEE is directly related to engine loading as can be seen in Equation 3.12. Thus, there exists the potential to increase the engine loading, by reducing the tractor size or increasing the implement widths. It must, however, be stressed that a detailed cost-to-benefit analysis should be conducted to determine whether such changes are economically feasible.

A Level 2 “simulated” assessment was conducted to assess the potential energy and carbon footprint savings by (i) decreasing the rated power of each tractor or (ii) increasing the tillage implement widths. The rated tractor powers were decreased to increase engine loading up to, but not exceed 100 % for all the operations. Similarly, the tillage implement widths were increased to obtain the highest possible engine loading. The results are contained in Table 6.3 and expressed as a percentage reduction of the current enterprise. The low OEE of operations in the re-establishment and ratoon management processes were the drivers behind this energy saving simulation. Therefore, both the combined savings in these two processes and the entire farming enterprise are considered.

Table 6.3 The reduction in EU and carbon footprint as a result of reduced tractor power or increased implement widths expressed as a percentage of the current energy use

Processes considered	**Reduced rated power**		**Increased implement widths**	
	Reduction in EU intensity [%]	Reduction in carbon footprint [%]	Reduction in EU intensity [%]	Reduction in carbon footprint [%]
Re-establishment and ratoon management	13.6	13.1	11.4	11.5
All processes (entire farming enterprise)	6.0	2.9	1.0	0.8

The results indicate that, for the re-establishment and ratoon management processes combined, there is a considerable potential saving in EU and carbon footprint. However, for the entire farming enterprise, savings are minimal. It would therefore be advised to consider these two options only when planning for the replacement of the tractors or implements at the end of their lifespans.

The difference between the Level 1 and Level 2 electrical energy use could be attributed to domestic and workshop EU that were not accounted in the Level 2 assessments. It is advised that, for the transformers supplying loads other than solely for irrigation pumps, simple electricity meters are installed to differentiate between the loads. In so doing, this would help apportion EU appropriately and will flag inefficiencies in the system.

6.2 Case Study 2: Pongola

The basic specifications for the farm located in Pongola are summarised in Table 6.4. The format of the summary to this assessment will follow the same structure as for the first case study in Section 6.1. Appendix 7 contains a summary of the processes with details of the mechanised operations that are carried out on the farm.

Table 6.4 The farm specifications that describe the Pongola case study

Detail	Value
Mill area	Pongola
Total arable area [ha]	123
Area under sugarcane [ha]	76
Break crop area [ha]	23.5
Fallow area [ha]	23.5
Average cane yield [$t.ha^{-1}$]	79.93
Average seasonal cane harvest [t]	6075
Area replanted per year [%]	50

In addition to the Level 1 and Level 2 assessments that were conducted in the first case study, a Level 3 "measured" assessment was conducted in Pongola. This Level 3 assessment was carried out on the low pressure pump in the pump station using the Pump Evaluation Kit (PEK).

The PEK was constructed to be used in a Level 3 "measured" assessment to identify energy inefficiencies. Figure 6.4 shows a simplified schematic of the PEK setup for the low pressure pump. The ultrasonic flow meter transducers were positioned on the longest straight length of pipe available. This is necessary to reduce the effect of turbulence and to obtain near-lamina flow. Pressure sensors were installed on the suction (P1) and delivery (P2) sides of the pump, as well as after the throttling valve (P3). The electricity metering device has clamp-on current transducers and direct connects for the measurement of current and voltage respectively. All sensors were connected to a data logger which is communicated with via a GSM modem.

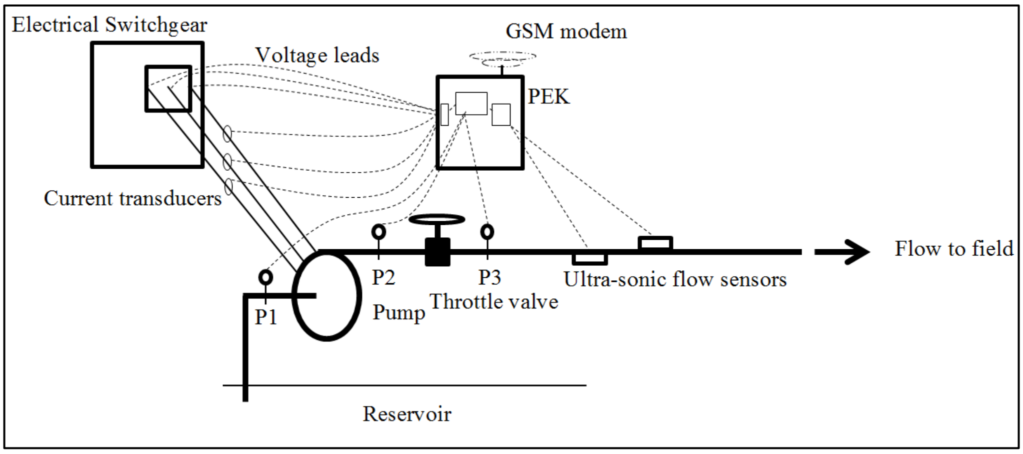

Figure 6.4 Layout of the pump evaluation kit installed on the low pressure

The following critical parameters for assessing EU were recorded:

- flow rate [$m^3.h^{-1}$],
- pressure (P1, P2, and P3) [bar],
- average of all three phase's voltage [V],
- average of all three phase's current [A], and
- power factor.

Data were recorded at 10 minute intervals over a period of one month that was considered by the farm manager to represent a typical crop demand. An extract of the measured data is contained in Appendix 5 and a statistical summary is described in Table 6.4.

6.2.1 Details of the farming enterprise

The case study took place at a research station where variety selection trials are conducted. As such, certain aspects of management and layout of the farm may differ in comparison to a commercial farm. There is one additional weighing operation before in-field loading of the cut sugarcane. This is for accurate yield monitoring of the different varieties.

6.2.1.1 Topography and ratoon management practices

The farm is situated on a hillside of moderate slope. The total elevation change from the lowest to highest reaches is approximately 90 m. There are no changes to ratoon management practices as a result of the topography.

6.2.1.2 Soil

The soils are deep, well drained with high total available moisture. The clay content of the soil is also considered to be high, and is approximately 60 %.

6.2.1.3 Irrigation

The farm is sub-divided into a high pressure irrigation zone of approximately 30 ha and a low pressure irrigation zone of approximately 93 ha. Each pressure zone is equipped with its own dedicated irrigation pump which sources water from a reservoir located on the farm. Water is pumped to the reservoir from an irrigation canal which runs along the lower boundary of the farm.

Surface drip irrigation is used for all but 5 ha of the farm. For various reasons, this 5 ha is limited to the use of quick-coupler overhead sprinklers. Overhead sprinklers are also used on the entire farm to wet the soil prior to land preparation operations as well as for the germination of newly planted fields.

6.2.1.4 Production system

As a consequence of the variety selection program on the farm, fields are divided into 0.4 ha panels made up of 12 cane rows spaced at 1.4 m apart. Re-establishment and ratoon management operations are common to those practiced in the area and follow SASRI’s best management practices. Crop cycles are, on average, very short with most being re-established after the first ratoon.

6.2.1.5 Harvest and transport

As with the first case study, the sugarcane is manually cut and bundled for mechanised infield loading. Prior to loading, all the cane is weighed using a purpose built, tractor-mounted, load-cell. Tractor-trailer rigs then haul the sugarcane from the field to a trans-loading zone.

Trans-loading is done using a three-wheeled loader into a 25 ton “hilo” truck for delivery to the mill. Both these operations are done by a contractor and were subsequently not accounted for in the Level 1 “accounts” assessment.

6.2.2 Results and discussion

The total electrical and diesel EU, as well as the associated carbon footprint for the Level 1 “accounts” assessment are shown as a percentage of the overall farm consumption in Figure 6.5. As mentioned above, it must be noted that the diesel EU does not take into account the fuel used by any sugarcane trans-loading operation and zone-to-mill transport.

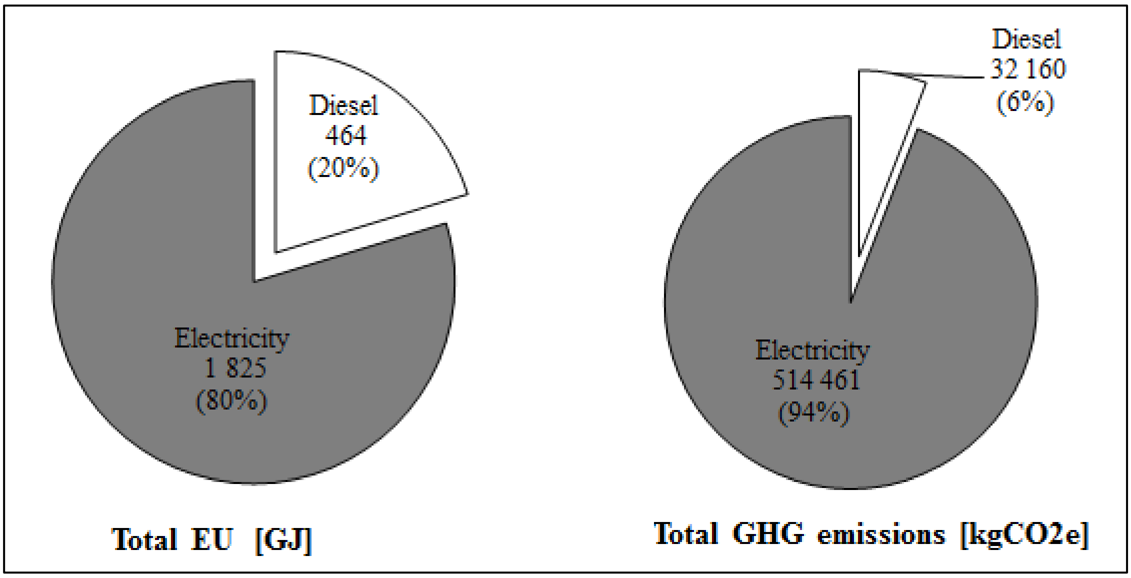

Figure 6.5 Energy use and associated greenhouse gas emissions from Level 1 “accounts” assessment

The results of the Level 1 and Level 2 assessments that were conducted are shown in Figure 6.5. The differences in the Level 1, “accounts” total diesel EI (47 $MJ.t^{-1}$) and the total diesel EI estimated in the Level 2 assessments (104 and 81 $MJ.t^{-1}$) are due to the contracted trans-loading and zone-to-mill transport used in Level 1. As with the first case study, it is noticed that the re-establishment and ratoon management processes account for only a small portion of the total EU in the entire farming enterprise.

A large discrepancy between the Level 1 "accounts" and Level 2 "simulated" electrical EU is evident in Figure 6.6. In this case study there are no other electrical loads drawing from the transformers apart from the irrigation pumps. A possible cause of this difference could then be related to the design and management of the irrigation systems. This discrepancy lead to further investigation by conducting a Level 3 "measured assessment".

The farm manager uses *CaneSim* (Singels, 2011) and soil moisture probes to schedule irrigation. As a result, it is assumed that the correct volumes are applied timeously to avoid plant stress and for the most efficient use of available water. Thus, inefficiencies were assumed to lie in the design and maintenance of the system.

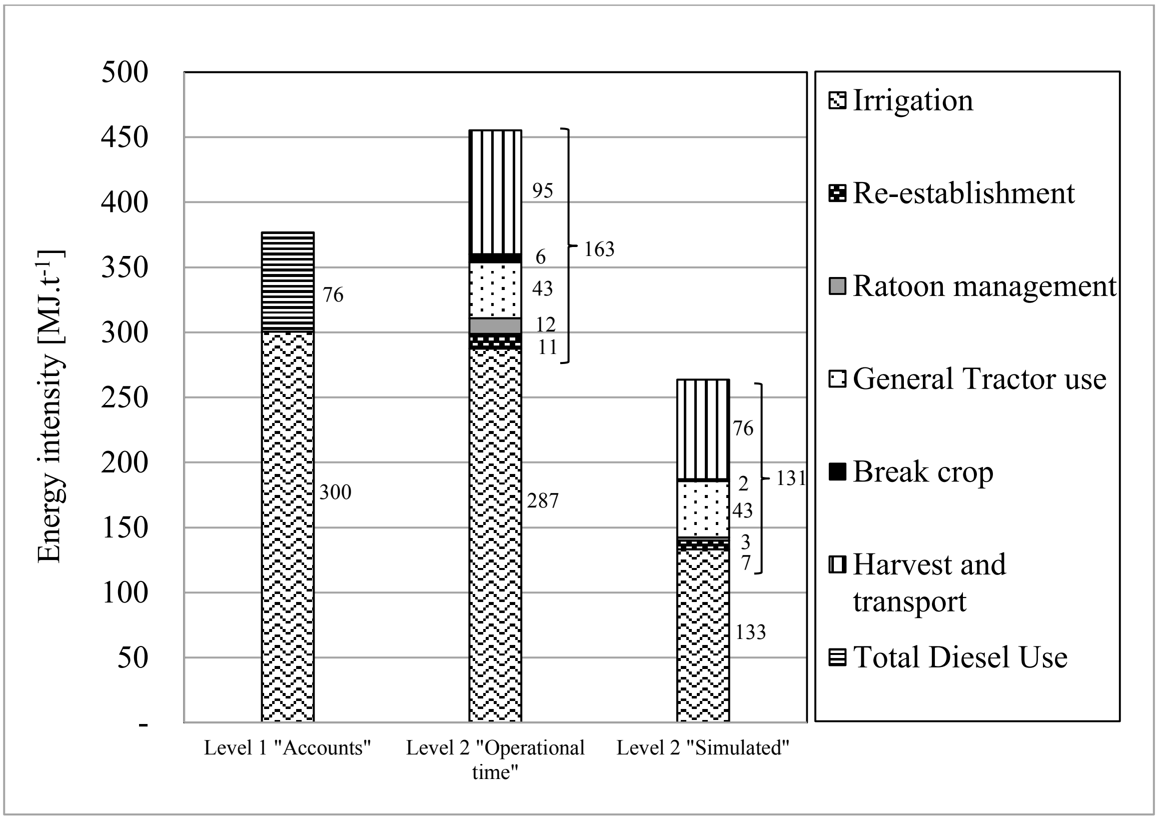

Figure 6.6 Stacked bar chart to compare the results of the Level 1 and 2 assessments for the Pongola case study

A summary of the data that was measured by the PEK is presented in Table 6.5. This contains the averages and standard deviation of active electrical power demand, hydraulic power produced by the pump, efficiencies and the power loss due to throttling. These results were calculated using the methods defined in Chapter 4.

Table 6.5 Statistics from data recorded at the low pressure pump for the Level 3 "measured" assessment

Statistic	**Electrical power demand [kW]**	**Hydraulic power before throttle valve [kW]**	**Total pump station efficiency [%]**	**Pump efficiency [%]**	**Hydraulic power after throttle valve [kW]**	**Power loss through throttle valve [%]**
Average	49	34	69	74	24	31
Standard deviation	7	7	16	17	7	13

The results in Table 6.5 show a substantial power loss through the throttle valve. Throttling of the flow is practiced on this farm due to the many duty points required for effective management of the on-demand block irrigation system. As all effort has been made to adhere to best management practices, the inefficient use of electrical energy needs to be addressed through the redesign of the system hardware.

The calculator only estimates tractor OEE for operations in the re-establishment, ratoon management, and break crop processes. As shown in Table 6.6, on average, the OEEs for all tractors fall within the 10 – 20 % range. In only one operation does this value drop below 10 % for the New Holland TT75. This minimum OEE occurs for a bed-forming operation where the soil is loosely tilled and soil draft forces are at a minimum. The Massey Fergusson MF 390, which is used for the majority of the soil engaging operations has an average OEE of 19 %, which indicates good tractor implement matching.

Table 6.6 Overall Energy Efficiency (OEE) statistics for all tractor field operations

Statistic	**New Holland TT55 2 WD - 45kW**	**New Holland TT75 2WD - 50kW**	**Massey Ferguson MF 390 2WD - 60kW**
Number of operations	3	3	4
Minimum	18%	9%	12%
Maximum	18%	12%	22%
Average	18%	11%	19%

6.2.3 Recommendations and potential savings

With contracted loading and mill transport, energy saving opportunities in these operations are out of the manager's control. The other avenues for saving exist in tractor operations and irrigation. Tractor operations in soil engaging operations and agronomic product application appear to be within acceptable ranges of energy efficiency. The number of operations also seems to be minimised to what is necessary.

It was deemed necessary to conduct a Level 3 "measured" assessment on the irrigation pump station. Only the low pressure pump was instrumented for measurement of electrical and hydraulic parameters with results showing notable energy loss brought about by throttling. The most cost effective means to reduce this would be to trim the impeller to meet the desired duty point. However, due to the "irrigation on demand" scheduling, using crop models and soil moisture probes, there is no consistency in the required duty points. Thus, it is recommended that a Variable Speed Drive (VSD) be considered to reduce the motor speed to match infield flow and pressure requirements.

Although only the low pressure pump was instrumented, visual inspection of the high pressure pump suggested a similar degree of throttling taking place. Based on the assumption that the losses at the low pressure pump are also experienced at the high pressure pump, the potential energy saving through installing VSDs on both the high and low pressure pumps are summarised in Table 6.7. As with the first case study, savings are expressed as a percentage reduction in EU intensity and carbon footprint for the irrigation process alone, as well as for the entire farming enterprise as a whole.

Table 6.7 The reduction in EU and carbon footprint as a result of correct load-supply matching through the installation of VSDs expressed as a percentage of the current EU and carbon footprint

Processes considered	Reduction in EU intensity [%]	Reduction in carbon footprint [%]
Irrigation	21	21
All processes (entire farming enterprise)	17	20

Results show a substantial potential energy and carbon footprint saving if VSDs are installed at both the high and low pressure pumps. Again, it is recommended that a comprehensive cost-to-benefit analysis is conducted to assess the economic feasibility of purchasing and installing the VSDs.

7. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

With the rapidly increasing cost of energy and worldwide concern for environmental sustainability of production, there has been a drive towards reducing direct Energy Use (EU) and greenhouse gas emissions in all sectors. In order to identify where energy can be saved it is necessary to accurately quantify EU in different stages of production and highlight areas of high energy intensity and low efficiencies. With this in mind, the objective of this study was to develop an energy calculator specifically for sugarcane production in South Africa.

7.1 Discussion

A spreadsheet based calculator was developed to calculate the consumption of diesel and electricity as the primary source of direct EU in sugarcane production. The results generated by the calculator are presented as energy intensities [$MJ.ha^{-1}$ or $MJ.t^{-1}$] together with their associated carbon dioxide equivalent value [$kgCO_2e.ha^{-1}$ or $kgCO_2e.t^{-1}$]. By normalising the results per unit of production area or mass of product, comparisons of different production systems, farming enterprises and milling areas can be made. The calculator was designed so that EU and carbon footprint can be assessed at three levels of varying detail depending on what information is available to the user. The different levels make it possible to compare actual, simulated and measured EU, thus highlighting where inefficiencies may occur.

The accuracy of three methods of estimating fuel consumption in tillage operations was compared. The tillage operations chosen for the comparison were the disk harrow, mouldboard plough and sub-soiling operations. Results from this comparison indicate that the ASABE method was the most accurate in estimating fuel consumption for the disk harrow and mouldboard plough operations. However, inconclusiveness in the results for the sub-soiling operation suggests that further testing should be conducted. Subject to further investigations into this matter, it was decided to use the ASABE method in the energy calculator.

Two case studies were conducted to test the calculator's ability to effectively conduct energy assessments. The first case study showed that the Energy Use Efficiency (EUE) of the farming operations were good. Other than the potential for slight increases in Overall Energy Efficiency (OEE) for tractor operations, no other areas of potential energy savings were highlighted. The exclusion of non-production related consumption of diesel and electricity (e.g. for domestic and workshop use) in the calculator was evident from this case study. In this study, as is the case for many private growers, no records are kept for domestic diesel and electricity use.

For the second case study in Pongola, the inefficiency in the irrigation system was evident from the comparison of results from the Level 1 assessment against the simulated Level 2 results. This led to further investigation and implementation of a Level 3 assessment which involved the instrumentation and measurement of electrical and hydraulic parameters at the pump house. The Level 3 assessment identified potential energy savings for the total EU of up to 17 % in electrical EU if variable speed drives were installed at the irrigation pumps.

For both case studies, irrigation together with harvest and transport were the most energy intense operations. The high energy requirements for irrigation coupled with a high carbon coefficient for electricity produced in South Africa meant that the carbon footprint of both farming enterprises was dominated by the irrigation process.

It was also noted that EU for the crop re-establishment and ratoon management processes contribute only a small percentage toward the total EU for sugarcane production scenario. This was expected for the re-establishment process and typical to perennial crop production. The ability of the crop to ratoon means that only a portion of the crop needs to be re-established annually. In light of this, the detail with which in-field tractor operations were defined and the preciseness of the calculation method may not be necessary for sugarcane production, but will be necessary for the application of the energy calculator to annual crop production systems. It is, however, common for private growers to contract out the harvesting and transport process which leaves only the infield tractor and irrigation operations for them to manage. The energy calculator could thus help growers increase the EU efficiency of the infield tractor and irrigation operations.

7.2 Conclusions

Research in this field is justified by the lack of published literature as well as the increasing concern over the cost of energy and environmental sustainability of sugarcane production. Currently available literature is predominantly international, and has a bias towards life cycle assessments. Typically, life cycle assessments of sugar production base the agricultural phase estimation of direct EU on mill level and industry level averages. Not much research has focussed on accurately assessing direct on-farm EU to isolate energy intense operations and identify opportunities for energy savings. As such, the research that was conducted, together with the energy calculator will contribute significantly towards this field.

The objective of this study was to develop an energy calculator to estimate the direct EU and carbon footprint of sugarcane production in South Africa. This was achieved in the form of a spreadsheet that makes use of equations developed from first principles, empirical equations and field measurements in order to estimate diesel fuel consumption and electricity use. Its functionality and practicality was tested on two case studies. Both case studies showed that the calculator was both practical and functional, and has the ability to identify inefficiencies in EU. It can thus be said that the energy calculator is a useful tool with the potential to assist in reducing EU and carbon footprint in sugarcane production in South Africa.

7.3 Recommendations for Future Research

It is the intention that SASRI develops the energy calculator into a web based application to extend its functionality beyond the research environment. This will enable growers and extension specialists to perform their own energy assessments. These assessments could then form part of existing self-audit systems predominantly focussed at environmental sustainability.

It is evident that the calculator does not take into account or calculate the EU of non-farming activities such as domestic and workshop electricity use as well as private motor vehicle diesel consumption. Including the functionality to estimate this would result in a more meaningful comparison of Level 1 and Level 2 assessments to identify energy losses or saving potential.

Much detail is included in the calculation of in-field tractor fuel consumption. However, for loading and transport operations, average fuel consumption values and industry norms were used. There is thus an opportunity to use existing transport logistics software to simulate more accurate regionalised diesel consumption values for sugarcane haulage. For loading operations, up-to-date fuel consumption and work rates need to be measured for loaders that are currently available and in use.

The calculator was developed for manually harvested systems typical to the South African industry and does not account for the mechanised alternatives. With the substantial increases in costs of labour and the potential for cogeneration of electricity from sugarcane residues, much interest has been shown in the use of mechanised systems to collect both the cane and residues. It would thus be useful to increase the calculator’s functionality to compare the EU and carbon footprint of manual systems and mechanised systems.

Finally, assessments completed on a web-based application will add to a database of EU information essential for further research in this field. It is envisioned that this database could be used to establish and regionalise benchmarks and profiles for EU processes and operations for sugarcane production in South Africa. Such outcomes will form a critical component of current and future lifecycle studies.

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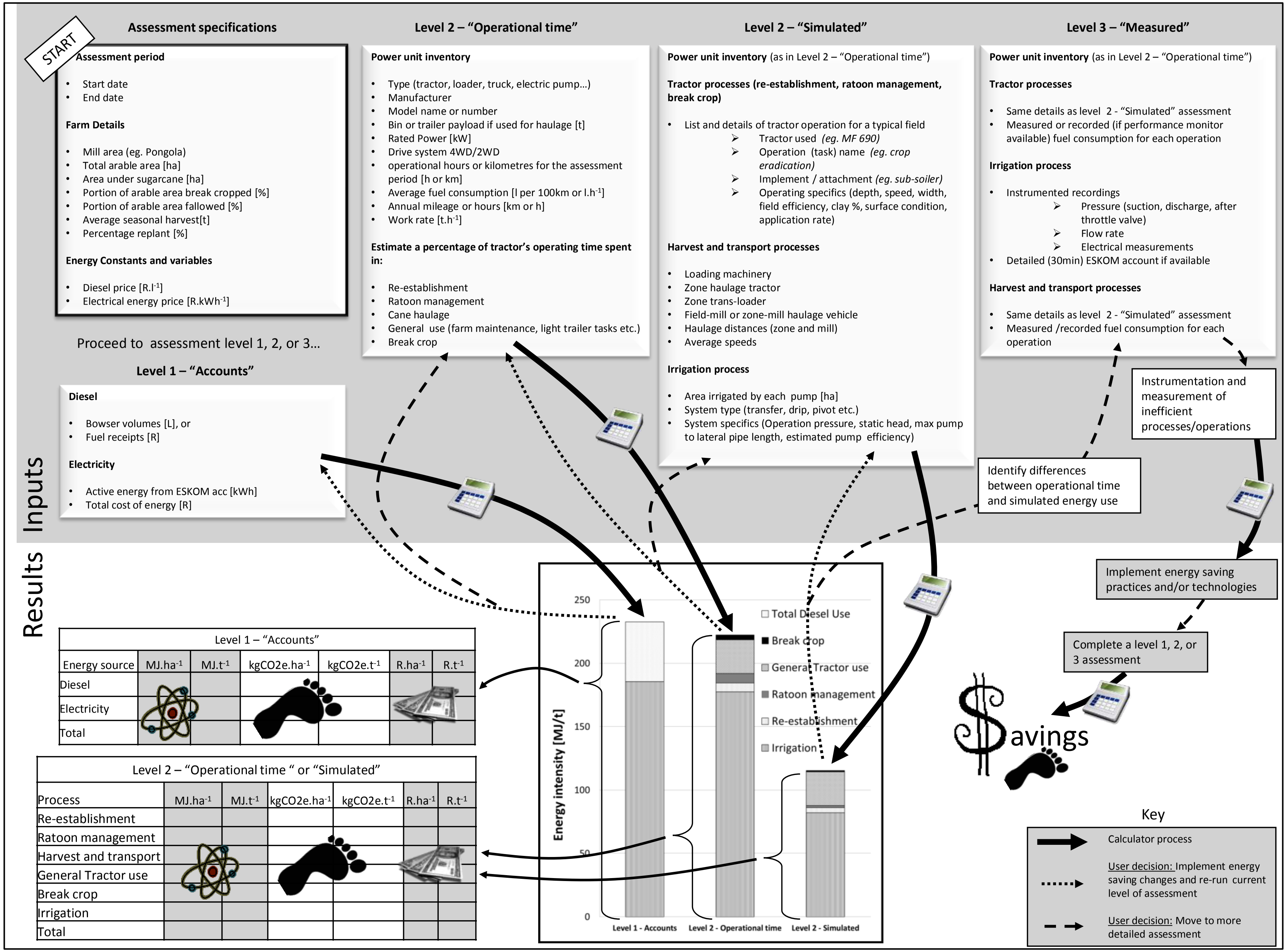
9. APPENDIX 1: ENERGY CALCULATOR FLOW DIAGRAM



Assessment specifications

Assessment period

- Start date
- End date

Farm Details

- Mill area (eg. Pongola)
- Total arable area [ha]
- Area under sugarcane [ha]
- Portion of arable area break cropped [%]
- Portion of arable area fallowed [%]
- Average seasonal harvest[t]
- Percentage replant [%]

Energy Constants and variables

- Diesel price [$R.l^{-1}$]
- Electrical energy price [$R.kWh^{-1}$]

Proceed to assessment level 1, 2, or 3…

Level 1 – "Accounts"

Diesel

- Bowser volumes [L], or
- Fuel receipts [R]

Electricity

- Active energy from ESKOM acc [kWh]
- Total cost of energy [R]

Level 2 – "Operational time"

Power unit inventory

- Type (tractor, loader, truck, electric pump…)
- Manufacturer
- Model name or number
- Bin or trailer payload if used for haulage [t]
- Rated Power [kW]
- Drive system 4WD/2WD
- operational hours or kilometres for the assessment period [h or km]
- Average fuel consumption [l per 100km or $l.h^{-1}$]
- Annual mileage or hours [km or h]
- Work rate [$t.h^{-1}$]

Estimate a percentage of tractor's operating time spent in:

- Re-establishment
- Ratoon management
- Cane haulage
- General use (farm maintenance, light trailer tasks etc.)
- Break crop

Level 2 – "Simulated"

Power unit inventory (as in Level 2 – "Operational time")

Tractor processes (re-establishment, ratoon management, break crop)

- List and details of tractor operation for a typical field
  - Tractor used *(eg. MF 690)*
  - Operation (task) name *(eg. crop eradication)*
  - Implement / attachment *(eg. sub-soiler)*
  - Operating specifics (depth, speed, width, field efficiency, clay %, surface condition, application rate)

Harvest and transport processes

- Loading machinery
- Zone haulage tractor
- Zone trans-loader
- Field-mill or zone-mill haulage vehicle
- Haulage distances (zone and mill)
- Average speeds

Irrigation process

- Area irrigated by each pump [ha]
- System type (transfer, drip, pivot etc.)
- System specifics (Operation pressure, static head, max pump to lateral pipe length, estimated pump efficiency)

Level 3 – "Measured"

Power unit inventory (as in Level 2 – "Operational time")

Tractor processes

- Same details as level 2 - "Simulated" assessment
- Measured or recorded (if performance monitor available) fuel consumption for each operation

Irrigation process

- Instrumented recordings
  - Pressure (suction, discharge, after throttle valve)
  - Flow rate
  - Electrical measurements
- Detailed (30min) ESKOM account if available

Harvest and transport processes

- Same details as level 2 - "Simulated" assessment
- Measured /recorded fuel consumption for each operation

Instrumentation and measurement of inefficient processes/operations

Identify differences between operational time and simulated energy use

Implement energy saving practices and/or technologies

Complete a level 1, 2, or 3 assessment

Level 1 – "Accounts"						
Energy source	$MJ.ha^{-1}$	$MJ.t^{-1}$	$kgCO2e.ha^{-1}$	$kgCO2e.t^{-1}$	$R.ha^{-1}$	$R.t^{-1}$
Diesel						
Electricity						
Total						

Level 2 – "Operational time " or "Simulated"						
Process	$MJ.ha^{-1}$	$MJ.t^{-1}$	$kgCO2e.ha^{-1}$	$kgCO2e.t^{-1}$	$R.ha^{-1}$	$R.t^{-1}$
Re-establishment						
Ratoon management						
Harvest and transport						
General Tractor use						
Break crop						
Irrigation						
Total						

Key

- Calculator process
- User decision: Implement energy saving changes and re-run current level of assessment
- User decision: Move to more detailed assessment

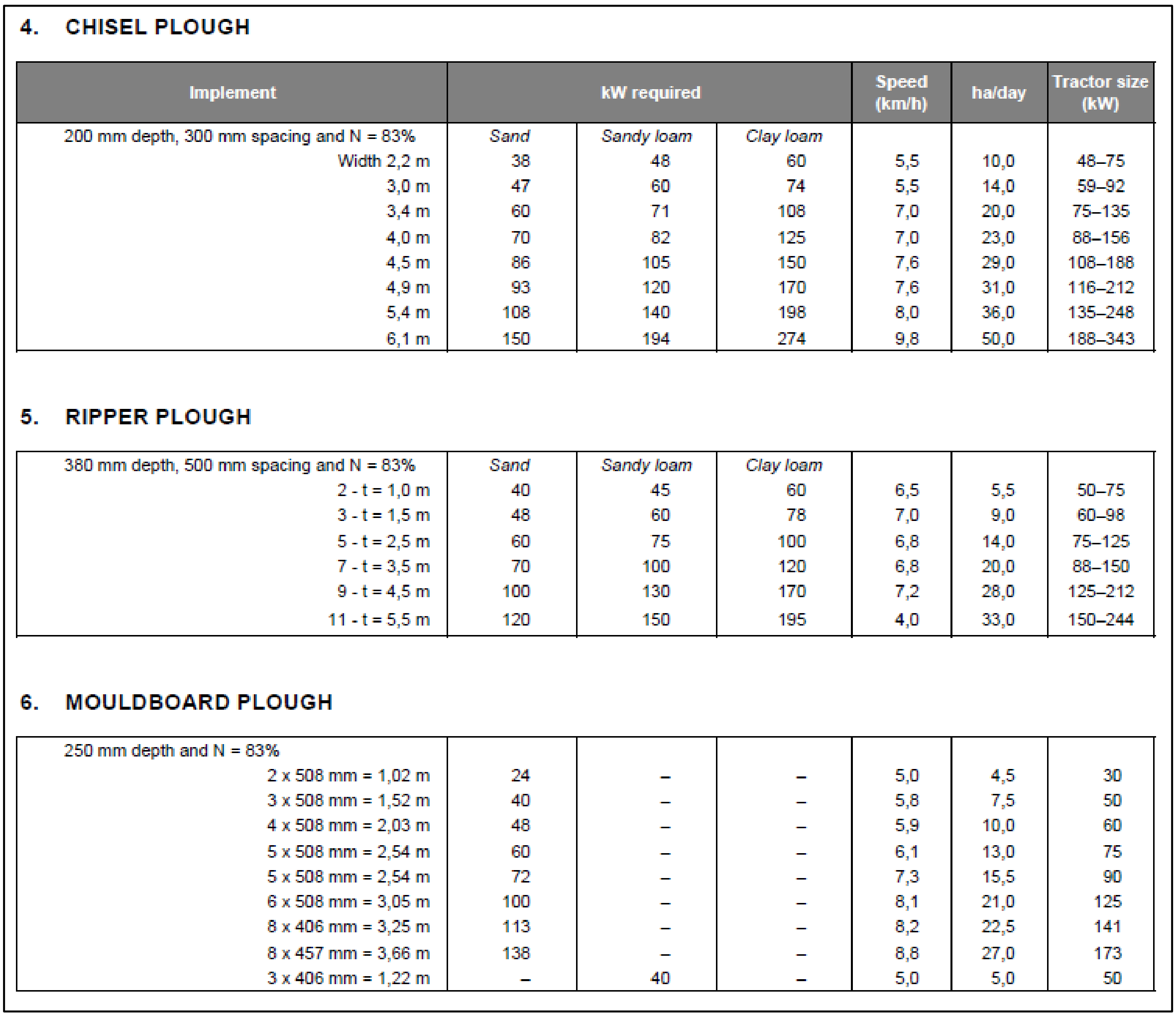
10. APPENDIX 2: PUMP EVALUATION KIT (PEK) COMPONENT DETAILS AND COST

The table below lists the description, details, supplier, quantity and cost of the components used in the PEK. The total cost of the kit is summed and displayed in the bottom right-hand corner of the table.

Component description	**Component details name and number**	**Supplier**	**Quantity**	**Unit cost (including vat) [ZAR]**	**Total Cost (including VAT) [ZAR]**
Electricity meter	WattNode Modbus WNC-3Y-400MB	CS Africa	1	8105.70	8105.70
Ultrasonic flow meter	Fixed Ultrasonic flow meter	Dalian Zerogo Instrument	1	5005.73	5005.73
Suction pressure sensor	Braumer CTX 3 B 3 B76 0	UIC Instrumentation	1	1254.00	1254.00
Discharge pressure sensor (after throttle valve)	Braumer CTX 3 B 3 B22 0	UIC Instrumentation	1	1254.00	1254.00
Discharge pressure sensor (before throttle valve)	Braumer CTX 3 B 3 B22 0	UIC Instrumentation	1	1254.00	1254.00
GSM antenna	GSM antenna	SASRI	1	On loan from SASRI	On loan from SASRI
Data logger	CS - CR1000	SASRI	1	On loan from SASRI	On loan from SASRI
GSM modem	Maestro 100 - gsm gprs	SASRI	1	On loan from SASRI	On loan from SASRI
Electrical box	600x450x250 box & plate	Just Electrical	1	718.20	718.20
Transformer	AC/DC 12V adapter	Just Electrical	1	227.16	227.16
Fuses	2A 600W Fastblow Fuse	Just Electrical	6	19.54	117.24
Fuse box	Fuse Holder 3/P 10x38	Just Electrical	1	97.07	97.07
Flow transducer sensor cable	Wire 2 core shielded	A1 Radio	100	3.90	389.88
Padlocks	2 padlocks	Penny Pinches	2	21.30	42.60
Extension lead to power instrumentation	extension lead	Penny Pinches	10	11.00	110.00
Misc. signal cable	Black/Red ripchord	K&K Electrical	100	2.28	228.00
Attachment adapters for pressure sensors	1/4" Nipple	PSAN Industrial	3	22.80	68.40
Attachment adapters for pressure sensors	1/4" T-piece	PSAN Industrial	3	77.52	232.56
Attachment adapters for pressure sensors	1/4" Socket	PSAN Industrial	3	29.64	88.92
Thread tape	Thread tape	PSAN Industrial	1	7.98	7.98
Airtime for GSM sim card	Data	Vodacom	1	49.00	49.00
Surge protected adapter	Surge protect adapter	Penny Pinches	1	74.00	74.00
				Total	**19324.43**

11. APPENDIX 3: DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF, 2013) DRAFT REQUIREMENTS FOR TILLAGE OPERATIONS - SAMPLE

The figure below is a sample of the draft requirements as recommended by the DAFF (2013). For each tillage implement, a power requirement is given depending on implement width and the soil type. Recommended speeds, field capacities and a tractor sizes are also given for each of the listed implement widths.



4. CHISEL PLOUGH

Implement	kW required			Speed (km/h)	ha/day	Tractor size (kW)
200 mm depth, 300 mm spacing and N = 83%	*Sand*	*Sandy loam*	*Clay loam*			
Width 2,2 m	38	48	60	5,5	10,0	48–75
3,0 m	47	60	74	5,5	14,0	59–92
3,4 m	60	71	108	7,0	20,0	75–135
4,0 m	70	82	125	7,0	23,0	88–156
4,5 m	86	105	150	7,6	29,0	108–188
4,9 m	93	120	170	7,6	31,0	116–212
5,4 m	108	140	198	8,0	36,0	135–248
6,1 m	150	194	274	9,8	50,0	188–343

5. RIPPER PLOUGH

380 mm depth, 500 mm spacing and N = 83%	*Sand*	*Sandy loam*	*Clay loam*			
2 - t = 1,0 m	40	45	60	6,5	5,5	50–75
3 - t = 1,5 m	48	60	78	7,0	9,0	60–98
5 - t = 2,5 m	60	75	100	6,8	14,0	75–125
7 - t = 3,5 m	70	100	120	6,8	20,0	88–150
9 - t = 4,5 m	100	130	170	7,2	28,0	125–212
11 - t = 5,5 m	120	150	195	4,0	33,0	150–244

6. MOULDBOARD PLOUGH

250 mm depth and N = 83%						
2 x 508 mm = 1,02 m	24	–	–	5,0	4,5	30
3 x 508 mm = 1,52 m	40	–	–	5,8	7,5	50
4 x 508 mm = 2,03 m	48	–	–	5,9	10,0	60
5 x 508 mm = 2,54 m	60	–	–	6,1	13,0	75
5 x 508 mm = 2,54 m	72	–	–	7,3	15,5	90
6 x 508 mm = 3,05 m	100	–	–	8,1	21,0	125
8 x 406 mm = 3,25 m	113	–	–	8,2	22,5	141
8 x 457 mm = 3,66 m	138	–	–	8,8	27,0	173
3 x 406 mm = 1,22 m	–	40	–	5,0	5,0	50

12. APPENDIX 4: TABLE OF "K" VALUES USED FOR THE PRETORIUS METHOD (AFTER PRETORIUS, 1986) - SAMPLE

The table below is a sample of Pretorius' (1986) "K" values. In this sample, the disk, spike tooth, and rotary harrow "K" values are listed. The magnitude of the "K" value depends on the surface condition, depth and soil type. A field efficiency value is also recommended for each scenario.

Attribute	**Depth [mm]**	**Sand** (5-15 % clay)	**Sand-loam** (15-25 % clay)	**Clay-loam** (25-40 % clay)	**Field efficiency [%]**
Disc harrow on firm surface	75	14	16	18	80
Disc harrow on firm surface	100	16	19	25	80
Disc harrow on firm surface	150	20	28	38	80
Disc harrow on loose surface (ploughed)	75	20	17	17	80
Disc harrow on loose surface (ploughed)	100	22	20	23	80
Disc harrow on loose surface (ploughed)	150	24	29	33	80
Spike tooth harrow	150	6	7	9	80
Rotary harrow	0	4	4	4	80

13. APPENDIX 5: PEK DATA FROM LOW PRESSURE PUMP AT THE PONGOLA RESEARCH STATION – SAMPLE

The table below is a sample of the data recorded at the Pongola Research Station. Flow, pressure and electrical parameters are used to calculate the potential savings that could be realised if a VSD is installed.

Time stamp	**Flow Rate [m³.h⁻¹]**	**P1 [bar]**	**P2 [bar]**	**P3 [bar]**	**Average Voltage [V]**	**Average current [A]**	**Power Factor [Fraction]**	**Electrical power demand [kW]**	**Hydraulic power before throttle valve [kW]**	**Total pump station efficiency [%]**	**Pump efficiency [%]**	**Hydraulic power after throttle valve [kW]**	**Potential savings with VSD [%]**
2013/07/09 12:10	169	-0.4	7.3	4.7	242	108	0.64	50	36	71%	77%	24	33%
2013/07/09 12:20	172	-0.4	7.3	4.7	242	109	0.64	50	36	72%	77%	24	34%
2013/07/09 12:30	166	-0.4	7.4	4.9	241	107	0.64	49	35	71%	76%	24	32%
2013/07/09 12:40	166	-0.4	7.4	4.9	242	107	0.64	50	35	71%	76%	24	32%
2013/07/09 12:50	172	-0.4	7.3	4.6	242	109	0.64	51	36	72%	77%	24	35%
2013/07/09 13:00	167	-0.4	7.4	4.9	243	107	0.64	50	35	71%	76%	24	32%
2013/07/09 13:10	165	-0.4	7.4	4.9	242	106	0.64	49	35	71%	76%	24	32%
2013/07/09 13:20	166	-0.4	7.4	4.9	242	107	0.64	49	35	71%	76%	24	32%
2013/07/09 13:30	173	-0.4	7.3	4.6	242	109	0.64	51	36	72%	77%	24	35%
2013/07/09 13:40	166	-0.4	7.4	4.9	242	107	0.64	50	35	71%	76%	24	32%
2013/07/09 13:50	166	-0.4	7.4	4.9	242	107	0.64	50	35	71%	77%	24	32%
2013/07/09 14:00	165	-0.4	7.4	4.9	242	107	0.64	50	35	71%	76%	24	32%
2013/07/09 14:10	172	-0.4	7.3	4.6	242	108	0.64	50	36	72%	77%	24	35%
2013/07/09 14:20	166	-0.4	7.4	4.9	242	107	0.64	50	35	71%	76%	24	32%
2013/07/09 14:30	166	-0.4	7.4	4.9	242	107	0.64	50	35	71%	76%	24	32%
2013/07/09 14:40	171	-0.4	7.4	4.7	242	109	0.64	50	36	72%	77%	24	34%
2013/07/09 14:50	166	-0.4	7.4	4.9	240	107	0.64	49	35	72%	77%	24	32%
2013/07/09 15:00	163	-0.4	7.4	5.0	242	106	0.64	49	35	70%	76%	24	31%
2013/07/09 15:10	163	-0.4	7.4	5.0	242	106	0.64	49	35	70%	76%	24	31%
2013/07/09 15:20	176	-0.4	7.3	4.4	242	111	0.64	51	37	72%	77%	23	38%
2013/07/09 15:30	170	-0.4	7.3	4.7	242	108	0.64	50	36	72%	77%	24	34%
2013/07/09 15:40	169	-0.4	7.4	4.8	242	108	0.64	50	36	72%	77%	24	33%
2013/07/09 15:50	169	-0.4	7.4	4.8	242	108	0.64	50	36	72%	77%	24	33%
2013/07/09 16:00	176	-0.4	7.4	4.5	242	111	0.64	52	37	73%	78%	23	37%
2013/07/09 16:10	172	-0.4	7.4	4.7	243	109	0.64	50	37	72%	78%	24	34%
2013/07/09 16:20	171	-0.4	7.3	4.7	243	108	0.64	50	36	72%	77%	24	34%

14. APPENDIX 6: CASE STUDY 1 (UMFOLOZI) – VARIABLES

The processes and details of each mechanised operation assessed for the Umfolozi case study are summarised in the tables below

	Process/ operation	**System**	**System description**	**Prevalence of system**	**Power unit**	**Implement/ machine**	**Depth [mm]**	**Number of tools/ rows/ furrows**	**Spacing between rows or tools [m]**	**Percent clay (%)**	**Tractive Condition**	**Operators speed [km/h]**	**Field efficiency**
Tractor operations	Re-establishment	1	Conventional	100%	Tractor - New Holland dt90 - 63kW	Boom Sprayer (6m)	150	2	1.5	25	Firm	10	65%
					Tractor - New Holland dt90 - 63kW	Ripper - 30cm sweeps	250	1	1.5	25	Firm	8	80%
					Tractor - New Holland dt90 - 63kW	Ripper - narrow point	250	2	1.5	25	Firm	8	80%
					Tractor - New Holland dt90 - 63kW	Ridger	150	2	1.85	25	Tilled	7	80%
					Tractor - New Holland dt90 - 63kW	Disk coverer	50	2	1.85	25	Tilled	12	80%
	Ratoon management	1	Only on flats	45%	Tractor - New Holland dt90 - 63kW	Ripper - narrow point	200	2	1.7	25	Firm	8	80%
					Tractor - New Holland dt90 - 63kW	Ripper - narrow point	75	6	0.3	25	Tilled	8	60%
					Tractor - Case IH jx90-07 - 63kW	Boom Sprayer (6m)				25	Tilled	10	60%
		2	Hills 1	22%	Tractor - New Holland dt90 - 63kW	Ripper - narrow point	75	6	0.3	25	Tilled	8	60%
		3	Hills 2	23%	Tractor - Case IH jx90-07 - 63kW	Boom Sprayer (6m)				25	Tilled	10	60%
	Break crop	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

	Process/ operation	**System**	**System description**	**Prevalence of system**	**Power unit**	**Payload**	**Average lead distance [km]**	**Average cycle time [min]**
Harvest and transport	Harvest	1	Manual	100%	n/a			
	In-field loading	1	Non-slewing grab	100%	Three_Wheeled_Loader - Bell_126			
	Field to zone transport	1	Piggy back trailer	100%	Tractor - Case IH jx90-07 - 63kW	10	1.5	20
	Trans-loading	1	No machinery	100%	n/a			
	Zone to mill transport	1	Tram	100%	Tram		20	

Irrigation	System	System description	Area [ha]	System type	Motor capacity [kW]	Number of towers	Static head [m]	Longest main + sub-main pipe length [m]	Assumed pump efficiency
	1	Dragline	51	Dragline	37		18	500	70%
	2	Pivot - flats	45	Pivot	37	7	10	500	70%
	3	Pivot - hillside	11	Pivot	19	2	25	1200	70%
	4	Dragline - hillside	57	Dragline	37		25	1000	70%
	5	Transfer pump	164	Transfer	45		5	300	70%

15. APPENDIX 7: CASE STUDY 2 (PONGOLA) – VARIABLES

The processes and details of each mechanised operation assessed for the Pongola case study are summarised in the tables below

	Process/ operation	System	System description	Prevalence of system	Power unit	Implement/machine	Depth [mm]	Number of tools/ rows/ furrows	Spacing between rows or tools [m]	Effective width [m]	Percent clay (%)	Tractive Condition	Operators speed [km/h]	Field efficiency
Tractor operations	Re-establishment	1	Conventional	100%	Tractor - New Holland TT55 2 WD - 45kW	Boom Sprayer (8m)					35%	Firm	8	60%
					Tractor - Massey Ferguson MF 390 2WD - 60kW	Disk Harrow - Offset - primary tillage	250			2.5	35%	Firm	6	80%
					Tractor - New Holland TT75 2WD - 50kW	Ridger	150	2	1.4		35%	Tilled	6	80%
	Ratoon management	1	Conventional	100%	Tractor - New Holland TT55 2 WD - 45kW	Boom Sprayer (8m)					35%	Tilled	10	60%
					Tractor - New Holland TT75 2WD - 50kW	Banded Fertiliser Applicator (4 row)					35%	Tilled	10	60%
					Tractor - New Holland TT75 2WD - 50kW	Banded Fertiliser Applicator (4 row)					35%	Tilled	8	60%
	Break crop	1	Conventional	100%	Tractor - New Holland TT55 2 WD - 45kW	Boom Sprayer (8m)					35%	Firm	10	60%
					Tractor - Massey Ferguson MF 390 2WD - 60kW	Ripper - narrow point	750	2	1.4		35%	Firm	5	80%
					Tractor - Massey Ferguson MF 390 2WD - 60kW	Disk Harrow - Offset - primary tillage	250			2.5	35%	Tilled	6	80%
					Tractor - Massey Ferguson MF 390 2WD - 60kW	Disk Harrow - Offset - secondary tillage	100			2.5	35%	Tilled	8	80%

	Process/ operation	System	System description	Prevalence of system	Power unit	Payload	Average lead distance [km]	Average cycle time [min]
Harvest and transport	Harvest	1	Manual	100%				
	In-field loading	1	Non-slewing grab	100%	Three_Wheeled_Loader - Bell_120			
	Field to zone transport	1	Basket trailer	100%	Tractor - Contractors - 50kW	5	1.5	20
	Trans-loading	1	Non-slewing grab	100%	Three_Wheeled_Loader - Bell_120			
	Zone to mill transport	1	Hilo	100%	Haulage_Truck - Mercedes Hilo	25	20	

Irrigation	System	System description	Area [ha]	System type	Motor capacity [kW]	Number of towers	Static head [m]	Longest main + sub-main pipe length [m]	Assumed pump efficiency
	1	Transfer 1	62	Transfer	30		18	500	75%
	2	Transfer 2	62	Transfer	30		18	500	75%
	3	High pressure	30	Surface drip	45		30	1500	75%
	4	Low Pressure	93	Surface drip	90		25	1500	75%