THE OPTIMISATION OF ELECTRICITY AND WATER USE FOR SUSTAINABLE MANAGEMENT OF IRRIGATION FARMING SYSTEMS

M. VENTER, B GROVÉ AND I. VAN DER STOEP

WATER RESEARCH COMMISSION

TT 717/17

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REPORT TO THE
WATER RESEARCH COMMISION

WRC REPORT NO. TT 717/17

ISBN 978-1-4312-0886-9

APRIL 2017

OBTAINABLE FROM
WATER RESEARCH COMMISSION
PRIVATE BAG X03
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The publication of this report emanates from a project titled *The optimisation of electricity and water use for sustainable management of irrigation farming systems (WRC Project No. K5/2279)*

EXECUTIVE SUMMARY

THE OPTIMISATION OF ELECTRICITY AND WATER USE FOR SUSTAINABLE MANAGEMENT OF IRRIGATION FARMING SYSTEMS

BACKGROUND AND MOTIVATION

Irrigation farming profitability is increasingly coming under pressure due to the increasing cost of pumping irrigation water. During 2013 the National Energy Regulator of South Africa (NERSA) approved a multi-year tariff determination strategy which allows for an average annual increase in electricity tariffs of 8% for the period 2013/2014 to 2017/2018 (Eskom, 2016/2017). However, NERSA has approved an increase in the average annual electricity tariff to 9.4% for 2016/17 and beyond. The dependence of commercial agriculture on electricity as a source of energy to pump water will continue in future, even though electricity tariffs are increasing, as the cost associated with the use of renewable energy sources in South Africa makes the use of alternative energy sources financially infeasible (FAO, 2015). Increasing electricity costs which constitute a significant part of operating costs (Breytenbach, Meiring and Oosthuizen, 1996 and BFAP, 2010) will increasingly require from irrigators to balance the cost of applying irrigation water with the expected economic benefit from doing so. Thus, the old paradigm with the biological objective of applying irrigation water to sustain maximum production will be replaced with the new paradigm where water use is optimised to increase profitability (English, Solomon and Hoffman, 2002). Irrigations farmers will need to evaluate different options to manage energy and water use in the future.

Significant opportunities exist for irrigation farmers to reduce energy costs through irrigation system design and operating practices to improve profitability. The design of an irrigation system and the operating practices needs to be evaluated in order to reduce energy costs. Potential energy savings can be achieved by adopting new technologies (variable speed drives, high efficiency motors) while taking cognizance of the trade-off between investments and operating costs. Operating costs include variable and fixed electricity costs. Fixed electricity costs are constant and can only be changed by the electricity supplier, Eskom. Irrigation farmers are left with the option to manage their variable electricity costs. The variable electricity cost is the product of irrigation hours, kilowatt (kW) requirement and electricity tariff. These three components constitute the areas that should be investigated to manage variable electricity costs. Irrigation hours are determined by irrigation management, systems capacity and the limits that are placed on irrigation hours during the week when using time-of-use electricity tariffs. Irrigation management will determine the timing of an irrigation event as well how much water to apply. The electricity tariff is obtained from Eskom's available tariff structures and is beyond the control of the irrigator apart from the choice of a specific tariff structure. The kW requirement is closely linked to the irrigation system layout and design. The kilowatt requirement is a function of total pressure required by the system, flow rate and the efficiency of the pump and motor. An important strategy to minimise variable electricity cost is to design irrigation systems such that it requires the minimum amount of kilowatt to drive the water through the system (Lamaddalena and Khila, 2012 and Moreno, Medina, Ortega and Tarjuelo, 2012). A design factor that has an impact on the required amount of kilowatts is the choice of the diameter of the mainline through which water is pumped from the water source to the infield irrigation system. Pipes with larger diameters result in less friction loss which reduces the kilowatt requirement. However, an economic trade-off exists between reducing the kilowatt requirement by means of increasing the diameter of the pipes to lower operating costs and the increasing cost of buying pipes with larger diameters. General practice in the design of the mainline is to select the pipe diameter such that the friction loss represents less than 1.5% of the length of the pipe (Burger, Heyns, Hoffman, Kleynhans, Koegelenberg, Lategan, Mulder, Smal, Stimie, Uys, Van der Merwe, Van der Stoep and Viljoen, 2003). Important to note is that the norm may not select the optimal pipe diameter. In the past, irrigation systems were designed to minimize the investment costs because energy was cheap and irrigators did not mind the higher electricity costs. Recent increases in electricity costs have renewed the importance of energy cost in irrigation farming. As a result irrigation farmers are increasingly focusing on the economic trade-off between investment costs and operating costs when deciding on an irrigation system design and management.

PROBLEM STATEMENT AND OBJECTIVES

The question, however, is not whether irrigators should adopt practises to improve energy and water management. Rather, the problem is how to evaluate the interrelated linkages between irrigation management, irrigation system design and choice of electricity tariffs simultaneously to improve energy and water management. Together these factors will determine the extent of water and energy savings in irrigated agriculture. A need exits for an integrated decision support model that include optimal irrigation management, irrigation system design in relation to the available electricity tariff choices.

The general objective of this research was to develop appropriate management approaches for reducing electricity cost, improving water use productivity and increasing profitability of irrigation farming for selected irrigation areas in South Africa.

In order to achieve the general objective of the research the following specific objectives were set:

- To review (a) design norms and standards for irrigation systems; (b) available methods to calculate electricity cost for irrigation; (c) changes in electricity tariff structures over the last 10 years; (d) current irrigation practice on farms.

- To determine the key decision variables for reducing electricity cost of current and alternative irrigation systems with reference to amongst others: - Planning, design and operation; - Water use for irrigation; - Electricity use (kWh) and electricity rates/tariffs.

- To develop methods and models for (a) calculating electricity cost; (b) providing decision support for capital investment, operating cost and irrigation water management; and (c) quantify reduced system and life cycle cost with increased profitability.

- To develop guidelines for farmer advisory services on reducing the impact of electricity cost for sustainable irrigation water use.

APPROACH AND METHODOLOGY

The point of departure of the study was a comprehensive literature review with the aim of developing a conceptual framework of factors influencing the life cycle cost of alternative electricity management interventions. Emphasis was placed on using life cycle costing as it incorporates not only the cost of acquiring new technology but also operational costs, maintenance costs and the cost of disposing the product. As these costs have different time dimensions a net present value (NPV) analysis was used to ensure fare comparison of the different cost components.

The review included but was not limited to a review of the SABI irrigation system design norms, electricity cost changes over the last 18 years, electricity cost calculation methods and water use management. With the necessary background knowledge the research team developed a preliminary conceptual framework taking cognisance of the irrigation system design process and the three focus areas that should be targeted to manage electricity costs. The design process includes the design of the power supply, water distribution network and the determination of the irrigation water demand and design of the infield irrigation system. Capital investments that influence the kilowatt requirement, management (operation and maintenance) of the irrigation system and choice of electricity tariff was identified as focus areas that should be investigated in order to reduce electricity costs. The conceptual framework was finalised after a workshop with stakeholders which include academia, SABI accredited designers, irrigators and irrigation scheduling consultants. The framework emphasised the interrelated linkages between irrigation system design and irrigation water and electricity cost management. Specifically a trade-off exist between reducing investment costs and increasing operating costs through higher electricity costs.

The next step was to develop a model to calculate the profitability changes resulting from electricity cost management interventions that embraced the conceptual framework of variables affecting the life cycle costs. In the process a highly sophisticated non-linear mathematical programming model was developed. The Soil Water Irrigation Planning and Energy Management (SWIP-E) programming model has the unique characteristic that irrigation pumping hours are determined through a daily soil water budget while simultaneously considering the time-of-use electricity tariff structure and changes in kilowatt requirements resulting from mainline design changes. Given the sophistication of the model it was decided to validate the model against data for eight specifically designed pivot irrigation systems obtained from a SABI accredited designer. The eight designs were evaluated through the application of the SWIP-E model to determine the impact of electricity tariff choice, irrigation system design capacity and system size on the design of the water distribution network. Separate procedures were also developed to model pumping efficiency changes resulting from the use of variable speed drives (VSD). In addition to the eight pivot irrigation system designs evaluated, seven other case studies were developed from actual data collected from case study participants. The case studies were used to evaluate the impact of VSD's, electricity tariff choice, mainline design changes and management on electricity costs.

RESULTS AND CONCLUSIONS

The analyses of the specifically designed pivots were the most comprehensive and will be discussed first. The results showed that Ruraflex is more profitable than Landrate irrespective of the centre pivot size and irrigation system delivery capacities. The average net present value for the small centre pivot was R 4 868 536 for Ruraflex and R 4 723 962 for Landrate while the average NPV for the large centre pivot was R 8 297 614 and R 7 985 143 for Ruraflex and Landrate, respectively. The larger centre pivot resulted in higher NPVs compared to the small centre pivot. The average NPV per hectare using Ruraflex was R 173 954 and R 161 211 for the large and small centre pivot, respectively. Smaller delivery capacities (8mm/day) resulted in the highest NPV for both of the centre pivot sizes and electricity tariff structures, except for the large centre pivot using Ruraflex where the 10mm/day delivery capacity had the highest NPV. The conclusion is that Ruraflex and larger centre pivot sizes are more profitable than Landrate and smaller centre pivot sizes, respectively. Another conclusion is that smaller irrigation system delivery capacities is more profitable compared to larger delivery capacities which is in contrast to the observation in the field where larger system delivery capacities are more commonly found. However, careful consideration of the management implications of smaller delivery capacities is necessary before recommending low delivery capacities.

The results of the management implications showed that small variation in total irrigation hours between centre pivot sizes was observed for a given irrigation system delivery capacity. Furthermore, the results showed that total irrigation hours were exactly the same between electricity tariff structures. However, variation in total pumping hours between maize and wheat were observed. Irrigation of maize was mostly in off-peak and standard hours while irrigation of wheat was in off-peak, standard and peak timeslots when considering small irrigation system delivery capacities. The conclusion is that smaller irrigation system delivery capacities requires much more intensive management and information to balance the cost of applying water with the possibility of crop yield reductions. Another conclusion is that irrigation designers cannot assume that all the available off-peak hours will be used first because the status of the soil water budget and crop will determine when and how much to irrigate.

The interaction between mainline design (kW) and management (pumping hours) are very important in explaining total variable electricity costs because a large portion of the electricity tariff is paid for the kilowatt hour consumed. The magnitude of the increase kilowatt requirement and decrease in pumping hours will determine the impact on kilowatt hours when increasing delivery capacity. The results show that the decrease in irrigation hours resulting from increasing delivery capacity is almost the same between the centre pivot sizes. On the other hand the increase in kilowatt requirement for larger centre pivots are much more significant compared to the small centre pivot when increasing delivery capacity from 8mm/day to 14mm/day. As a result the impact of increasing delivery capacity on kilowatt hours is mixed for the small pivot whereas the kilowatt hours will increase for the large centre pivot. The conclusion is that the importance of the interaction between kilowatt requirement and irrigation management is much more profound for small centre pivots.

The optimal irrigation mainline design results showed that the higher electricity tariff associated with Landrate causes the optimal pipe diameter to change at lower delivery capacities. The optimal pipe diameter changed if the delivery capacity increased to 10mm/day for Landrate and to 12mm/day for Ruraflex. The breakeven percentage friction that will cause the pipe diameter to increase is between 0.6% and 0.66% for Ruraflex and between 0.4% and 0.6% for Landrate which is much lower than the design norm of 1.5%. The conclusion is that the electricity tariff structure should be considered when an irrigation mainline is designed since the electricity tariff structure may increase electricity costs which has an effect on the optimal pipe diameter. Furthermore the conclusion is that the design norm of 1.5% friction is too high which will result in non-optimal pipe diameters with low investment costs and high electricity costs.

Results from the actual case studies confirmed that Ruraflex provides significant reductions in electricity costs. However, the benefits of Ruraflex is only possible given good management. VSD seems to be an important technology that should be considered when trying to lower electricity costs under condition that the significant changes in set points exists.

RECOMMENDATIONS

IRRIGATION SYSTEM DESIGN CONSIDERATIONS

- It is recommended that the SABI design norm for the maximum allowable friction losses in main pipelines must be reduced from the current 1.5% to 0.7%, to ensure that there is a better balance between investment and operating costs. Lowering the norm will decrease operating costs while increasing the investment costs. However, applying a stricter norm will ensure that pipe diameter is closer to the optimal pipe diameter.

- Irrigation designers should apply economic principles when designing irrigation mainline designs since it will increase the overall profitability of the investment compared to applying the friction percentage design norm. Applying economic principles will automatically differentiate between electricity tariff structures (Ruraflex and Landrate) when designing an irrigation system.

- Irrigation designers should include both the investment costs and an estimate of the operating costs of the irrigation system design in order to allow farmers to make informed decisions.

KNOWLEDGE DISSEMINATION

- It is recommended that a number of knowledge dissemination sessions be held with irrigation designers and water users across the country to inform them of the project outcomes and proposed changes to the irrigation design norms. This can be further supported with popular articles on the project outcomes in relevant magazines.

- It is further recommended that SABI should oversee the development of software to support irrigation designers to apply economic principles when designing irrigation mainlines.

FUTURE RESEARCH

- It is recommended that risk is included in the SWIP-E model in order to evaluate the risk associated with smaller irrigation system delivery capacities in combination with load shedding.

- The SWIP-E model can be further expanded to include a combination of irrigation systems, which imply that more than one operating point will exist. Multiple operating points will have an effect on the kilowatt requirement at the pumping station, electricity costs and irrigation water management.

- The model furthermore provides a powerful basis to evaluate the profitability of new technology such as variable speed drives, energy efficient pumps and motors as well as modification of existing irrigation system designs.

- The SWIP-E model provides a powerful basis for crop water use optimisation for a given irrigation system design. The model may prove invaluable in determining the impact of compulsory licensing of agricultural water use on irrigation farming profitability.

- The model could be expanded to include intra-seasonal competing crops, such as maize and groundnuts, which implies that crops will compete for water during a growing season.

- It is recommended that the global optimality of the solutions of the model be tested with a genetic algorithm.

- Lastly, it is recommend that the economic benefit of alternative energy sources, such as wind energy, hydroelectricity and solar panels be investigated.

ACKNOWLEDGEMENTS

The research presented in this report emanated from a project in response to a directed call, initiated, managed and funded by the Water Research Commission entitled:

"The optimisation of electricity and water use for sustainable management of irrigation farming systems"

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The project team would like to express our sincere appreciation to the reference group for their guidance during the course of the project, especially the chairperson.

The contributions made by Potato SA that allowed the project team to include valuable case studies of potato producers are hereby gratefully acknowledge, especially the help from Mr P van Zyl.

The project team is also thankful towards the numerous workshops participants whose inputs were invaluable to improving the quality of the research.

LIST OF ACRONYMS AND ABBREVIATIONS

ARC-IAE	Agricultural Research Council – Institute of Agricultural Engineering
BRWC	Below Root Zone Water Content
CU	Christiansen Uniformity
CV	Coefficient of Variation
DU	Distribution Uniformity
DWAF	Department of Water Affairs and Forestry
EU	Emitter Uniformity
FAO	Food and Agricultural Organisation
GAMS	General Algebraic Modelling System
kVA	Kilo-Volt Ampere
kW	Kilowatt
LCC	Life Cycle Cost
LP	Linear Programming
MYPD	Multi Year Price Determination
NER	National Electricity Regulator
NERSA	National Electricity Regulator of South Africa
NIA	Net Irrigation Amount
NMD	National Maximum Demand
NPV	Net Present Value
PET	Potential Evapotranspiration
POD	Point Of Delivery
RAM	Readily Available Moisture
RD	Root Depth
RDP	Reconstruction and Development Program
RWCAP	Root Water Capacity
SABI	South African Irrigation Institute
SARS	South African Revenue Service
SASRI	South Africa Sugar Association
SMD	Soil Moisture Deficit
SWIP	Soil Water Irrigation Planning
SWIP-E	Soil Water Irrigation Planning and Energy
TAM	Total Available Moisture
TEFC	Totally Enclosed Fan Cooled Motors
TOU	Time-Of-Use
VAT	Value Added Tax
VFD	Variable Frequency Drive
VSD	Variable Speed Drives

WARMS	Water Authorisation Registration and Management System
WHC	Water Holding Capacity
WRC	Water Research Commission

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Chapter 1
INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Irrigation farming profitability is increasingly coming under pressure due to the increasing cost of pumping irrigation water. During 2013 the National Energy Regulator of South Africa (NERSA) approved a multi-year tariff determination strategy which allows for an average annual increase in electricity tariffs of 8% for the period 2013/2014 to 2017/2018 (Eskom, 2016/2017). However, NERSA has approved an increase in the average annual electricity tariff to 9.4% for 2016/17 and beyond. The dependence of commercial agriculture on electricity as a source of energy to pump water will continue in future, even though electricity tariffs are increasing, as the cost associated with the use of renewable energy sources in South Africa makes the use of alternative energy sources financially infeasible (FAO, 2015). Increasing electricity costs which constitute a significant part of operating costs (Breytenbach, Meiring and Oosthuizen, 1996 and BFAP, 2010) will increasingly require from irrigators to balance the cost of applying irrigation water with the expected economic benefit from doing so. Thus, the old paradigm with the biological objective of applying irrigation water to sustain maximum production will be replaced with the new paradigm where water use is optimised to increase profitability (English, Solomon and Hoffman, 2002). Irrigations farmers will need to evaluate different options to manage energy and water use in the future.

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1.2 PROBLEM STATEMENT AND OBJECTIVES

The question, however, is not whether irrigators should adopt practises to improve energy and water management. Rather, the problem is how to evaluate the interrelated linkages between irrigation management, irrigation system design and choice of electricity tariffs simultaneously to improve energy and water management. Together these factors will determine the extent of water and energy savings in irrigated agriculture. A need exits for an integrated decision support model that include optimal irrigation management, irrigation system design in relation to the available electricity tariff choices.

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- To develop methods and models for (a) calculating electricity cost; (b) providing decision support for capital investment, operating cost and irrigation water management; and (c) quantify reduced system and life cycle cost with increased profitability.

- To develop guidelines for farmer advisory services on reducing the impact of electricity cost for sustainable irrigation water use.

1.5 ORGANISATION OF THE REPORT

Chapter 1 provides the background and motivation for the research as well as the problem statement and objectives of the research.

Chapter 2 is devoted to a review of the knowledge with respect to the relevant irrigation system design norms, electricity cost changes over the last 18 years, electricity cost calculation methods and water use management. The chapter provides much of the necessary literature background to do the research.

Chapter 3 develops a conceptual model of life cycle assessment to evaluate alternative management interventions. The development of the conceptual model starts through the identification of focus areas of energy management and the factors affecting electricity costs within each of the focus areas. The information is used to develop a conceptual model of life cycle assessment to evaluate alternative management interventions. The last part of the chapter demonstrates the method of application of the conceptual model to evaluate energy management intervention options. Chapter 4 provides a detail description of the specific methods and calculation procedures necessary to evaluate the profitability of alternative electricity cost management interventions.

The results of applying the methods and models to evaluate the profitability of alternative interventions to manage electricity costs are discussed for several case studies in Chapter 5. Based on the results of the analyses guidelines were developed for reducing electricity costs which are reported in Chapter 6. Chapter 7 provides some conclusions and recommendations for further research.

Chapter 2

KNOWLEDGE REVIEW OF DESIGN NORMS, ELECTRICITY AND WATER USE COSTS

2.1 INTRODUCTION

The South African Irrigation Institute (SABI) is currently the custodian of the irrigation design norms in South Africa. The norms are published by the Agricultural Research Council's Institute for Agricultural Engineering in their Irrigation Design Manual (Burger et al., 2003), and covers all the applicable variables in the planning and design of irrigation systems. The origin and relevance of the current norms is reviewed here and benchmarked internationally where applicable. The project focus only on the relevant norms (energy norms).

A norm is defined as a widely accepted or required standard against which performance or achievement can be assessed. The SABI design norms serve to guide the designer in calculations and decision-making in the planning and design of agricultural irrigation systems. The design of appropriate irrigation systems requires a balanced approach that results in both technically, financially and ethically acceptable solutions for the irrigator. Diverging from the norms is acceptable if it can be well motivated from a both a technical and an ethical perspective by the designer.

The norms are applicable to various components of the irrigation system design process, which is presented graphically in Figure 2.1. The process consists roughly of the following phases:

- Irrigation planning
- Infield irrigation system design
- Water supply system design
- Pump station design

The designer takes two distinctly different approaches during the design of the infield and water supply system components of the irrigation system – when designing the infield components, the aim is to achieve a set minimum uniformity of application, while the focus of the supply system design is to convey the water as economically as possible from the source to the infield system. Both these requirements unintentionally assist the designer to produce a system that has the minimum power requirement, even though the focus is on water application and financial savings rather than energy management.

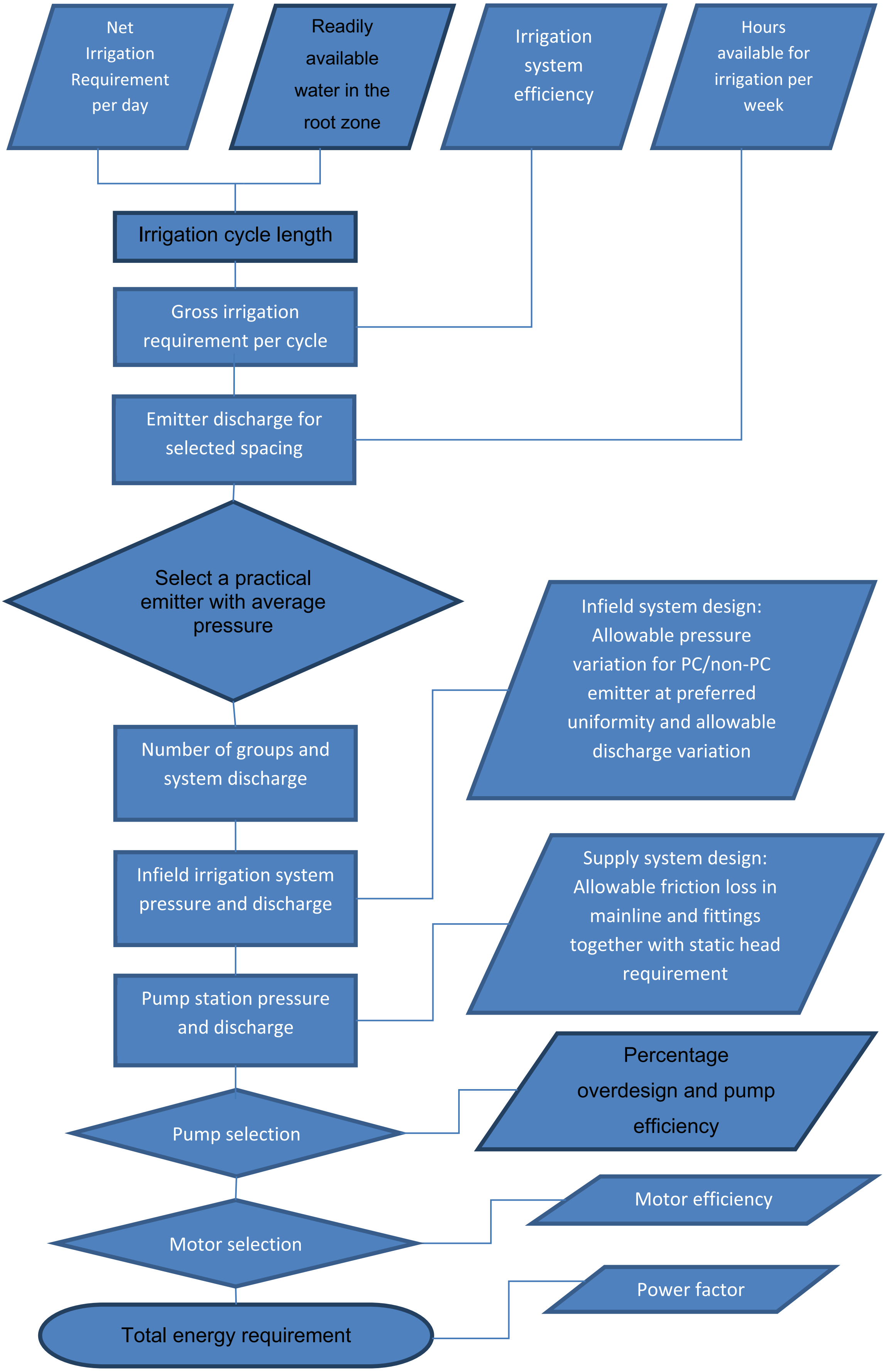

Figure 2. 1:Irrigation system design process

The final power requirement of an irrigation system powered by a hydraulic pump and an electrical motor depends on the system discharge and pressure requirement, and pump and motor efficiencies, as shown in Figure 2.2 and defined in Equation 1:

$$P_i = \frac{\rho \times gr \times H \times q}{36000 \times \eta_{motor} \times \eta_{pump}} \quad (1)$$

Where

P_i	Input power requirement of the electrical motor (kW)
ρ	Constant
gr	Gravity (m/s)
H	Pressure requirement at the pump station (m)
q	Flow rate (m^3/h)
η_{motor}	Motor efficiency (%)
η_{pump}	Pump efficiency (%)

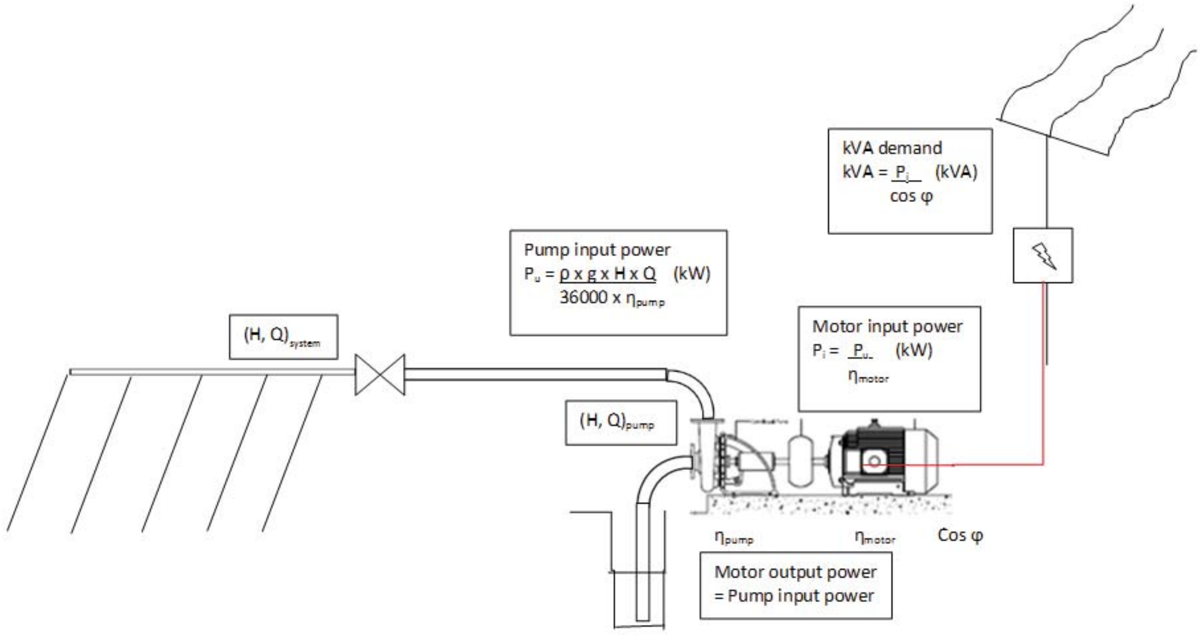

Figure 2. 2: Schematic diagram of energy demand at a pump station

Decisions made during every step of the process will influence these variables, and the norms therefore have a direct effect on the power requirement of the system. These norms are discussed in this section. The pump input power equation in Figure 2.2 calculate the kilowatt requirement of the irrigation system. The Kilovolt-Ampere (kVA) equation calculate kVA which is necessary in the calculation of reactive energy costs.

2.2 SYSTEM DESIGN NORMS

This section presents an overview of the South African Irrigation Institute (SABI) design norms that have an effect on the energy demand of an irrigation system, as defined by the power required to operate the system. According to 2013 Water Authorisation Registration and Management System (WARMS) data, 80.3% of registered irrigation systems in South Africa are pressurized types of irrigation systems (centre pivots, sprinkler, drip and micro sprinkler systems), and the majority of these systems are powered by centrifugal pumps driven by electrical motors. Any practices that will reduce the power demand of such systems, will therefore have widespread application in the irrigation sector.

It is not always clear how great the effect of a single variable is on the final power requirement of an irrigation system, and part of this project is to compile a model with which the sensitivity of the system to variables can be assessed. The existing norms should be used as a point of departure.

2.2.1 GROSS IRRIGATION REQUIREMENT

The amount of water required by the crop is the most basic input when planning an irrigation system. Most systems are designed to provide adequate water during the peak irrigation requirement period of the crop's growing season, and it is at the irrigator's discretion to use the system at a reduced capacity during the rest of the season.

Although not a design norm, the most widely recognised method of determining evapotranspiration of crops in South Africa is the SAPWAT3 program (Van Heerden, Crosby, Grové, Benadé, Schulze and Tewolde, 2009). SAPWAT3 is essentially an enhanced and improved version of SAPWAT, the program that was developed with funding from the Water Research Commission (WRC) in the 1990s to establish a decision-making procedure for the estimation of crop irrigation requirements by irrigation engineers, planners and agriculturalists. Subsequent to the development of the first SAPWAT programme, the Food and Agricultural Organisation (FAO) published the Irrigation and Drainage report No. 56 (Allen, Pereira, Raes and Smith, 1998), Crop evapotranspiration Guidelines for computing crop water requirements. This intuitive and comprehensive document is highly acclaimed and is accepted internationally. SAPWAT3 has at its core the computer procedures contained in FAO 56 (Allen, Pereira, Raes and Smith, 1998). All recommendations have been applied following the procedures set out in FAO 56 (Allen et al., 1998).

The irrigation requirement of crops is dominated by weather, particularly in the yearly and seasonal variation in the evaporative demand of the atmosphere as well as precipitation. SAPWAT3 has included in its installed database comprehensive weather data that is immediately available to the user. It contains long-term monthly average data for calculating Penman-Monteith ET_0 values as well as rainfall.

SAPWAT3 utilises the four stage crop development curve procedure based on relating crop evapotranspiration in each stage to the short grass (Penman-Monteith) reference evapotranspiration by applying a crop coefficient. Typical values of expected average crop coefficients under a mild, standard climatic condition are published in FAO 56 and applied in SAPWAT3. The crop coefficient files were developed according to rules derived with the help of crop scientists. Experience showed that it was necessary to modify the approach to suit irrigation as opposed to the normal rain-fed development stages. Editing has been simplified by the provision of options available on drop-down menus. It is envisaged that users concerned with groups of irrigators would develop their own sets of defaults tailored to their conditions.

SAPWAT3 incorporates the internationally recognised Köppen-Geiger climatic system. The system is based on temperature-rainfall combinations so that the climate of the weather station can be classified by using the temperature and rainfall data of a weather station record. One adaptation was made, that is the second letter of the three-letter code that indicates rainfall seasonality, is not used because rainfall seasonality is superseded by irrigation scheduling. In the case of South Africa this resulted in the number of climatic regions being reduced to five and it is no longer necessary for the user to have to decide in which climatic zone a weather station falls because this is determined by the program.

SAPWAT3 makes use of the FAO 56 (Allen et al., 1998) procedure that separates soil evaporation from plant transpiration and, therefore, conforms to the FAO 56 (Allen et al., 1998) defaults that determine soil water characteristics and evaporation parameters. Fortunately FAO 56 (Allen et al., 1998) specifies soils according to the familiar sand, silt and clay criterion into nine classes. The profile water balance during irrigation is also calculated and tabulated strictly in accordance with FAO 56 (Allen et al., 1998) methodology.

The methodology for estimating crop evapotranspiration under standard conditions has been well researched and due allowance can be made for nonstandard conditions arising from unusual circumstances and the realities of practical management. Crop evapotranspiration and net irrigation requirements can therefore be estimated accurately with SAPWAT3.

In estimating the gross irrigation requirement (how much water must be made available to match the evapotranspiration plus the losses that occur), the program provides for the user to simulate different scenarios.

Water that evaporates in the air or is blown away from sprinkler systems is regarded as a loss, so is water that is applied to uncultivated areas of the field. In SAPWAT3 this is reflected by System Efficiency. If too much water is applied and penetrates below the roots, this is also regarded as a loss – it is normally the result of an uneven distribution of water by the system or by lack of uniformity in the soil itself. In SAPWAT3 this is referred to as Standard Distribution Uniformity (DU). It is very difficult to provide standardised or even defensible defaults for these values. The approach that SAPWAT3 has followed is to provide a preliminary default value for System Efficiency and to set Standard DU at 100%. If, through measurement or judgement, however, the user can come up with real-life values, these should be substituted.

SAPWAT3 is a powerful tool particularly when the derived weather stations with their 50 years of daily weather data (1950-1999) are utilised. Its application from an energy management perspective should be such as not to over-estimate the crop evapotranspiration, as this leads directly to the over-design of systems which will have a higher than necessary power requirement.

The latest version of the program is SAPWAT4, which was published in July 2016 by the Water Research Commission of South Africa (Van Heerden and Walker, 2016). SAPWAT4 is essentially an enhanced and improved version of SAPWAT, the program includes FAO CLIMWAT weather database and the installed set of weather data also include derived weather stations for all quaternary catchments of South Africa. SAPWAT4 has at its core the computer procedures contained in FAO 56 (Allen et al., 1998).

2.2.2 SYSTEM EFFICIENCY

Table 2.1 shows the recommended and minimum values for the efficiency of different types of irrigation systems based on the results of a WRC project (Reinders, Van der Stoep, Lecler, Greaves, Vahrmeijer, Benadé, Du Plessis, Van Heerden, Steyn, Grové, Jumman and Ascough, 2010) and is determined by a water balance approach. The assumption is that the maximum theoretical efficiency of any irrigation system should be 100%. Assumptions are then made for acceptable losses in any system that can occur and the total losses deducted from 100%, to obtain the maximum (recommended) attainable efficiency. The minimum acceptable value is based on the previous norms. Although this process makes it possible for the designer to determine an appropriate efficiency for any specific situation that is being designed for by putting together the loss percentage values, he/she must however always strive for a system designed for the maximum attainable efficiency.

The efficiency values shown in Table 2.1 apply only to the physical performance of the irrigation system and it is assumed that the irrigator applies appropriate and economical management practices.

Table 2. 1: Typical irrigation system efficiencies

Irrigation system	Losses (%)				Default system efficiency (%) (net to gross ratio)	
	Non-beneficial spray evaporation and wind drift	In-field conveyance losses	Filter and minor	Total	Min	Recommend
Drip (surface and subsurface)	0	0	5	5	90	95
Micro sprinkler	10	0	5	15	80	85
Centre Pivot, Linear move	8	0	2	10	80	90
Centre Pivot LEPA	0	0	5	5	85	95
Flood: Piped supply	0	0	2	5	80	95
Flood: Lined canal supplied	0	5	5	10	70	90
Flood: Earth canal supplied	0	12	5	14	60	86
Sprinkler (permanent)	8	0	2	10	75	90
Sprinkler (movable)	10	5	2	17	70	83
Traveling gun	15	5	2	22	65	78

Source: Adapted from Reinders et al. (2010)

In consideration of energy demand, the maximum possible system efficiency value should be used to prevent irrigation systems from being over-designed and using excessive energy.

2.2.3 *IRRIGATION HOURS PER WEEK*

These values are used to determine the required system discharge (q). The principle is that the more hours available to undertake the irrigation of an area, the smaller the discharge will be and therefore the power requirement. On the other hand, it should also be kept in mind that the number of hours used for irrigation, contributes to the total number of kilowatt-hours demanded from the energy source. A designer should therefore strive to optimize the system at the point where the minimum energy demand occurs rather than the maximum number of hours. The norms recommended by Department of Water Affairs and Forestry (DWAF) (1985) are accepted:

- Micro and permanent sprinkler systems ≤144 hours
- Centre pivots systems ≤144 hours
- Moveable sprinkler and other movable systems ≤110 hours
- Flood irrigation systems ≤60 hours

It is also highly recommended that the Eskom tariff structure applicable to the irrigation system is taken into account when determining the number of hours available for irrigation per week.

2.2.4 SYSTEM LAY-OUT

Both horizontal and vertical displacement of water is considered.

Horizontally speaking, the most economical system lay-out will always be one where the water source is as central to the area to be irrigated as possible. However, the location of the water source relative to the irrigated area is often beyond the control of the designer.

When considering the vertical movement of water, there is no fixed limit to which water should be lifted with an irrigation system. In parts of the country, however, rules of thumb exist that suggest that it is uneconomical to irrigate areas located more than 50 m above the level of the water source. The origin of this rule of thumb is not known and it is usually applied in the context of surface water sources, as groundwater is often pumped from much greater depths than 50m.

It is only in the case of moving irrigation systems where there are limitations on the topography that the system can handle. Centre pivots are subject so manufacturer specific limitations on the slopes and angles that can be handled. In the case of travelling irrigators, it is recommended that cross slopes over the strips be limited to less than 5% during system lay-out. A pressure regulator is recommended for travelling irrigators on steep slopes to ensure a constant flow rate. The effect of large topographic difference that must be overcome, is an increase in the pressure required from the pump and therefore an increase power demand.

Another consideration that is affected by topographic height differences, is the decision regarding which blocks or systems served by a single pump station should be irrigated simultaneously. Conventional design practice is to combine areas of similar sizes into different shifts as this will ensure an almost constant discharge at any given time during the irrigation cycle. The blocks or system irrigated simultaneously would also typically be scattered around the whole farm as to reduce the discharge in the mainline and therefore make it possible to use smaller pipe sizes. The result is a fairly constant power demand on the pump station. However, with the implementation of Variable Speed Drives (VSD), designers have to consider whether it isn't more beneficial to divide the total irrigated area into pressure zones and vary the speed of the motor to adjust the pressure and discharge of the pump. A decision regarding which strategy to follow should be taken at the outset of the design.

2.2.5 *MINIMUM GROSS APPLICATION RATE*

Overhead type of irrigation systems usually have to apply water a minimum gross application rate in order to prevent excessive losses (especially evaporative losses) from occurring during every irrigation event. While systems can be designed to apply water at lower rates to save energy, it is not advisable as the application efficiency of the system will be very low and additional irrigation amounts or events will be required to make up for the losses.

The following minimum gross application rates are recommended for impact sprinkler systems:

- Moveable systems ≥ 5 mm/h
- Permanent systems ≥ 4 mm/h

The application rate of micro sprinklers should be equal to or greater than 3 mm/h on the wetted area (Lategan, 1995). Distribution tests can be done with the selected micro sprinkler on soils with poor water distribution ability, to ensure that dry patches will not occur in the wetting area of the sprayer.

2.2.6 *EMITTER SELECTION*

When selecting an emitter for an irrigation system, the main consideration of the designer (apart from the fact that the emitter should supply water a suitable discharge, litre per hour), is the application uniformity that can be achieved by a newly manufactured emitter under ideal conditions. The performance is defined by various indicators, depending on the type of irrigation system. An emitter that performs well from an uniformity perspective, will benefit energy management as the irrigator will be assured that the largest part of his/her crop is getting near the optimum amount of water, minimizing the need for over-irrigation to compensate for poor uniformity.

2.2.6.1 *Sprinkler systems*

The operating pressure, sprinkler application, wetted diameter and spacing of the sprinklers all influence the performance of the specific sprinkler and nozzle combination. The Christiansen's Uniformity coefficient (CU) is used to determine the water application in a laboratory. The sprinkler with the best CU value must be selected. The following norms for the selection of sprinklers based on the laboratory-tested CU values are recommended: (Keller, 1990):

- CU ≥ 85% for vegetable crops
- 75% ≤ CU ≤ 85% for deep rooted crops e.g. lucern
- CU ≥ 70% for tree crops

When applying chemicals through the system, the CU should be ≥ 80%.

2.2.6.2 Micro irrigation

In the case of micro sprinklers and drippers, the manufacturer's Coefficient of Variation (CV) provides an indication of the variability in the flow rate of a random sample of a given emitter model before it has been subjected to any field operation. The CV is defined as the standard deviation over the average discharge of a sample of emitters.

For point source emitters (non-overlapping wetting patterns), CVs are classified as follows (Sne, 2006):

CV < 5%	Excellent
5% < CV < 7%	Good
7% < CV < 11%	Average
11% < CV < 15%	Poor
CV> 15%	Unacceptable

With recent improvements in technology, most point source emitters have CVs better than 10%, and selecting an emitter with a CV of better than 5% is recommended. Pressure compensating emitters have a slightly higher CV than pressure sensitive emitters because of the variability of the compensating mechanism.

For non-point source emitters (overlapping wetting patterns, especially drip tapes), the CV classification is:

CV < 10%	Good
10% < CV < 10%	Average
CV > 20%	Marginal to unacceptable

2.2.6.3 Centre pivots

It is recommended that the CU as calculated by the supplier for the selected nozzle package should be ≥ 95%. In the field, an 85% CU value can then be expected.

2.2.7 AVERAGE EMITTER PRESSURE AND ALLOWABLE PRESSURE VARIATION

When an emitter is selected, the emitter discharge, q_e, is defined at a specific pressure, p_{ave}, especially in the case of pressure sensitive emitters. The designer will design the irrigation system so that all the pressures occurring in the infield part of the irrigation system varies below and above this average value, within certain system type specific limits, Δp_{ave}, which will result in the discharge variation in the system being limited to allowable values, Δq_e, leading to uniform application of water.

The average emitter pressure therefore has a direct effect on the power as it determines the starting point of the hydraulic pressure gradient, while the allowable pressure variation will set the maximum value of the pressure at the inlet to the infield part of the irrigation system. The aim should always be to select an emitter at the lowest possible average pressure without compromising the performance of the emitter, and to set the minimum allowable pressure variation without resulting in impractical and expensive system lay-outs (large allowable pressure variations make it possible to design systems with longer laterals and smaller diameter laterals and manifolds, which results in lower capital costs).

2.2.7.1 Sprinkler systems

The classification of sprinklers is shown in Table 2.2. Most agricultural systems fall in the medium pressure category. Manufacturers often specify preferred pressure ranges and spacing for their products; care should be taken not to use sprinklers at low pressures as it will have negative effect on the distribution patterns and thereby on the CU.

Table 2. 2: Sprinkler classification according to pressure

Sprinklers	Pressure [m]	Flow rate [m³/h]	Typical application
Low pressure	< 20	< 0,7	orchards
Medium pressure	25 - 40	< 3	cash crops
High pressure	> 40	< 50	pastures and sugarcane
High volume	> 45	20 - 100	pastures and maize

High pressure means high energy costs and application rates, while larger spacing mean low capital outlay and low application rates. Thus a combination must be chosen that gives the required gross application at a low total cost, while meeting the required minimum gross application rate.

As far as the allowable pressure variation for sprinkler systems are concerned, the system should be designed so that the pressure variation between different sprinklers irrigating simultaneously is not more than 20% of the design pressure (Jensen, 1983).

2.2.7.2 Micro irrigation

Although not a norm, the nominal operating pressure of pressure sensitive drip emitters is usually 10m and of micro sprinklers it is 15m. However, the manufacturer’s recommendations should be used.

As far as the allowable pressure variation is concerned, two different approaches are discussed here.

a) Conservative approach

The percentage emitter discharge variation of micro irrigation systems should not exceed 10% of the design emitter discharge. In the case of emitters with a discharge exponent of 0.5, this will result in a maximum allowable pressure variation of 20% of the design pressure.

b) Emitter uniformity (EU) approach

EU is a statistic parameter by means of which the expected uniformity of the emitter discharge within an irrigation block can be established, and where only the lowest and average emitter discharges are taken into account.

The following minimum EU values are recommended for micro sprinklers:

- Level terrain where slope < 2%: EU = 95%
- Undulating terrain or slopes > 2%: EU = 90%

The following EU values are recommended for pressure sensitive drip emitters:

Table 2. 3: Recommended EU Values of pressure sensitive drip irrigation systems

Emitter Type	**Number of emitters per plant**	**Topography or slope**	**EU (%)**	
			Min	**Recommended**
Point application	≥3	≤2%	90	95
Point application	<3	≤2%	85	90
Point application	≥3	Undulating terrain or slope >2%	85	90
Point application	<3	Undulating terrain or slope >2%	80	90
Line source	All	≤2%	80	90
Line source	All	Undulating terrain or slope >2%	80	85

If the EU value of 90% cannot be obtained with pressure sensitive emitters, it is strongly recommended that pressure compensating emitters should be used. It is recommended that maximum allowable pressure variation of PC emitters will be within the following limits:

- Minimum pressure = the minimum pressure at which compensation takes place as per the manufacturer + 3m
- Maximum pressure = the maximum pressure at which compensation takes place as per the manufacturer – 5m

2.2.7.3 Centre pivots

Sprinkler packages of different pivot manufacturers vary, but the following general guidelines are followed by the classification shown in Table 2.4.

Table 2. 4: Classification of pivot sprinkler packages according to pressure

Package	Pressure [m]	Typical wetted diameter [m]	Typical CU values [%]	Comments
Ultra-low pressure	4 - 10	7 - 12	90	
Low pressure	10 - 14	11 - 18	88 - 93	Low energy requirements
Medium – low pressure	21	25 - 32	90	
Medium pressure	28	27 - 34	>90	
High pressure	35	33 - 40	85 - 90	Not used often

The diameter of the centre pivot lateral should be designed so that the total friction loss along the machine is ≤ 2.5% (m/100m) of the total centre pivot length. It has been suggested that this value is closer to 3.6% in practice.

2.2.7.4 Traveling irrigators

The type of sprinkler and pressure may be selected from the manufacturer's catalogue. Big gun sprinklers with a high jet angle (> 23 degrees) are only recommended for low wind areas. The following minimum working pressures are recommended to limit droplet size:

- 300 kPa for 12 mm nozzles
- 400 kPa for 14 mm and 16 mm nozzles
- 500 kPa for 18 mm and 20 mm nozzles

The moving direction of a travelling irrigator must be such that the pressure difference between the upper and lower ends of a strip does not exceed 20% of the working pressure.

2.2.8 PIPE FRICTION IN MAIN-AND SUB MAIN LINES

The design of the main line of an irrigation system presents a problem to the designer. If a smaller pipe diameter is used, the capital costs of installing the system will be lower than when a larger diameter is used. On the other hand, the pump costs will be higher if a smaller pipe diameter is preferred to a larger pipe diameter. The optimum pipe size, or most economical diameter, can be determined through economic analysis that will result in graphs showing capital vs running costs for a range of possible pipe sizes that can be used (Figure 2.3). The most economical diameter will be the one that occurs at the lowest point of the total cost graph.

This principle is valid for not only the pipe diameter but also all the ancillary fittings and accessories – smaller sizes means lower capital cost but higher friction loss and therefore higher power demand.

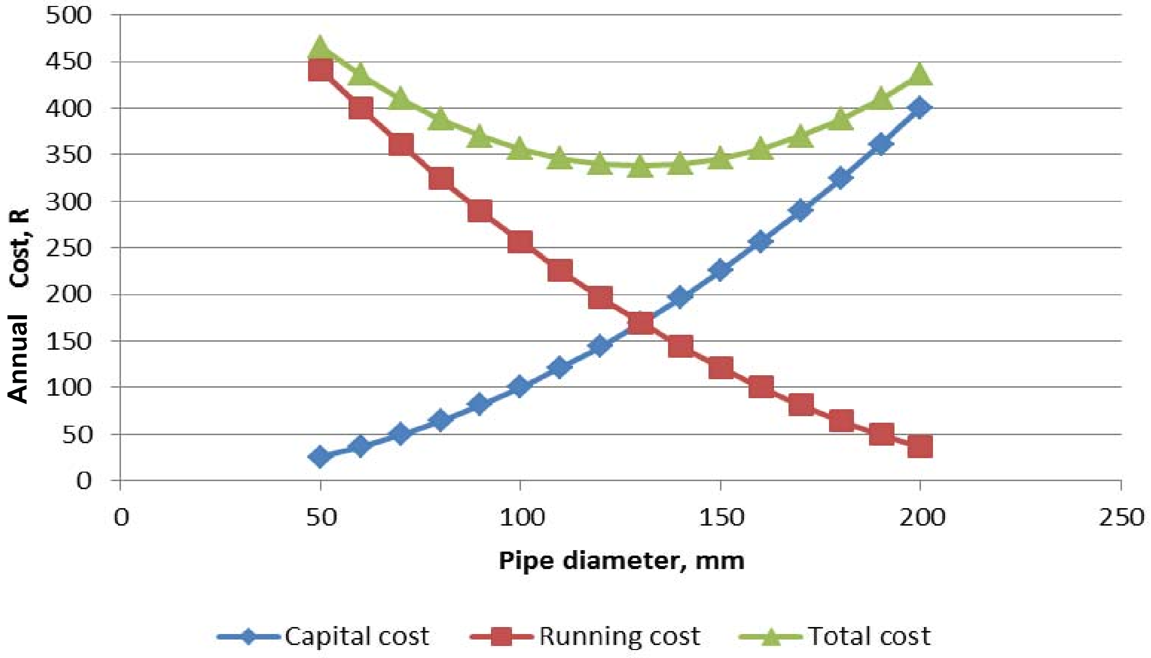

Figure 2. 3: Economic design approach based on life cycle costing

The designer must take into account the possible effect of water quality on pipes as well as the deterioration of pipes with age during the pipe's life time. The following values for allowable pipe friction in mainlines are accepted as norms:

The following applies for pipelines with a diameter of 200 mm or smaller:

- Rising pipeline: Maximum friction loss = 1.5% (m/100m pipe length)
- Gravity pipeline: Maximum allowable flow velocity of 3.0 m/s

If the above figures are exceeded, then the designer must show that the chosen pipe diameter's total cost (capital and annual running cost) have been optimized and is the best of the available options.

For pipes with larger diameters, a full life cycle cost analysis (capital and annual running cost) is recommended to find the most economical pipe sizes.

For all pipes, and especially in the case of diameters larger than 200 mm, the effect of water hammer is critical and must be investigated and optimized. An adequate number of air valves must be included in the design.

2.2.9 VALVES

The size of the valves at the inlet of the irrigation system must be chosen according to the manufacturer's recommendations for the specific application. In the absence of any recommendations, the valve must be chosen so that the pressure loss through the valve under normal operating conditions is less than 20 kPa.

2.2.10 FILTERS

The specification of filters is subject to any requirements stated by the manufacturer, for example the minimum pressure or flow rate required for the backwash of filters.

2.2.10.1 Disc and mesh filters

Disc / mesh filter openings must be ≤ 1/5 that of the emitter orifice diameter. The appropriate micro emitter manufacturer's recommendations must be used for flow path openings of ≤ 1mm. The following norms are accepted (ASAE EP405.1, 1997):

Table 2. 5: Allowable pressure difference over a filter bank

Type	Allowable pressure difference over clean filter/-bank (kPa)		Allowable pressure build-up (kPa)	Allowable pressure difference before backwashing (kPa)	
	Single filter	Filter bank		Single filter	Filter bank
Disc-/Mesh filter	10	30	40	50	70

2.2.10.2 Sand filters

When using a sand filter, a 200 μm control mesh or disc filter must be placed on the downstream side of the sand filter to catch the impurities in case of damage to the sand filter. The drip manufacturer's recommendations must be followed when using a disc- / mesh filter. The following norms are accepted.

a) Flow rate

The maximum allowable flow rate through a clean sand filter: Flow rate ≤ 50 m^3/h per m^2 of sand surface area with an allowable pressure difference over the clean sand filter of ≤ 10 kPa. A minimum of 50% of the maximum filtration rate (50 m^3/h per m^2 sand surface area) is required to backwash the filters (Burt and Styles, 1994). The maximum backwash rate must not exceed 1.2 times the filtration rate.

b) Pressure difference

The allowable pressure difference over a sand filter with disc-/ mesh filters: Allowable pressure difference over a clean filter bank (including sand and disc filter) ≤ 40 kPa and over the filter bank before backwashing should be ≤ 60 kPa. When using a disc-/ mesh filter, the allowable pressure difference norms must be complied with.

Table 2. 6: Allowable pressure differences over sand filters

Type	Allowable pressure difference over clean filter/-bank (kPa)		Allowable pressure build-up (kPa)	Allowable pressure difference before backwashing (kPa)	
	Filter	Filter bank		Filter	Filter bank
Sand filter	10	40	20	30	60

c) Outlet pressure during backwash

Minimum pressure during backwash of a sand filter: ≥200 kPa (Smith, 2010)

d) Sand specifications used in sand filters

Silica sand with a particle size that varies from 0.6 to 1.4 mm, with an acceptable sand grading, is recommended for sand filters. The recommended particle size grading must be 80 micron. A filtration performance of ≥90% must be achieved under laboratory conditions.

2.2.11 DESIGN PUMP CAPACITY (SAFETY FACTOR FOR WEAR AND TEAR)

These values are added to the calculated system capacity and are used to determine the duty point (pressure and flow) when selecting a pump. The present norms are accepted:

- Discharge 10%
- Pressure head 5%

If fertilizers are pumped through the irrigation system then an additional 20% flow capacity can be designed for in the system.

When a hydraulically driven travelling irrigator is used, the design flow rate must be increased by ± 2.5 m^3/h to allow for driving power. Confirmation of this value is required by the specific supplier.

Care should be taken to not include too many safety or overdesign factors in various points of the system as this will lead to an oversized and energy inefficient system.

2.2.12 PUMP EFFICIENCY

Although a fixed minimum value for efficiency of a pump cannot be given, the designer must always strive to choose the most efficient pump for the system.

2.2.13 MAXIMUM MOTOR POWER OUTPUT

The correct selection of an electric motor will ensure that the motor is never overloaded. It is therefore necessary to either select a motor with a power rating that is large enough for the selected pump and impellor, or to make provision against overload by means of protection devices. Table 2.7 indicates norms for minimum power rating of an electric motor for specific output power if the motor is selected according to the normal duty point (output power required).

Table 2. 7: Minimum power rating of electric motors for certain output powers

Output Power [kW]	< 7,5 kW	7,5 kW to 37kW	>37 kW
Minimum power rating of motor	Output power +20%	Output power + 15%	Output power + 10 %

An alternative approach is to consult the pump's power curve to determine the maximum possible power requirement. If this approach is followed, then the values in Table 2.7 must not be added as this would result in over designing of the motor.

The reduction in the power rating of the motor, as set out in Irrigation Design Manual of the ARC-IAE (2003 edition), must also be applied where necessary.

2.2.14 MOTOR EFFICIENCY

It is recommended that electric motors with a rating of at least "EFF2" (or "IE1") are used to drive the pump.

Table 2. 8: Efficiency classes of electrical motors

Efficiency	EFF system	IE systems
Premium		IE3
High	EFF1	IE2
Standard	EFF2	IE1
Lower than standard	EFF3	

2.2.15 VARIABLE SPEED DRIVES (VSD)

The VSD’s main function is the ability to vary the speed of the motor it is connected to. In the case of a centrifugal pump it is therefore possible with the VSD to use the same pump and impeller combination to supply water at various flow rates and pressure heads (duty points) without changing the impeller of the pump.

2.2.15.1 General

- The basic principles of correct pump and motor design and selection apply at all times.
- The integration of the VSD with the control system and automation of the irrigation system should be investigated in order to find the most appropriate and cost effective solution.
- Alternative options should be considered first, such as cutting the impeller to the correct size and using soft starters, especially in the case of single duty point applications, as they can offer more cost effective solutions than the installation of a VSD.
- The motor should be capable of delivering the required power of the pump at all the different duty points but should not be oversized.
- If no other information is available, it is recommended that the supply frequency to the motor should not be less than 25 Hz and not be more than 60 Hz.
- At very low frequencies, it may be necessary to install an auxiliary fan to the motor to ensure adequate cooling takes place.
- The motor with which the VSD is to be used, should be rated VSD compatible according to the manufacturer.

- The enclosure of the VSD to be used should have a suitable IP rating for the environment in which it is to be used (dust, moisture, etc.)
- When more than one VSD is used in parallel, or if more than one pump is used per VSD, the designer should make sure that the pumps will operate in all cases without influencing one another negatively from a hydraulic perspective.
- The integration of the VSD with the rest of the electrical system at the pump station must be assessed and if the situation requires it, the necessary electrical filters should be installed to protect all components of the system.
- Before a VSD is supplied, the designer should ensure that support or maintenance services for the VSD are readily available in the area.

2.2.15.2 Totally Enclosed Fan Cooled Motors (TEFC)

- Where running speeds are expected to exceed the normal 50 Hz frequency levels, contact the pump and motor manufacturers to find out if the proposed maximum running frequency of the motor is acceptable. Generally ≤ 60 Hz is accepted as the maximum but the manufacturer should confirm this.
- The motor maximum kilowatt (power rating) must not be exceeded when pumping at any given time but in particular when running at higher than normal speed (> 50 Hz).
- It is generally advisable not to run the motor at a lower frequency than 25 Hz for prolonged periods of time. If this is required, it is suggested that the motor manufacturer should be contacted to establish if the minimum running frequency of the motor can be decrease to below 25 Hz.

2.2.15.3 Submersible motors

- See first two points under TEFC.
- The minimum running frequency of a submersible motor will be determined by the minimum flow velocity across the motor, as stipulated by the motor manufacturer, as the flow also contributes to cooling of the motor.
- The necessary precautions need to be taken to prevent prolonged periods of no flow through the pump as it may lead to the damage of the motor.
- The maximum number of starts per day of the motor is as stated by the motor manufacturer.
- The maximum current demand of a submersible motor is usually greater than the current demand of a TEFC motor of similar power rating. The VSD must be able to meet both the current and the power requirements of the motor.

2.2.15.4 Electrical supply and connection

- The maximum allowable cable length between the motor and the VSD as recommended by the VSD manufacturer should be adhered to. This is of particular importance in the case of submersible motors. In general, it is recommended that all situations where the distance between the VSD and the motor is greater than 15 m, is investigated from a cable sizing perspective.
- The earthling of the VSD and motor must be in accordance to the requirements of the VSD manufacturer.
- If a VSD is used in conjunction with a generator, approval should be sought from both devices' manufacturers that the generator and the VSD can be used together.

2.3 AVAILABLE METHODS TO CALCULATE ELECTRICITY COST FOR IRRIGATION

2.3.1 CALCULATING ELECTRICITY COST

Various irrigation cost calculators are freely available on the internet. The main purpose of this section is not to review all of these, but to gain a better understanding of the principles that are used to calculate electricity costs. Throughout the report variables are indicated with capital letters and data parameters with small letters.

The universal equation that is used to calculate variable electricity cost is the following:

$$VEC = P_i \times PH \times k_e \quad (2)$$

Where:

VEC	Variable Electricity Costs (R)
P_i	Input power requirement of the electrical motor (kW)
PH	Pumping Hours (hours)
k_e	Electricity tariff (R/kWh)

The Kilowatt (kW) requirement is closely linked to irrigation system layout and design. Although not explicitly shown, it is important to note that flow rate (q) will have an important impact on the way the system could be operated to manage water applications and electricity usage. Therefore flow rate cannot be chosen independent of management considerations. Ultimately PH will be determined by irrigation management and the limits that are placed on irrigation hours during the week when using time of use electricity tariffs.

Equation 2 shows that total variable electricity costs is influenced by the design of the irrigation system (kW), management (PH) and choice of electricity tariff structure. These three components constitute the areas that should be investigated to manage electricity costs.

In terms of design, determining the required flow rate is fairly straight forward when proper design principles are used. However, the design of the mainline is more complicated due to the trade-off that exists between investment costs and operating costs. Small diameter pipes are less expensive than larger diameter pipes. As a result the investment cost of an irrigation system is reduced by choosing thinner pipes. However, the friction losses that occur in smaller diameter pipes are more when compared to larger diameter pipes. Since larger friction losses necessitates more power to drive the water though the system, a trade-off exist between investment costs and operating costs. Electricity tariff increases the past few years have renewed the importance of considering the correct pipe diameter for the mainline that is used to transport the water from the source to the irrigation system.

The irrigation design manual (Burger et al., 2003) proposes two methods to aid in the choice of pipe diameter. The first option provides only an approximation of the optimal pipe diameter. The second approach is based on a comparison of the investment cost and the electricity cost associated with operating the system. Radley (2000) developed a Linear Programming (LP) model to choose optimal pipe diameters for a mainline of a combination of irrigation systems given the layout of the system, static height differences, flow rates and pressure requirements are known.

The ARC-IAE mainline linear programming model (Radley, 2000) choose the optimal pipe diameter in each phase such that the present value of the sum of investment costs and electricity costs is minimised while adhering to pressure requirements. The following equation is used to calculate the annualised pipe investment costs:

$$A_{pc} = r_p l \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \tag{3}$$

Where:

A_{pc}	Annualised investment cost (R)
r_p	Cost of the pipe (R/m)
l	Length of the pipe (m)
i	Discount factor (decimal)
n	Lifespan of the pipes (years)

The assumption that the pipes have no salvage value is assumed in the above calculation of annualised investment costs. The annualised energy cost is calculated with the following formula:

$$A_e = \frac{\rho \times gr \times q \times H}{36000 \times \eta_{motor} \times \eta_{pump}} \, k_e \, PH \left(\frac{1-(1+g_e)^n(1+i)^{-n}}{(i-g_e)}\right)\left(\frac{i(1+i)^n}{(1+i)^n-1}\right) \quad (4)$$

Where:

A_e	Annualised variable electricity cost (R)
ρ	Constant
gr	Gravity (m/s)
H	Pressure requirement (m)
q	Flow rate (m^3/h)
η_{motor}	Motor efficiency (%)
η_{pump}	Pump efficiency (%)
k_e	Electricity tariff (R/kWh)
PH	Pumping hours (hours)
g_e	Energy inflation rate (decimal)
n	Lifespan of the pipes (years)
i	Discount factor (decimal)

The total annualised cost is minimised to facilitate the trade-off between investment and operating costs. You need to make certain assumptions regarding the pumping hours and the cost of energy. Proper irrigation planning is therefore necessary to apply the formula.

Although the spreadsheet model seems straight forward to apply, evaluation of alternative mainline designs are tedious since a new spreadsheet model needs to be developed for each alternative. The benefit of using a modelling system such as General Algebraic Modelling System (GAMS) (Brooke, Kendrick, Meeraus and Raman, 1998) is that a node network structure could be employed to define the layout of the mainline using data inputs.

2.3.1 IRRIGATION COSTS CALCULATORS

2.3.1.1 IRRICOST

IRRICOST (Meiring, Oosthuizen, Botha and Crous, 2002) was developed to estimate both the annual fixed and variable irrigation costs for several irrigation systems in combination. Only irrigation costs are estimated and typically the output of the model is used in other economic models to evaluate the profitability of irrigation farming systems. Recently the model was expanded to include drip irrigation costs (Reinders, Grové, Benadé, Van der Stoep and Van Niekerk, 2012). In order to allocate the costs appropriately the model makes a distinction between the costs associated with the mainline that distributes water to the different irrigation systems and the irrigation systems itself. The fixed costs associated with the mainline are allocated to each irrigation system based on the area of the system. The variable costs associated with pumping water are allocated to each irrigation system based on the proportional share of the kilowatts required to pump the water to each system when operated alone. The total amount of water pumped is assumed. A node network system is used to present the layout of the system and to facilitate the inputs of the pipe characteristics of each phase. Knowing the precise layout of the irrigation system design allows for the calculation of the pressure at each node which is beneficial to check whether the sufficient pressure is available.

A critical assumption that is made while estimating the irrigation costs is that all the irrigation systems are used to irrigate their respective fields simultaneously. In essence only one pump operating point is considered. Due to differences in the water requirements of different crops and soil variations such an assumption may not be justifiable all of the time. The cost estimation procedure needs to be further developed to handle more than one operating point. Such a development should be complimented with proper irrigation planning to ensure that costs are calculated realistically especially when Ruraflex is used. Integrating multiple operating points into irrigation and energy management is supported by Hillyer (2011) and Moreno et al. (2012).

2.3.1.2 IRRI - ECON

Due to a need to evaluate irrigation farming profitability of alternative irrigation systems in the sugarcane industry, researchers from South African Sugar Association (SASRI) worked with CANEGROWERS to develop the IRRIECON model (Armitage, Lecler, Jumman and Dowe, 2008). In essence the model uses the procedures embedded in IRRICOST to estimate the fixed and variable cost of irrigation which is then linked to enterprise budgets to evaluate sugarcane irrigation farming profitability.

2.4 AVAILABLE METHODS TO CONTROL FLOW RATE AND PRESSURE FOR AN IRRIGATION SYSTEM

Control methods are used to control the flow rate and pressure in an irrigation system to achieve the required flow rate and pressure. The performance of a single pump can be regulated in several ways. The most common approaches for centrifugal pumps are throttling, bypass control, modifying impeller diameter and change of speed. Not all these approaches are necessarily advisable. Furthermore, the supply of water from a pump station can be adjusted by using more than one pump for the system, operated either in parallel or in series, as discussed below.

2.4.1 SINGLE PUMPS

2.4.1.1 Throttling

Throttling increases the friction in a pumping system and raises the system curve to a higher position. Energy consumption is typically the same as before throttling, but with a reduced flow. Throttling is often used in irrigation when one pump must supply different irrigation systems or blocks with different flow and/or pressure requirements.

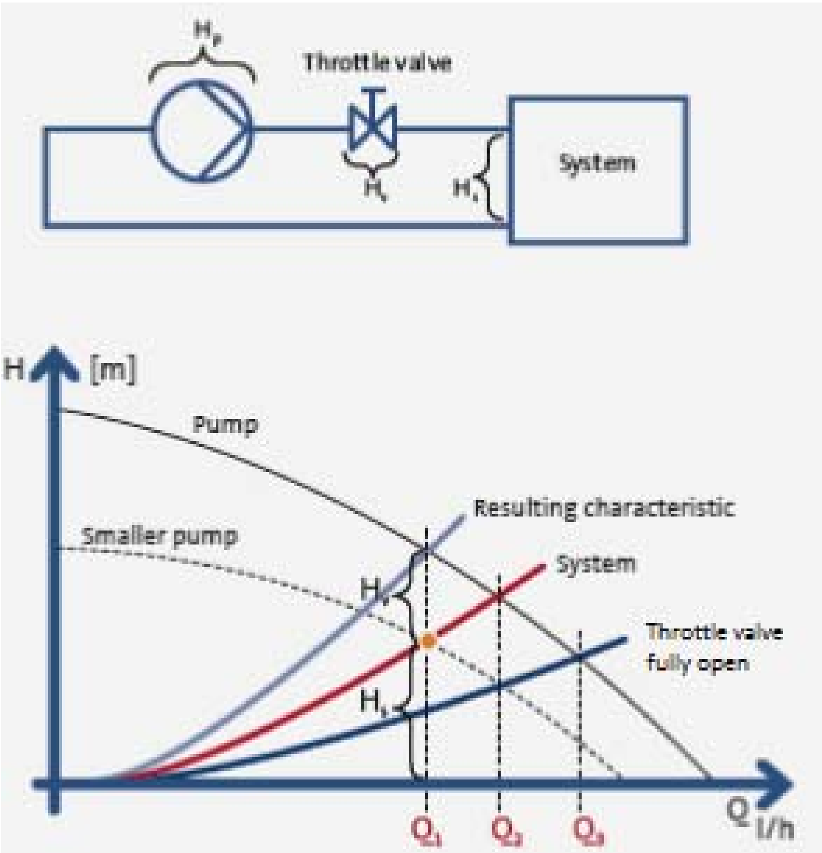

Figure 2. 4: Effect of throttling on pump performance

Source: Grundfos (2009)

The application is shown in Figure 2.4. In order to supply the correct flow to the system (Q_1), the valve must be throttled to reduce the flow from Q_3 to Q_1. In the process, the pressure generated by the pump ($H_s + H_v$) is much higher than the required system pressure H_s.

This approach for performance regulation wastes energy. The same performance could have been obtained by using a smaller pump, or by reducing the speed of the pump with a variable speed drive.

2.4.1.2 Bypass control

Bypass control effectively has the opposite effect of a throttling valve as it lowers the system curve, and ensures a certain minimum flow through the pump at all times (even if system demand is zero). The application is shown in Figure 2.5. With the pump running but zero system demand, the pump will generate a pressure of H_{max} and all the flow will recirculate through the bypass valve. When the system demand increases to Q_S, the pump will provide a flow of Q_P, of which Q_{BP} will recirculate through the bypass valve ensuring the system pressure demand H_P is met. Bypass systems are seldom used in irrigation systems.

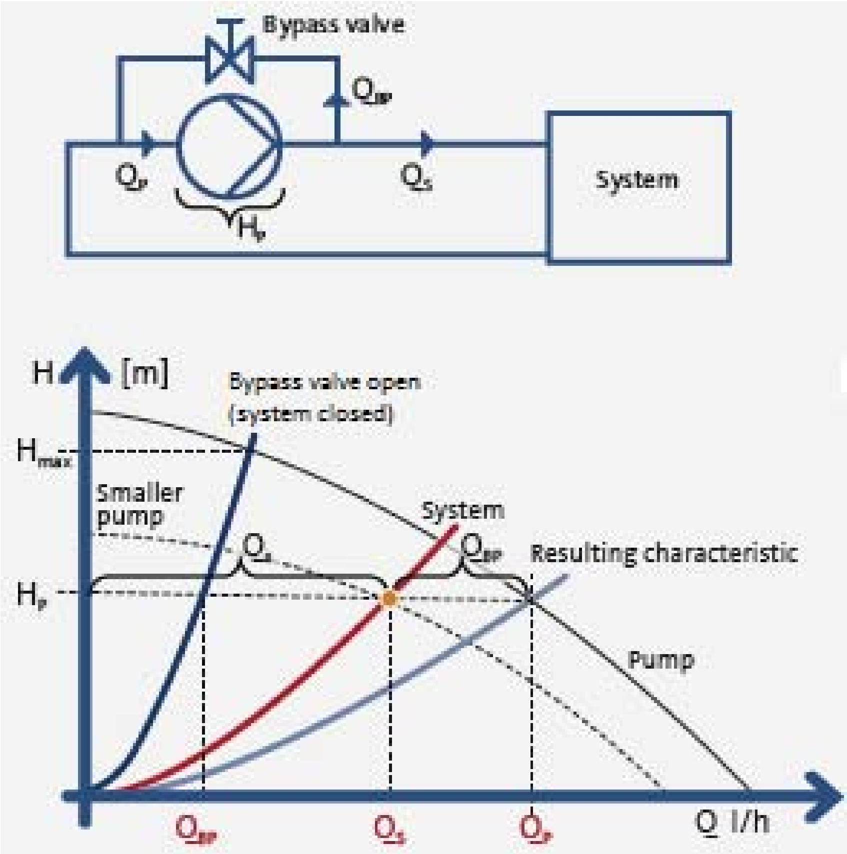

Figure 2. 5: Effect of a bypass valve on pump performance

Source: Grundfos (2009)

Energy consumption is typically the same for the pump, but since some of the water is recirculated, the overall efficiency of the system goes down as the pump is running towards the right of the curve during system operation.

2.4.1.3 Modifying the impeller diameter

If the pump is giving too much pressure or flow the diameter of the pump impeller can be reduced without any major consequences. The reduction is done by machining, and is fairly costly. When the diameter is reduced the flow, head and power is affected as shown in Figure 2.6 where D_n represents the pump curve before the impeller was modified and D_x the pump curve after the impeller was modified. The resulting change in the pressure (H) and flow (Q) are H_x and Q_x.

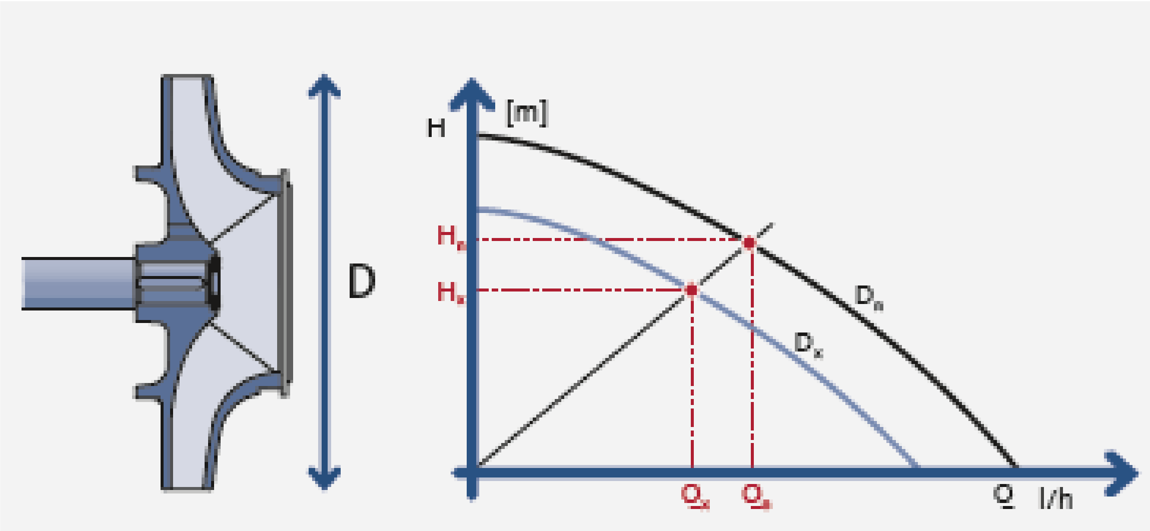

Figure 2. 6: Effect of reduction in impeller diameter on pump performance

Source: Grundfos (2009)

Modifying the impeller diameter permanently changes the performance of the pump (unless the impeller is changed again), and is not useful for situations where continuous changes in duty point is required, and throttling or bypassing will then have to be applied again to achieve this.

2.4.1.4 Speed regulation

Variation of the pump speed, or rpm, is the most effective way to regulate a pump's performance. When the speed is changed, the parameters change as shown in Figure 2.7 below. Again the subscript x is used to indicate the resulting H, efficiency (η) and power (P) from changing the speed of the motor. The use of variable frequency drives (VFD) or Variable Speed Drives (VSD) is becoming increasing popular as an effective tool to vary the speed of a pump and thereby the pump performance. One of the major benefits of this type of regulation is that the efficiency remains more or less unchanged over a wide performance range. This gives significant energy savings by reduced speed.

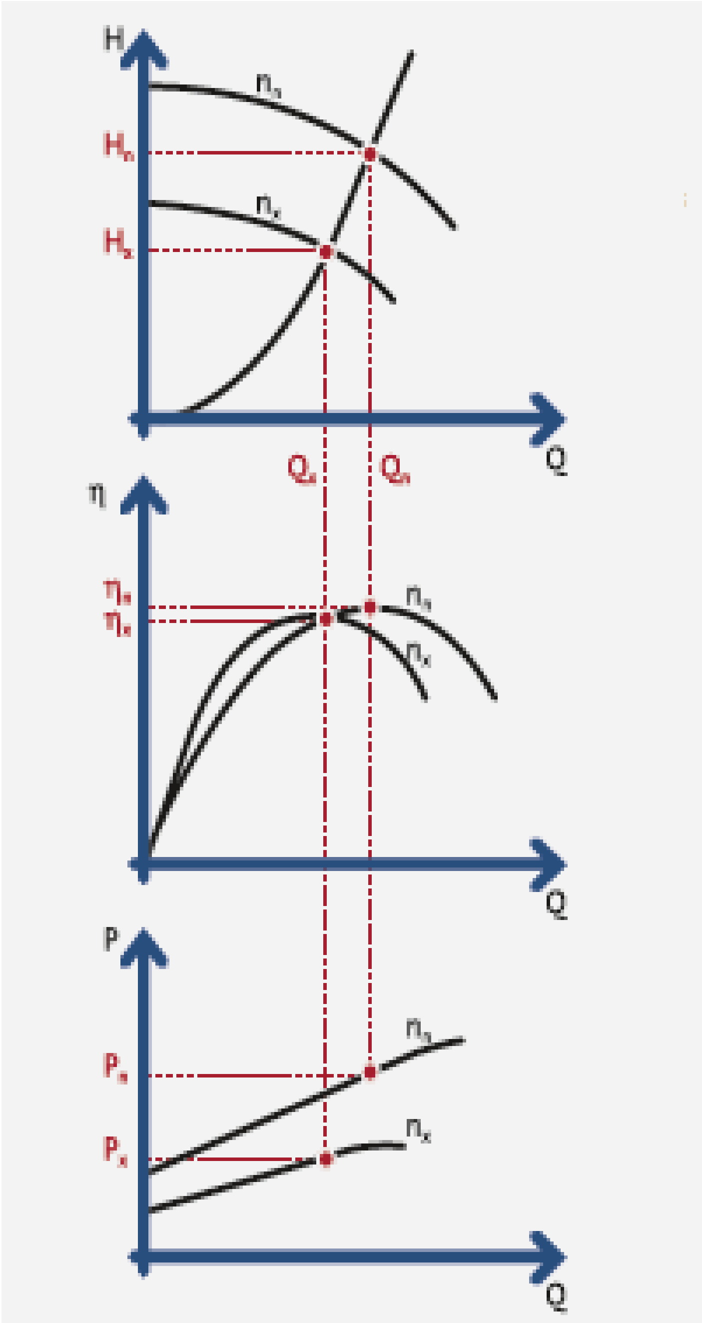

Figure 2. 7: Effect of speed regulation on pump performance

Source: Grundfos (2009)

The effect of applying speed control in systems with significant static head is much different from systems with no static head. Figure 2.8 shows the impact of speed control with no static head while Figure 2.9 shows the impact when there is a significant static head.

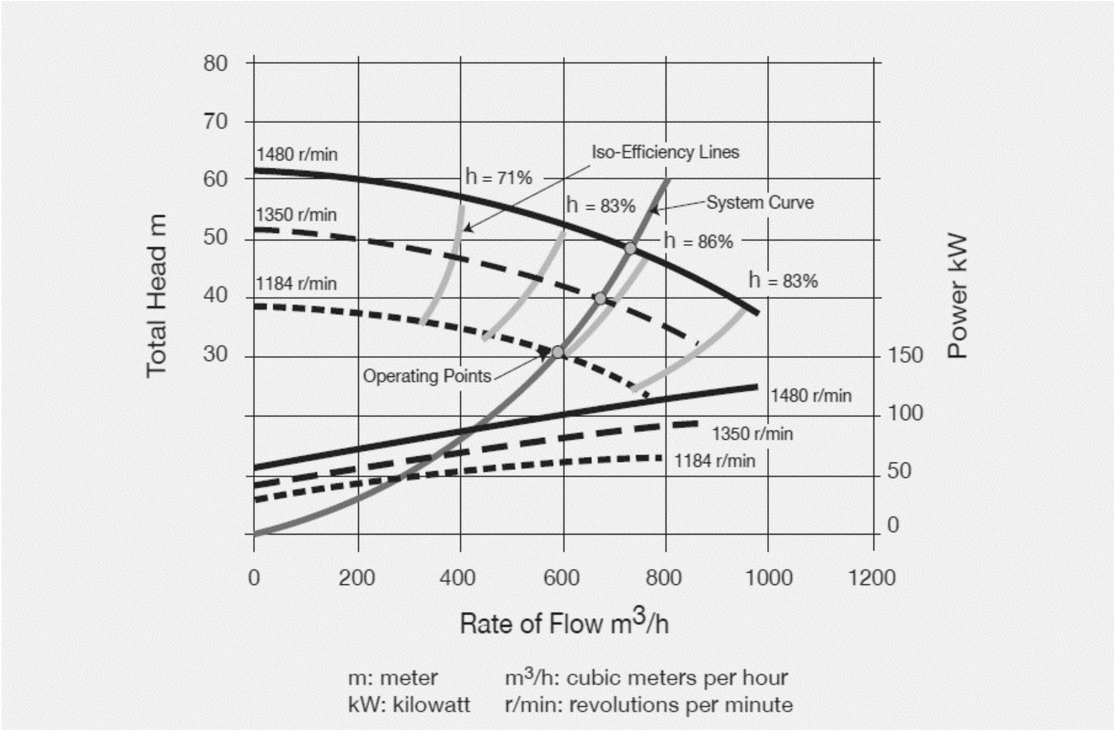

Figure 2. 8: Change in operating point with a zero static head using a VSD

Source: US Department of Energy (Undated)

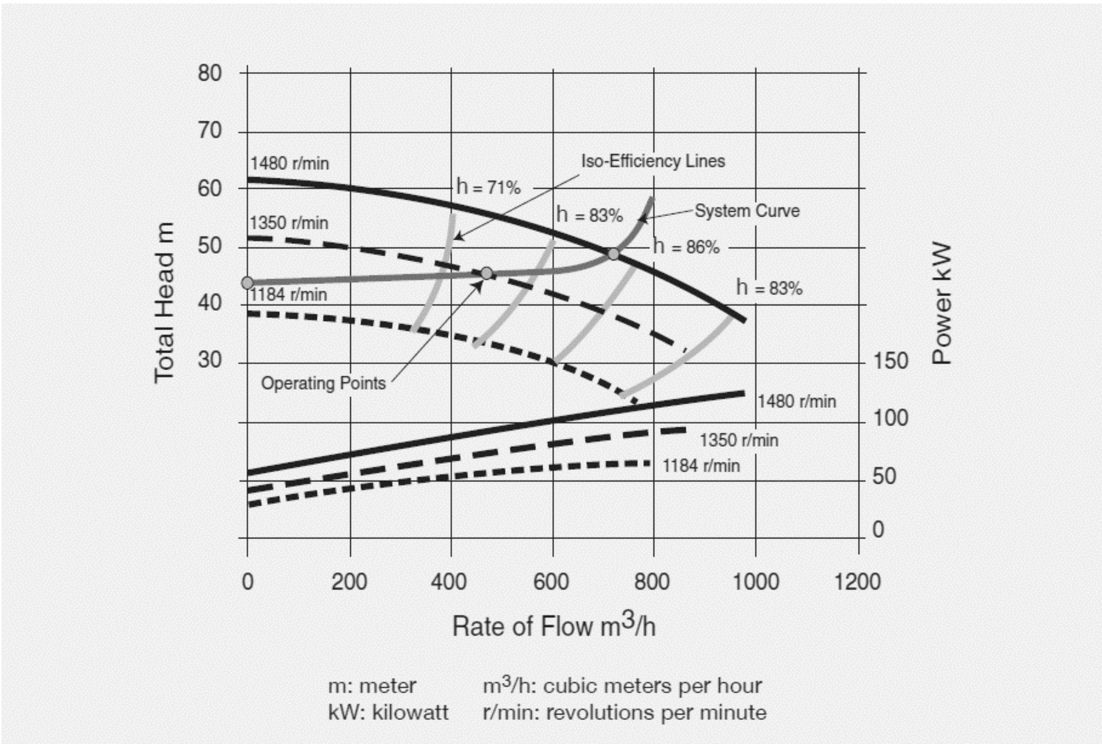

Figure 2. 9: Change in operating point with a static head using a VSD

Source: US Department of Energy (undated)

Figure 2.8 shows that for systems with a zero static head, reducing pump speed moves the operating point along with the system curve, parallel with the efficiency curves, keeping the efficiencies more or less constant. The operating point is reduced proportionally; this allows the pump to keep operating at the best efficiency point at a lower flow rate and pressure. The operating point is determined through the use of affinity laws.

Figure 2.9 shows that when a static head exists the system curve does not start at the origin but at the static head value. Hence the system curve is not parallel with the efficiency curve but intersects the efficiency curves. A small reduction in flow rate has a significant effect on the pump efficiency. The affinity laws can no longer be used to obtain the operating point and energy savings (US Department of Energy, undated).

The examples above clearly show that care should be taken when evaluating the energy savings that can occur through the use of new technologies such as variable speed drives. As a result the evaluation of the feasibility of a VSD should be case specific. Methods are available to estimate the changes in the pump efficiency in situations with zero static head. However, procedures to estimate efficiency changes for systems that are characterised by static head are not readily available. The Gator Pump Tuner software from Irri-Gator ignores changes in efficiency arguing that the irrespective what the reduction in inefficiency will be, the reduction in kW required due to changes in H will always be more (Chalmers,2010).

2.4.2 MULTIPLE PUMPS

2.4.2.1 Operating pumps in parallel

Pumps connected in parallel are mostly used when the required flow rate is more than what a single centrifugal pump can supply, or when the system has variable flow requirements. The regulation is done by turning one or two pumps on or off. This is a good approach for an irrigation system, where the layout has several zones that are not always used at the same time.

Two pumps of the same size will perform as shown in the curve in Figure 2.10.

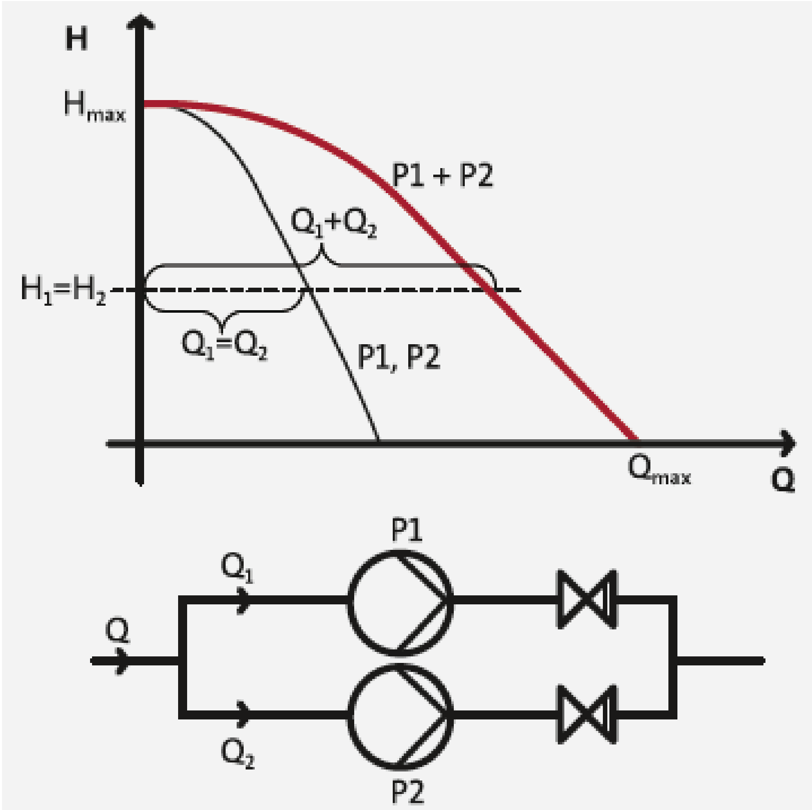

Figure 2. 10: Performance curves for two similar pumps installed in parallel

Source: Grundfos (2009)

The resulting performance curve for system consisting of several pumps in parallel is determined by adding the flow delivered by each pump for every value of head (from H = 0 to H = H_{max}). For the situation in Figure 2.10, the resulting pump curve for the two pumps in parallel has the same maximum head as what one single pump can deliver but the maximum flow is twice as big as the flow that can be delivered by a single pump.

Normally, pumps connected in parallel are of similar type and size. However, the pumps can vary if one or more of the pumps are fitted with a VSD. To avoid bypass circulation in pumps connected in parallel, a non-return valve must be installed after each pump.

Figure 2.11 shows the curve for two different sized pumps connected in parallel. It is obtained from adding Q_1 and Q_2 for every value of H. The hatched area shows the performance area where pump P1 alone will be able to supply water.

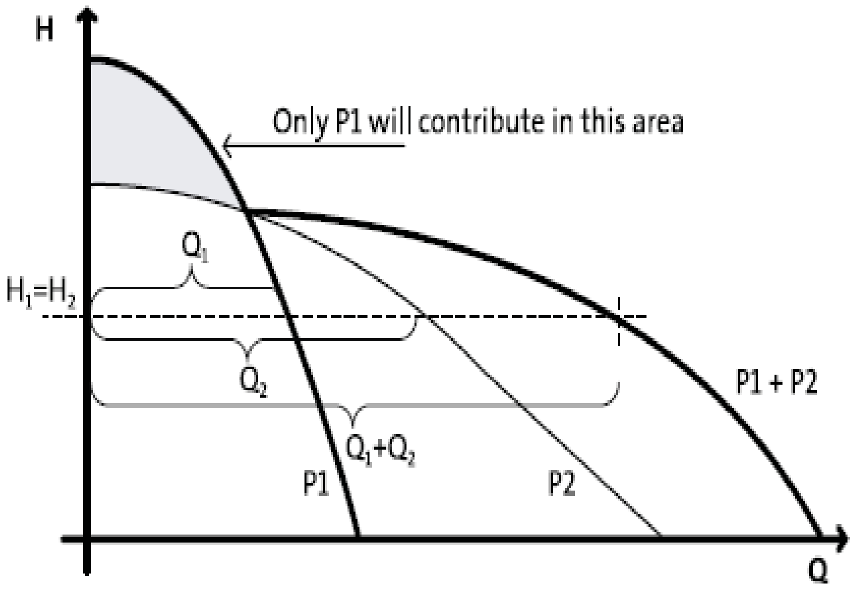

Figure 2. 11: Performance of 2 different sized pumps in parallel

Source: Grundfos (2009)

By adding speed control in the form a VSDs to parallel pumping systems, very efficient pump performance can be achieved for systems with varying flow demand. An example of such a system is shown in Figure 2.12. One single pump is able to cover the performance range up to Q1. For flow rates higher than Q1, both pumps have to operate to meet the system demand. If both pumps are running at the same speed, the resulting pump curves will look like the orange curves in Figure 2.12 to cover the performance range of Q = 0 up to Q = Q_2.

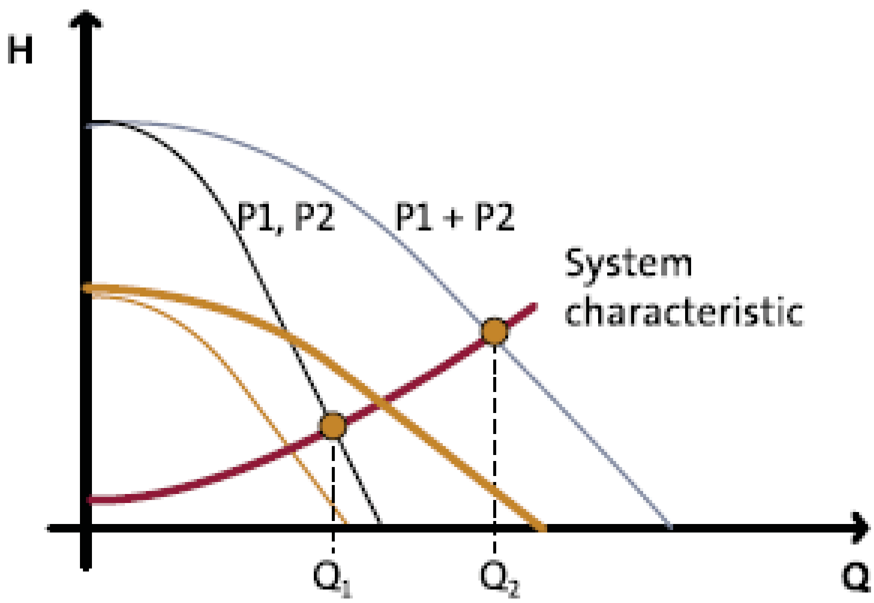

Figure 2. 12: Performance of two pumps in parallel, with speed control

Source: Grundfos (2009)

The duty point at Q1 in Figure 2.12 can also be achieved by using both pumps but both of them running at reduced speed, as shown in Figure 2.13.

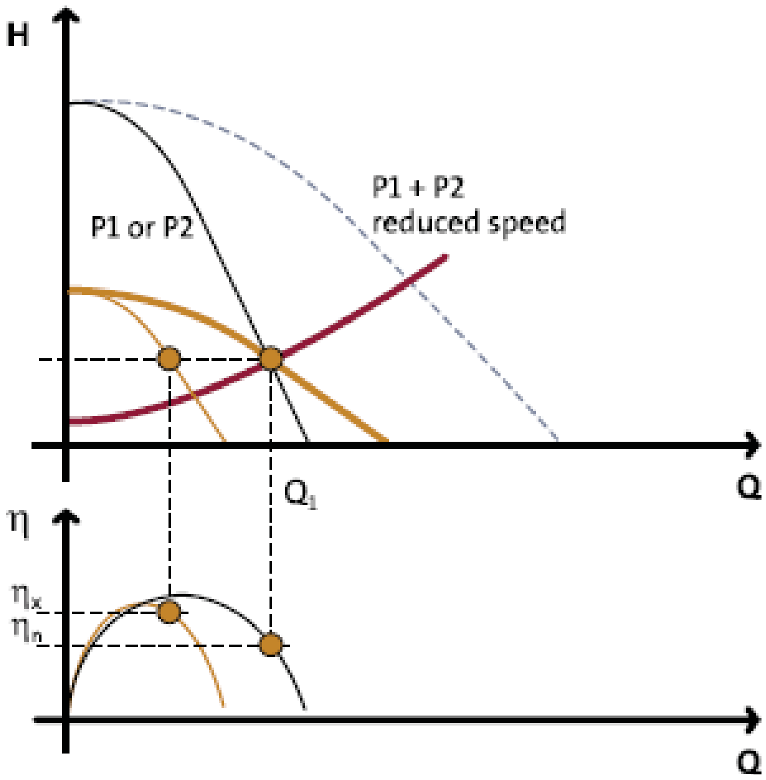

Figure 2. 13: Performance of two pumps in parallel, with speed control, but running at the same speed

Source: Grundfos (2009)

The advantage of using two pumps at reduced speed to achieve the lower flow rates lies in the efficiency of the pumps. The duty point for one single pump running at full speed to provide maximum flow, results in lower pump efficiency if the duty point lies to the far right of the pump curve (η_n). The total efficiency of two pumps running at reduced speed to supply the required flow rate, is better, as each pump is now operating at a duty point closer to the best efficiency point of the curve (η_x). Reduced energy consumption can therefore be achieved by using pumps in parallel with speed control but the specific situation will determine the need for this type of system.

2.4.2.2 Operating pumps in series

Pumps connected in series are used in systems where a high pressure is required (more than what can be delivered by a single centrifugal pump). An alternative to pumps in series are multistage pumps which are based on the same principle (1 stage = 1 pump). Figure 2.14 and Figure 2.15 show the difference in performance when two identical pumps and two different pumps are connected in series.

The resulting performance curve is obtained by adding the head generated by each individual pump over the range of flow rates the pumps can provide. As the pumps are identical in Figure 2.14, the maximum pressure on the curve is equal to two times the maximum pressure a single pump can supply (2 x H_{max}).

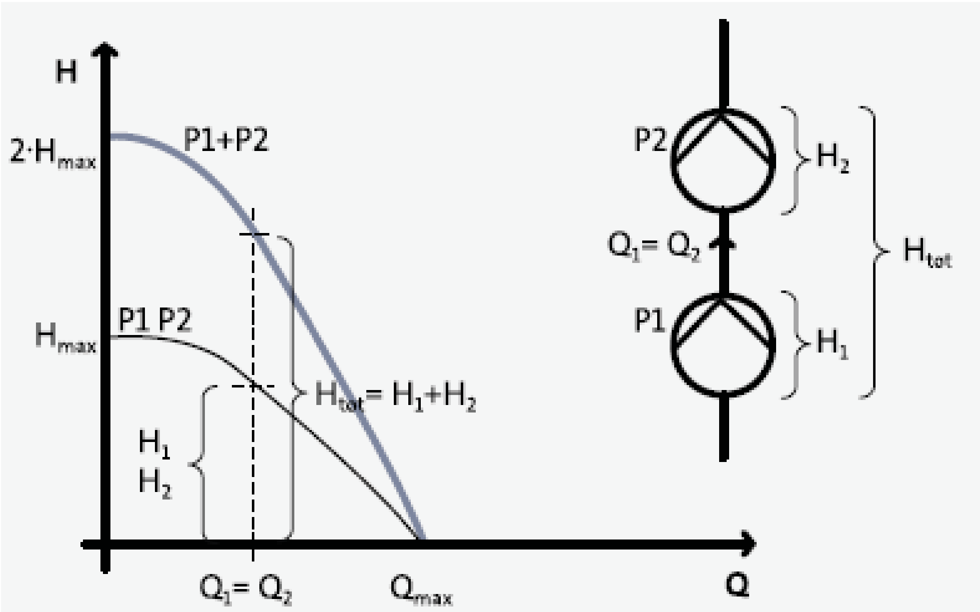

Figure 2. 14: Performance curve for two identical pumps connected in series

Source: Grundfos (2009)

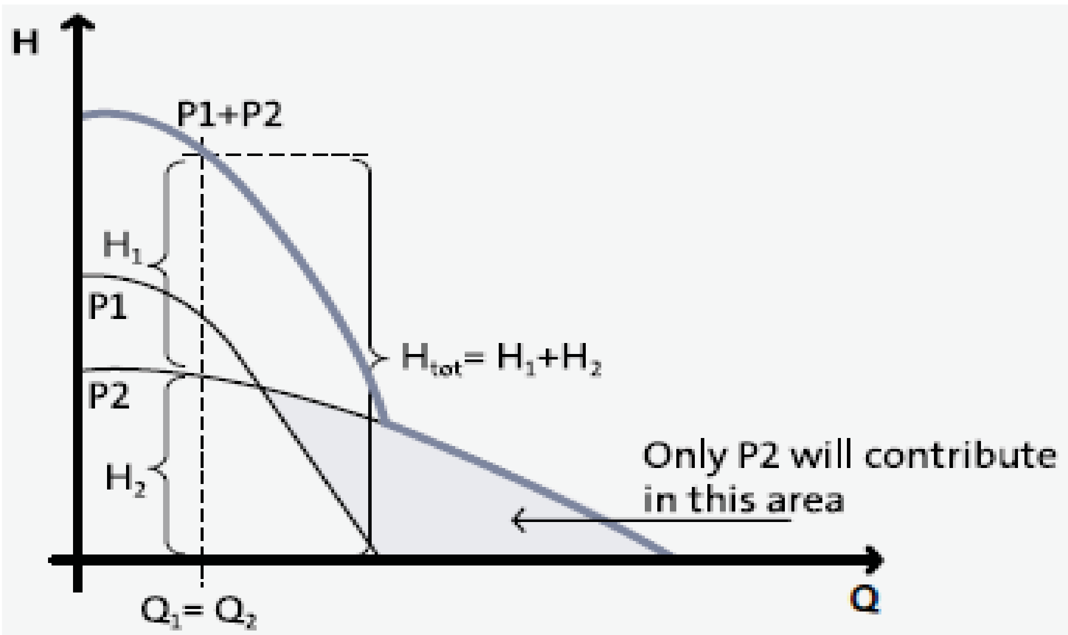

Figure 2. 15: Performance curve of two different pumps connected in series

Source: Grundfos (2009)

In Figure 2.15 the two pumps have different sizes and the resulting performance curve is found by adding H_1 and H_2 over the range of possible flows, Q. The hatched area in Figure 2.15 shows the range over which one single pump (P2) will be able to satisfy the required flow rates.

Pumps of different sizes and pumps with VSDs can be used in series. The combination of a fixed speed pump and pump with a VSD in series is often used in systems where a high and constant pressure is required. The fixed speed pump supplies the water to the speed-controlled pump, of which the output is controlled by a pressure transmitter (PT) as shown in Figure 2.16.

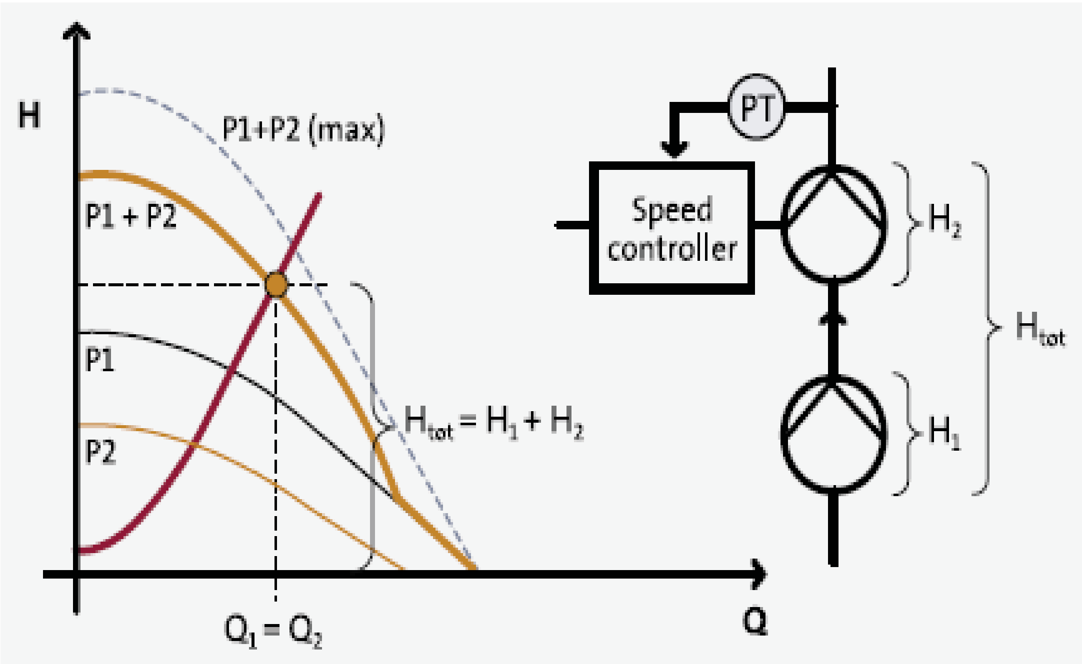

Figure 2. 16: Equal-sized fixed speed and controlled speed pumps connected in series

Source: Grundfos (2009)

2.5 *CHANGES IN ELECTRICITY TARIFF STRUCTURES OVER THE LAST 18 YEARS*

Eskom was one of the cheapest electricity suppliers in the world, but this has changed in recent times. The demand for electricity has increased due to an increase in population, costs of fossil fuels and difficulties with infrastructure. Eskom has struggled to meet the electricity demand. The lack of electricity supply has caused an increase in electricity tariffs and a change in the structure of electricity tariffs.

The purpose of this section is firstly to explain the tariffs applicable to irrigation farmers and secondly to give an overview of the changes in electricity tariffs over the last 18 years.

2.5.1 ELECTRICITY TARIFF INCREASES OVER THE PAST 18 YEARS

The average electricity tariff adjustments from 1998 to 2013 are shown in Table 2.9. Next the tariff adjustments are discussed in more detail.

Table 2. 9: Eskom's average nominal tariff adjustments for the last 18 years

Year	Average Tariff Adjustment (%)
1 January 1998	5.00
1 January 1999	4.50
1 January 2000	5.50
1 January 2001	5.20
1 January 2002	6.20
1 January 2003	8.43
1 January 2004	2.50
1 January 2005	4.10
1 April 2006/7	5.10
1 April 2007/8	5.90
1 April 2008/9	27.50
1 April 2009/10	31.30
1 April 2010/11	24.80
1 April 2011/12	25.80
1 April 2012/13	16.00
1 April 2013/14	8.00
1 April 2014/15	8.00
1 April 2015/16	12.08

In 1991, Eskom entered into an agreement to reduce the real tariff of electricity by 20% for the period 1992 to 1996. In 1994, a second Reconstruction and Development Program (RDP) contract was entered into in which the company committed it to a further 15% reduction in the real tariff of electricity for the period 1995 to 2000.

In 1998 Eskom increased the average tariff of electricity by 5%. The 5% increase gave the customers a tariff reduction of 2.5% in real terms for 1998. Inflation rate was 7.5%, thus the increase in the tariff of electricity was below the inflation rate (Eskom, 1998).

In 1999 Eskom increased the average tariff of electricity with 4.5%. Inflation rate was 6.8%, the adjustment in tariff of electricity was 2.3 percentage points under the consumer price index (CPI). Eskom were also able to achieve their RDP compact, which is to reduce the real tariff of electricity by 15% between 1994 and 2000. Eskom has submitted its proposed tariff adjustments to the National Electricity Regulator (NER) for approval. The regulator has studied the proposal and agreed that the adjustment is necessary in order to maintain the financial sustainability of the company. The NER also recommended a poverty tax in order to assist customers who were unable to pay due to poverty (Eskom, 1999).

The average tariff of electricity supplied by Eskom increased with 5.5% on 1 January 2000. Eskom announced a structural tariff adjustment to align their tariff structures more with the guidelines given in the Energy White Paper. The effect of the structural change will be that some customers will experience an effective tariff increase of either below or above the 5.5% average increase. Eskom has achieved a tariff reduction of 15.4% in 1999. Thus, with the annual increases in electricity Eskom has achieved the RDP compact (Eskom, 2000).

In 2001 the average tariff of electricity supplied by Eskom increased with 5.2%. The average tariff increase was below the inflation rate which was 6.2%, Eskom did achieve the compact of a 15% reduction.

On 14 September 2001 Eskom proposed a structural tariff change for 2002. The process took longer than anticipated, which made it impossible for Eskom to implement the structural changes from 1 January 2002. The NER approved the structural changes and it was implemented on 1 July 2002. Therefore, from 1 January 2002 until 30 June 2002, the same tariff structure as 2001 was in operation. The structural changes were implemented from 1 July 2002 until 31 December 2002. However, the tariff rates were increased with 6.5%. This general tariff increase is marginally above the expected inflation rate for 2002. Eskom has reduced the real tariff of electricity by 25% and achieved its mission to be the lowest-cost producer of electricity in the world, confirmed by an independent survey done by The Electricity Association Ltd, based in the United Kingdom. However, there are two factors that make it impossible for Eskom to continue for the real- tariff reductions. Eskom realized that they will run out of surplus capacity and it will require significant amounts of capital to be spent on new capacity. The second factor was that their current levels of return did not attract investment into the industry. For this reasons Eskom had to increase the tariff of electricity in real terms (Eskom, 2002).

On 13 September 2002 Eskom submitted its proposed structural changes and rates for 2003 to NER. The NER approved the proposal. The following structural change was effective from 1 January 2003:

- The postponement of the next phasing in step of network charges for Ruraflex and Landrate until a later date.
- A real increase of more or less 4%, on average, for the Landrate and Ruraflex tariffs, over and above the annual tariff adjustment of 8.43% (Eskom, 2003).

On 16 October 2003 the NER awarded Eskom a 2.5% annual tariff increase. From 1 January 2004 the following structural tariff changes were effective:

- An increase of not more than 4% on average (in real terms) for Ruraflex and Landrate, in order to reduce subsidies to the rural tariffs.
- A change to the Ruraflex tariff description in order to allow dual-phase supplies.

From 1 April 2004 the following structural tariff changes were effective:

- For the R2/kVA connection charge rebate, the demand rebate was based on 60% of the chargeable demand.
- The administration and service charges were based on the greater of the actual demand, measured in kilovolt-ampere (Eskom, 2004).

On 1 January 2005 the average tariff of electricity increased with 4.1% as approved by the NER. The following tariff structures were approved by the NER board, effective from 1 January 2005:

- The reactive energy charge for Ruraflex will only be applicable in high-demand season.
- An R/day charge instead of an R/month charge for service, administration and fixed network charges.

The structural adjustments resulted in a 4.1% average increase in tariff of electricity. The Board of Eskom Holdings Limited approved the request from the Department of Public Enterprises to change Eskom's financial year end from 31 December to 31 March. As a result the tariffs and charges were effective from 1 January 2005 to 31 March 2006 (Eskom, 2005)

The tariff a customer pays for electricity depends on two processes within Eskom. The first process is the annual tariff adjustment (normally inflation related). In 2006/7 the process was determined through a Multi-Year Price Determination (MYPD) process, which was led by the NER. Eskom applied for a revenue requirement in order to ensure the business sustainability. The average tariff of electricity increased with 5.1% that was approved by the NER. The second process deals with tariff structures. Eskom's tariffs were spilt into standard Eskom tariffs and local Eskom tariffs. All standard Eskom tariffs increased with 5.1% from 1 April 2006 until 31 March 2007. All Eskom tariffs to local authority supplies increased with 6.89% from 1 July 2006 until 30 June 2007 (Eskom, 2006/7).

In 2007/8 the average tariff of electricity supplied by Eskom increased with 5.9% from 1 April 2007 and the tariff was valid until 31 March 2008. No structural changes were proposed for 2007/8 (Eskom, 2007/8).

The retail electricity tariffs were adjusted to recover the National Electricity Regulator of South Africa (NERSA) approved revenue requirement for 2008/9. The revenue is the sum of the costs Eskom is allowed to incur and the returns Eskom can make during a financial year.

- The average tariff increase for tariffs used by customers supplied directly by Eskom, excluding local-authorities, is 14.2% effective from 1 April 2008 until 31 March 2009.

Eskom proposed structural changes for the 2008/9 financial year, but it was postponed by the NERSA. The changes were aimed at enhancing Eskom tariffs cost-reflectivity and transparency. The changes include the following:

- All tariff rates were based on the latest cost of supply study.
- Transmission and distribution network charges for Ruraflex tariffs was unbundled as follows:
  - Transmission network charges were differentiated as per the approved transmission zones.
  - Distribution network charges were differentiated according to the approved voltage and between rural and urban supplies.
  - Technical losses on the transmission and distribution system were shown and charged for separately in accordance with the NERSA-approved distribution and transmission loss factors.
- In order to make the voltage differentials more cost-reflective, Eskom increased the tariff differential of network charges between high-voltage and low-voltage customers from 0-17% to 0-25%.
- The time-of-use (TOU) conversion surcharge will be removed for existing and new supplies.
- The bill was simplified by introducing a rate matrix for Ruraflex tariffs (Eskom, 2008/9).

For the period July 2008 until March 2009 there were no structural changes. Eskom's tariffs were split between tariffs applied to bulk supplies to local authorities and tariffs that were applicable to all other supplies (non-local authorities). In December 2008 NERSA allowed for a 14.2% average tariff increase for the 2008/9 financial year. In March 2008 Eskom made an extraordinary application to NERSA for a further increase. The demand for coal and diesel has caused significant increases in the price of these commodities, resulting in large increases in primary energy costs. On 18 June NERSA decided to allow Eskom to recover additional primary energy costs of R2.827 billion through electricity tariff. Based on NERSA's decision the average tariff of electricity for 2008/9 showed an average tariff increase 27.5% compared to 2007/8. Note the following regarding the application of tariffs:

- NERSA approved an increase of 14.2% effective from 1 April 2008 for non-local authority tariffs.
- A further increase of 20% has been granted for implementation on 1 July 2008 for all non-local authority tariffs.
- The average tariff increase for all non-local authority tariffs was higher than 27.5% over the 2008/9 financial year.
- As Eskom is only being able to implement the NERSA approved increase on 1 July and not 1 April (for both local-authority and non-local authority tariffs) an increase of 34.2% was applied as from 1 July 2008 and replaced the previously approved increase of 14.2%.

- The April increase of 14.2% was applicable for three months (1 April 2008 to 30 June 2008) and the 34.2% increase implemented on 1 July was applicable for a nine-month period until 31 March 2009.

In the budget speech the Minister of Finance announced the introduction of a 2c/kWh levy on electricity produced from non-renewable sources (coal, gas and diesel). This levy was applied from 1 September 2008 (Eskom, 2008/9).

On 25 June 2009 NERSA approved an average tariff increase of 31.3% for Eskom from 1 July 2009. NERSA approved the retail tariff restructuring plan on 11 December 2008 and it was implemented in 2009/10. The main features of the structural changes were:

- Technical loss factors were used to differentiate energy costs instead of the voltage surcharges.
- The voltage differentials were increased between the high and low voltage network charges.
- Energy rates increased and network charges were reduced to reflect the higher cost of energy.

Government introduced an Environmental Levy of 2c/kWh on electricity produced by non-renewable generators (coal, nuclear and petroleum) in South Africa. To recover the Eskom costs for the Environmental levy paid to South African Revenue Service (SARS), the following charges were effective from 1 July 2009:

- An Environmental levy charge of 1.97c/kWh that is equally applied on all electricity sales to end users.
- Indirect Environmental levy costs for the non-renewable electricity generation that is the auxiliary consumption and line losses costs.
- From 1 July 2009, the environmental levy charge was reflected as a separate line item on the customer bill.

The Notified Maximum Demand (NMD) is the maximum demand contracted between Eskom and a customer for a period of 12 months.

The following aspects explain the 1 July 2009 tariff increase and the reasons why the tariff rates of 2008/9 can’t be used to determine the new rates for 2009/10:

- Firstly Eskom tariffs were restructured. This resulted in the tariff increase, increases to the energy rates and network charges proportionally reduced.
- The Environmental levy was introduced as a separate charge for all tariffs. This mean that the average tariff increase of 33.6% was adjusted to exclude the levy revenue
- This increase was applied to the restructured rates and not the 2008/9 tariff book rates
- The effective increases, excluding the levy, applied to the 2008/9 restructured rates were as follows:
    - Local authority tariffs: 23.23%

- Non-local authority tariffs: 26.18% (Eskom, 2009/10)

On 24 February 2010, NERSA approved an annual average tariff increase on the Eskom revenue of 24.8% for the Multi Year Price Determination 2 (MYPD 2) period (2010/11 to 2012/13) that allowed Eskom to recover revenue of R85 180 billion calculated from the annual revenues and sales volumes between the 2009/10 and 2010/11 financial years (Eskom, 2010/11).

In the 2011/12 NERSA allowed Eskom to recover R109.48 billion on 210.210TWh of electricity sales, resulting in a further increase in the average electricity tariff supplied by Eskom. The Minister of Finance announced that the environmental levy was increased from 2c/kWh to 2.5c/kWh to fund the costs associated with the rehabilitation of roads due to coal haulage damage. The increase in rural tariffs that include the environmental levy charge was 25.78% (Eskom, 2011/12).

The rural non-local authority rates increased with 15.74% in the 2012/13 financial year. These increases were approved by NERSA and were effective from 1 April 2012. NERSA originally approved an increase of 25.9%. The lower electricity tariff increase were a result of a combined effort by the government and Eskom to lessen the impact of higher electricity tariffs on consumers and the economy in the short term without comprising Eskom's ability to supply electricity and ensure its long term financial sustainability. The environmental levy increased from 2.5c/kWh to 3.5c/kWh. The increase of 15.74% includes the increase in the environmental levy (Eskom, 2012/13).

NERSA allowed Eskom to increase tariffs with 8% per annum for the next five years. For 2013/14, Eskom is permitted to recover R 135 226 million from sales of 206 412 GWh at an average tariff of 65.51c/kWh, increasing to 89.13c/kWh in 2017/18. The increase in rural tariffs applicable to irrigation farmer's increase with 9.3% (Eskom, 2013/14).

The average percentage increase in tariffs for 2014/15 differed between the tariff categories, but the overall average increase was at 8% which was approved by NERSA (Eskom 2014/15).

The average percentage increase for 2015/16 was at 12.08% but the percentage increase was different for the different tariff categories. In 2015/16 NERSA approved the following changes to the winter peak time-of-use period (Eskom, 2015/16):

- The morning and evening winter peak period moved one hour earlier.
- There is no change to the total number of peak, standard and off-peak hours.
- There are no changes to the summer time – of –use periods.

2.5.2 CONCLUSION

The proper evaluation of electricity tariffs is important to illustrate the effect of rising electricity costs on irrigation farmer's profitability and sustainability. The average tariff of electricity has increased significantly in the last 18 years. From 1998 until 2007 the increase in the average tariff of electricity supplied by Eskom was moving along with the inflation rate. In the year 2008 the average tariff of electricity increased rapidly maintain the company's sustainability and to cover expenses associated with the expansion of infrastructure.

The increase in the tariff of electricity has a significant effect on the cash flow, profitability and sustainability of irrigation farmers. The increases in the tariff of electricity created an incentive to improve electricity and water use for irrigation farmers. New technologies and improved managing methods will play an important role in the optimisation process of water and electricity.

Chapter 3

DEVELOPMENT OF CONCEPTUAL MODEL OF LIFE CYCLE COST ANALYSES

3.1 INTRODUCTION

Chapter 3 identify the main focus areas for managing energy costs and develop a conceptual model of life cycle cost analyses to evaluate the impact of alternative energy management interventions. Life cycle costing is advocated in the development of the conceptual framework as it not only includes the investment costs but all the costs over the life cycle of the investment (Grundfos, 2009). By implication life cycle costing involves considering investment costs, operational, maintenance costs and the cost of disposing the product. Taking cognisance of all the costs over the life cycle of the investment ensure for a fare comparison between alternatives as the operational cost over the life cycle of an investment may outweigh the initial cost of the investment (ARC-IAE, 2003; Grundfos, 2009).

3.2 IDENTIFYING FOCUS AREAS FOR ENERGY MANAGEMENT

The universal calculation procedure for calculating pumping energy costs was explored to identify the main focus areas for lowering pumping electricity costs. The universal calculation is given in Equation 5:

$$VEC = P_i \times PH \times k_e \quad (5)$$

Where:

VEC	Variable electricity costs (R)
P_i	Input power requirement (kW)
PH	Pumping hours (hours)
k_e	Electricity tariff (R/kWh)

TECHNOLOGY: $P = \frac{\rho \times gr\ q \times H}{36000 \times \eta_{pump} \times \eta_{motor}}$

P_i	Input power requirement of the electrical motor (kW)
ρ	Constant
gr	Gravity (m/s)
q	Flow rate (m^3/h)
H	Pressure requirement (m)

	η_{pump}	Pump efficiency (%)
	η_{motor}	Motor efficiency (%)
MANAGEMENT:	$PH = \frac{\frac{\sum_c IR}{\eta_{system}} \times A \times 10}{q}$	
	PH	Pumping hours (hours)
	IR	Irrigation requirement for a specific crop (mm)
	η_{system}	Irrigation system application efficiency (%)
	A	Irrigated area (ha)
TARIFF:	k_e	Electricity tariff (R/kWh)

Total pumping costs is the product of the kilowatt (kW) required to drive the water through the system, the total amount of hours (PH) the system is used to pump water and the electricity tariff applicable. The kW requirement was labelled TECHNOLOGY since it is a function of the design process and choice of technology. The second component is labelled MANAGEMENT because this component is a function of the irrigator's choice of crops, area irrigated and irrigation scheduling strategy. The last component is concerning the choice of Eskom electricity tariff structure and is simply labelled TARIFF.

Important to note is that the total pumping cost is the product of each of the components. As a result the impact of changes in any of these components on pumping costs cannot be determined without making assumptions about the others. These three focus areas also represent the key disciplines involved within irrigated agriculture namely engineering, agronomy and economics. Each of these components respectively can be unpacked to show the key variables according to which the focus areas are assessed.

Each one of the components in Equation 5 is determined from a series of variables that must be determined for the specific situation for which the design is being done. Although some regional "rules of thumb" has been developed over time (for example, for the cost of pumping 1 m^3 of water or to apply 1 mm of water, or the cost to irrigate 1 ha of a specific crop, etc.), good design practice requires every new system to be investigated individually as it presents a new situation for the variables that determine the pumping cost.

Next each of these focus areas are discussed in more detail.

3.2.1 TECHNOLOGY

Technology is represented by the total kW requirement to drive the water through the system when considering the calculation of total pumping costs. Evaluating the factors influencing kW is the output from the design process. Figure 3.1 is used to represent the design process resulting in the kW requirement.

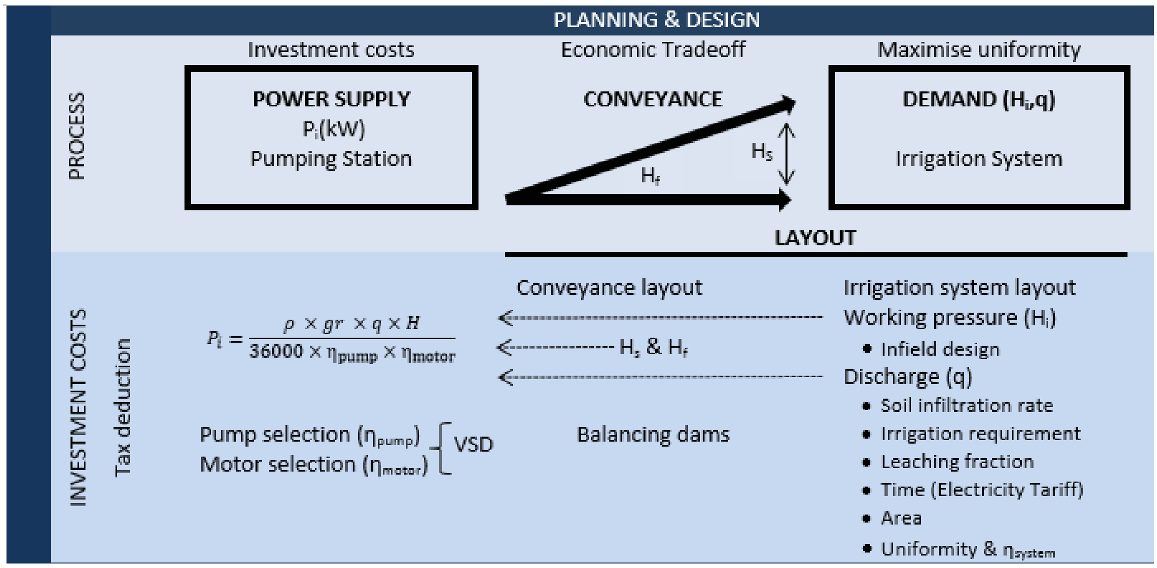

Figure 3. 1: Irrigation system design process

Three distinct components or steps are identifiable in Figure 3.1 which is carried out during the planning and design phase. Firstly a demand for a specific volume of water (q) with a specific pressure (H) is created through the infield design of the irrigation system. Once the infield design is completed the next step is to design the water distribution network that is used to convey the water from the source to the irrigation system. Together conveyance and demand will determine the layout of the system. The main output from conveyance and demand components is the kW requirement to drive the water through the system. The last step is to match a specific pump and motor according to the required operating point (q and H) of the system.

3.2.1.1 Demand

Demand represents the infield design of the irrigation system to determine the required irrigation system water discharge (q) and the pressure (H). The main objective during the design process is to design the system such that the distribution of water over the area is as uniform as possible. The design uniformity of the system is mainly a function of the infield irrigation system design and therefore controlled by the designer.

Inputs from the irrigator are required to determine the appropriate discharge of the irrigation system which is defined as the maximum volume of water that can be applied within a set time interval with an irrigation system of a certain size. Specifically the discharge of the irrigation system is a function of the design area of the system, the gross irrigation requirement and time available to apply the required amount of water. The gross irrigation requirement is determined by the crops grown in a specific climate and the irrigation system application efficiency (η_{system}). An important factor determining the time interval is the time available within the time of use electricity tariff (e.g. Ruraflex).

Flow rate is directly proportional to the power requirement and therefore directly proportional to the pumping cost. A larger system discharge (resulting in higher pumping costs) will be required under the following conditions:

- Climatic regions where the potential evapotranspiration (PET) is higher
- Crops for which the potential evapotranspiration (PET) is higher
- Selecting an irrigation system with a lower system efficiency
- Reducing the number of hours available to complete an irrigation event
- Irrigating a larger area

3.2.1.2 Conveyance

The conveyance component has to do with the design of the water distribution network. Designing the distribution network has a direct influence on the pressure requirement (H) at the pump station through the hydraulic design process which aims at defining the system that will be able to deliver the discharge, q, to the desired area. The hydraulic design process consists of two basic components – static head and friction loss. The static head component makes provision for overcoming the topographical height difference between the pump station and the irrigation system, as well as the providing water at the correct working pressure to the irrigation system. The friction loss component is variable and depends on the system discharge through the pipes, length of the pipe, type of pipe as well as the inside diameter of the pipe.

The design of the main line of an irrigation system presents a problem to the designer. If a smaller pipe diameter is used, the capital costs of installing the system will be lower than when a larger diameter is used. On the other hand, the pump costs will be higher if a smaller pipe diameter is preferred to a larger pipe diameter. The irrigation design manual (Burger et al., 2003) proposes two methods to aid in the choice of pipe diameter. The first option provides only an approximation of the optimal pipe diameter. The second approach is based on a comparison of the investment cost and the electricity cost associated with operating the system that will result in graphs showing capital versus running costs for a range of possible pipe sizes that can be used. The most economical diameter will be the one that occurs at the lowest point of the total cost graph. This principle is valid for not only the pipe diameter but also all the ancillary fittings and accessories – smaller sizes means lower capital cost but higher friction loss and therefore higher power demand.

As an alternative to economic analysis to determine the most economical pipe diameter a norm was developed which ensures that the friction loss is no more than 1.5% of the length of the pipeline.

The designer must take into account the possible effect of water quality on pipes as well as the deterioration of pipes with age during the pipe's life time.

H is also directly proportional to the power requirement and therefore also directly proportional to pumping cost. A larger pressure requirement (resulting in higher pumping cost) will result under the following conditions:

- In steep terrain, where the elevation differences are bigger
- For irrigation systems with higher working pressure requirements
- If the pipe diameters of the system is reduced for a certain required system discharge
- If excessive safety factors are included in the design calculations

3.2.1.3 Power supply

The outputs from the irrigation system design process (DEMAND) and the water distribution network design process (CONVEYANCE) provides the required irrigation discharge as well as the total pressure requirement to overcome the hydraulic gradient known as the operating point of the system. The main objective of the pump station design is to combine a hydraulic pump and an electrical motor in such a manner that it will supply the necessary pressure and flow at the operating point using the lowest amount of kW.

Choice of a specific pump might not be straight forward because it might be impossible to choose a pump that will provide enough flow and pressure at high efficiencies. Thus, some form of modification is necessary to modify the pump curve to supply the correct amount of flow and pressure. Two alternatives exist for modifying the pump curve. The first method requires cutting the impellor of the pump. With the second method the speed of the pump is altered through the application of variable speed drive (VSD). Both methods are highly effective, however, the circumstances under which each apply is situation specific. Typically VSD is appropriate for situations that are characterised by multiple operating points. Another complicating factor is that modifying the pump curve also modifies the efficiency of the pump. Each pump and motor in the system will operate at specific energy efficiency (input / output ratio). This efficiency will be determined by two factors:

- The quality of the technology used as defined by the efficiency rating of the pump or motor
- The duty point or load factor of the technology as defined by the design and selection process

The efficiencies are indirectly proportional to the power requirement and therefore a decrease in efficiency will lead to an increase in power requirement. Efficiencies are optimised by selecting high efficiency pumps and motors, operating them at the correct duties or loads, and by performing timely and effective maintenance.

3.2.2 MANAGEMENT

The second focus area, MANAGEMENT, is concerned with operating the designed irrigation system with the overall objective of maximising profit. According the ARC-IAE (2003) the total operating can be calculated on an annual basis for all the fields or systems supplied from one pump station with Equation 6:

$$PH = \frac{\frac{IR}{\eta_{system}} \times A \times 10}{q} \quad (6)$$

Where:

PH	Pumping hours (hours)
IR	Irrigation requirement for a specific crop (mm)
η_{system}	Irrigation system application efficiency (%)
A	Irrigated area (ha)
q	Flow rate (m^3/h)

This calculation is usually done on an annual basis but a different time step such as a season, month or week can also be used.

The total amount of operating hours is highly dependent on choices the farmer are making with regards to irrigation technology, crops, areas irrigated and irrigation scheduling. All of these factors are import factors affecting the overall profit margin of the farm. The discharge of the irrigation system and the application efficiency of the system are fixed during the irrigation system planning and design process. Although provision is made during the design process to oversize the system within reasonable limits to make provision for application losses, the way the producer manages the system also influences the amount of losses that occur. As the system efficiency is indirectly proportional to the power requirement, it is in the producer's interest to manage the system in such a way as to minimise losses. Practices to be avoided include:

- Applying small amounts of irrigation water at very short intervals
- Irrigating with overhead systems during very windy periods of time
- Neglecting system maintenance that is essential to prevent poor system uniformities

Choices regarding crops and areas are fixed at the beginning of the season. Although the system may have a certain discharge capacity (q) as determined for typical potential evapotranspiration values for the selected crop in the specific climatic region, it is up to producer to decide how often and how much will be irrigated during the growing season. Given foreseen increases in electricity tariffs irrigators will increasingly be required to balance the costs of irrigation with the benefit derived from applying water. Thus, irrigators will increasingly use economic principles to determine Net Irrigation Amounts (NIA) (English et al., 2002).

Irrigation system application efficiency only determines the relationship between the amount of water leaving the irrigation system and the amount of water entering the soil profile. As a result of the uniformity with which the irrigation system applies water, a portion of the field will be over irrigated and another portion under irrigated. In order to achieve high yields some percolation will occur if irrigation applications are increased to sustain crop yield in the portion in the under irrigated portion of the field. The uniformity of the irrigation system therefore has an important impact on the profit margins of the crop (Li, 1998; Lecler, 2004; Mantovani, Villa Lobos, Orgaz and Fereres, 1995). The impact of the last mentioned can only be quantified trough the evaluation of daily soil water budget calculations.

Several factors may influence the total amount of hours irrigated within a specific time period. These factors include the soil water holding capacity of the soil, hours available within time-of-use (TOU) electricity tariff structures, irrigation water supply limitations and labour requirements to move sprinklers. Inappropriate design of the irrigation system discharge rates will increase the severity of these restrictions.

Finally, the way in which the water distribution system is laid out, can also influence the total number of hours that power is consumed (Moreno, Co'Rcoles, Tarjuelo and Ortega, 2010). Elevated storage systems can be used to decrease the number of pumping hours, or to move the pumping hours to periods where lower electricity tariffs are applicable. On the other hand, the use of balancing dams, especially in the case of boreholes, can increase the power requirement as water may have to be pumped twice before reaching the field.

3.2.3 ELECTRICITY TARIFF

The third focus area is concerned with the choice of Eskom electricity tariff structure. The drastic increase in electricity tariffs over the past few years have seen energy management becoming more imperative for farmers, with special reference to irrigation farmers. The choice of the electricity tariff has increasingly been seen as a tool to curb the effect of the tariff increase. Eskom's tariff structure is divided into categories that satisfy different customers with different needs. It is vital to understand this tariff structure to enable irrigation farmers to choose the most appropriate tariff option to achieve minimum pumping costs. Figure 3.2 provide the tariff options by Eskom.

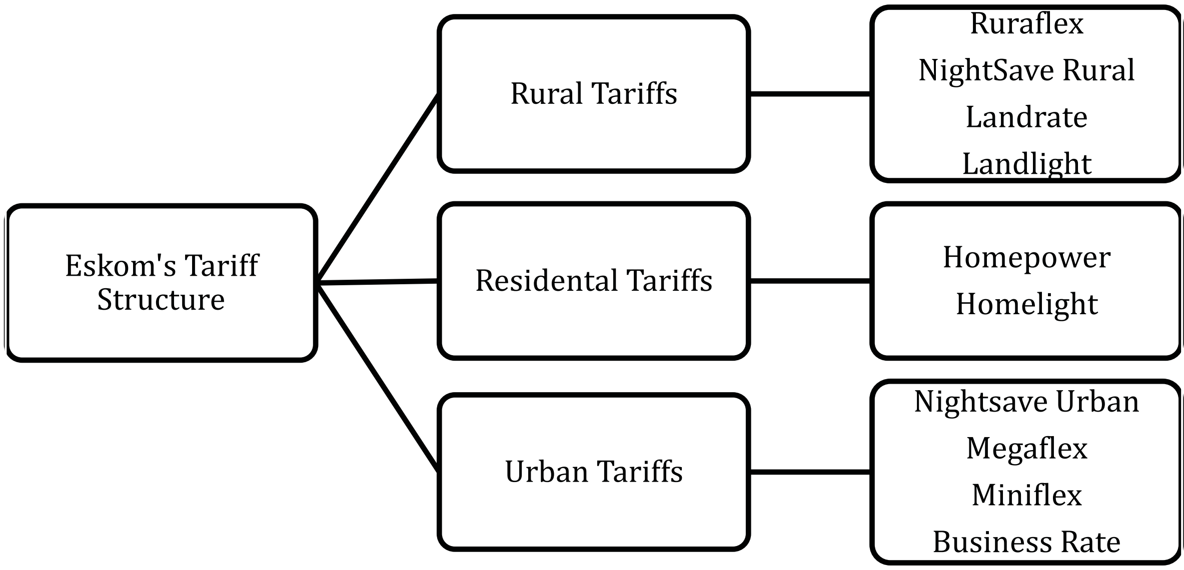

Figure 3. 2: Eskom electricity tariff structure

Source: Eskom (2013/14)

As highlighted in Figure 3.2, Eskom has three major categories of tariffs which are namely Rural, Residential and Urban Tariffs. Electricity utilized for agricultural purposes fall under the Rural tariff category. The electricity tariff plans that are applicable for irrigation are Ruraflex and Landrate. It is essential note that both tariff plans comprise of both fixed and variable costs. Fixed charges for electricity are charges that are payable by consumer which are independent of consumption of electricity and they include service charges, network charges and administration charges (Eskom, 2013/14). Variable charges comprises of the active energy charge, reactive energy charge, ancillary service charge and the network demand charge and these are dependent on the amount of electricity consumed.

3.2.3.1 Ruraflex

Ruraflex tariff is a TOU tariff with differentiated active energy charges. The tariff caters for rural consumers whose dual and three phase supplies have a NMD from 25kVA and a supply voltage greater than or equal to 22kV. The TOU tariff discourages the straining of the national electricity system during high demand or peak periods of consumption by charging a higher energy charge during these periods. Contrastingly, it creates an incentive for using electricity during the off-peak periods and low demands seasons by charging lower energy charges. Ruraflex provides irrigators with an opportunity to use electricity efficiently to counterpart to a certain extent the escalating tariffs. The season and the time of the day are the two main distinguishing aspects for the different tariff rates for the TOU tariff (Eskom, 2013/14). The seasonal aspect differentiates the charges according to high and low demand while the daily aspect differentiates according to the time of day.

The daily aspect is effectively categorized into three periods which are off-peak, standard and peak periods. Contrasting from the previous years, the daily time periods allocation during the high demand season is now different from that of the low demand season. Below is an illustration of the three periods for each season.

Figure 3.3 illustrates the time of the day applicable to each period for each season. The peak, standard and off peak periods entail periods of high, medium and low energy costs respectively. During the weekdays, total available hours for the peak, standard and off-peak periods are 5 hours/day, 11 hours/day and 8 hours/day respectively for both low and high demand season. A total of 17 hours/day and 7 hours/day are available on Saturdays during the off- peak and standard time slots respectively with no peak periods available for both seasons. An entire day of off-peak period is available on Sundays. A slight difference on the allocation of the daily hours to the three slots can be noted during weekdays for the two seasons. As depicted in Figure 3.3, the lower tariffs are charged during the early and late hours of the day with lowest demand making it difficult for consumers to totally take advantage of this tariff structure. However, a handy management tool known as the Ruraflex Controller was developed to help avoid unintended irrigation pumping during peak periods. For irrigation farmers, the TOU tariff cost saving is a noteworthy incentive to irrigate during off peak or standard periods. Nonetheless, this is not a guaranteed advantage as many other aspects are taken into consideration when calculating electricity costs for irrigation farmers such as technology, irrigation systems and irrigation scheduling techniques. Table 3.1 contains the 2015/16 approved Ruraflex tariffs for non-local authority.

As represented in Table 3.1 above, the charges are dependent on the three time of use slots, the seasons, the distance of the transmission zone and the voltage. A significant difference in active charges during peak and off peak periods and during high demand and low demand seasons can be noted. For instance, vat inclusive charges of 293.86c/kWh and 290.95c/kWh are applicable for a transmission zone of ≤ 300km during the peak period in a high demand season. In contrast, 48.35c/kWh and 47.86c/kWh is charged during off peak periods for the same transmission zone and demand season with all charges vat inclusive. Likewise, charges of 95.86c/kWh and 94.92c/kWh during peak periods and 41.85c/kWh and 41.43c/kWh during off peak periods are applicable during a low demand season for the same transmission zone. It is also interesting to note a VAT inclusive reactive energy charge of 8.16c/kVArh that is only applicable during the high demand season. The reactive energy charge is based on the tariff and a distinct power factor for each motor. Keeping in mind the existence of fixed costs component for electricity usage, the service, network access and administration charges constitute fixed costs for the Ruraflex tariff plan. Contrasting to the variable electricity costs that are dependent on usage, fixed costs are payable monthly regardless of consumption of electricity.

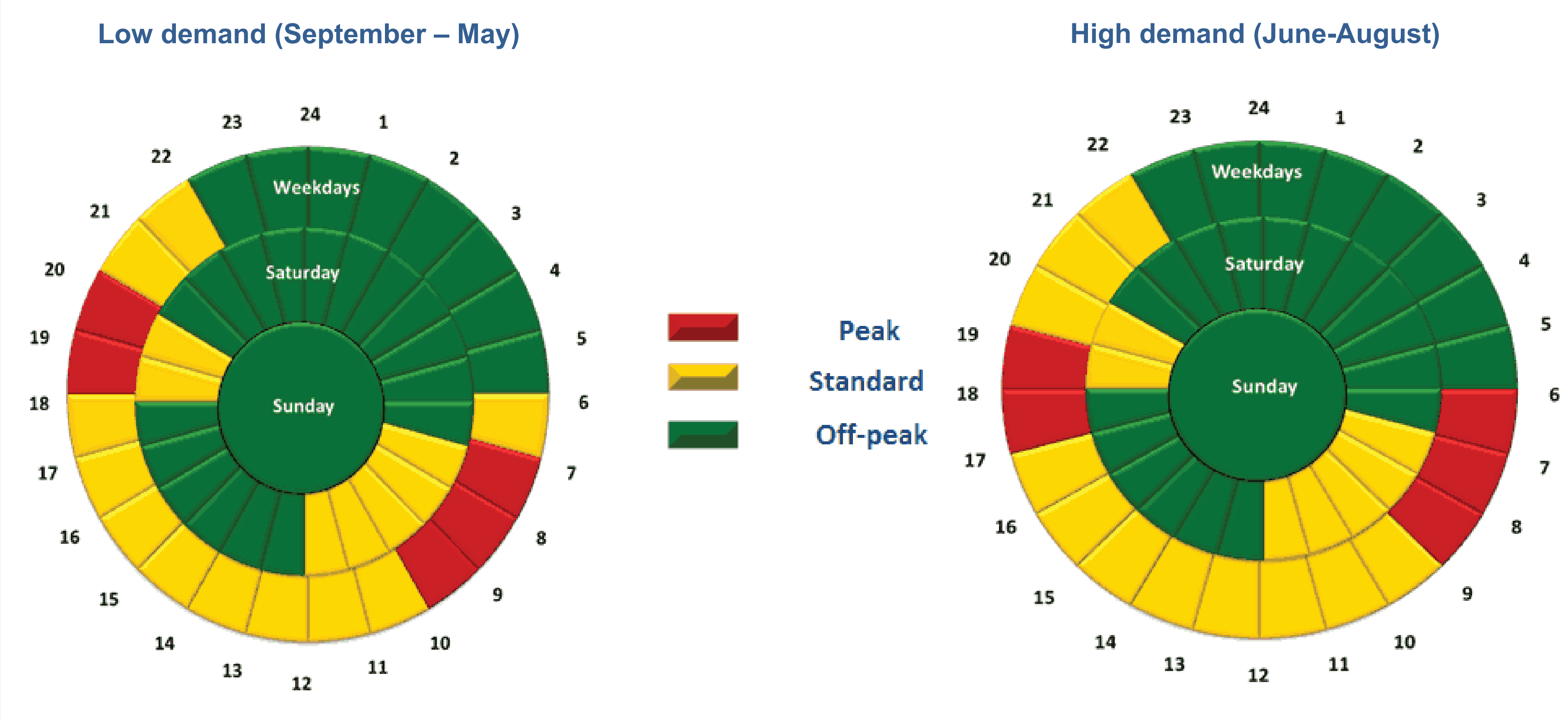

Figure 3. 3: Ruraflex's daily periods Eskom electricity tariff structure

Source: Eskom (2015/16)

Table 3. 1: Non – local authority Ruraflex tariff option

Ruraflex tariff

Non-local authority

Transmission zone	Voltage	Active energy charge [c/kWh]												Network capacity charges [R/kVA/m]	
		High demand season [Jun - Aug]						Low demand season [Sep - May]							
		Peak		Standard		Off Peak		Peak		Standard		Off Peak			
			VAT incl		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*
≤ 300km	< 500V	**257.77**	*293.86*	**78.09**	*89.02*	**42.41**	*48.35*	**84.09**	*95.86*	**57.87**	*65.97*	**36.71**	*41.85*	**R 14.88**	*R 16.96*
	≥ 500V & ≤ 22kV	**255.22**	*290.95*	**77.32**	*88.14*	**41.98**	*47.86*	**83.26**	*94.92*	**57.29**	*65.31*	**36.34**	*41.43*	**R 13.64**	*R 15.55*
> 300km and ≤ 600km	< 500V	**260.35**	*296.80*	**78.87**	*89.91*	**42.83**	*48.83*	**84.92**	*96.81*	**58.45**	*66.63*	**37.09**	*42.28*	**R 14.93**	*R 17.02*
	≥ 500V & ≤ 22kV	**257.76**	*293.85*	**78.08**	*89.01*	**42.41**	*48.35*	**84.09**	*95.86*	**57.86**	*65.96*	**36.71**	*41.85*	**R 13.73**	*R 15.65*
> 600km and ≤ 900km	< 500V	**262.95**	*299.76*	**79.66**	*90.81*	**43.25**	*49.31*	**85.78**	*97.79*	**59.03**	*67.29*	**37.46**	*42.70*	**R 15.01**	*R 17.11*
	≥ 500V & ≤ 22kV	**260.34**	*296.79*	**78.86**	*89.90*	**42.83**	*48.83*	**84.92**	*96.81*	**58.45**	*66.63*	**37.09**	*42.28*	**R 13.78**	*R 15.71*
> 900km	< 500V	**265.58**	*302.76*	**80.46**	*91.72*	**43.68**	*49.80*	**86.62**	*98.75*	**59.62**	*67.97*	**37.83**	*43.13*	**R 15.07**	*R 17.18*
	≥ 500V & ≤ 22kV	**262.94**	*299.75*	**79.66**	*90.81*	**43.25**	*49.31*	**85.78**	*97.79*	**59.03**	*67.29*	**37.46**	*42.70*	**R 13.79**	*R 15.72*

Customer categories	Service charge [R/account/day]		Administration charge [R/POD/day]	
		VAT incl		*VAT incl*
≤ 100 kVA	**R 14.64**	*R 16.69*	**R 4.16**	*R 4.74*
> 100 kVA & ≤ 500 kVA	**R 49.94**	*R 56.93*	**R 23.15**	*R 26.39*
> 500 kVA & ≤ 1 MVA	**R 153.63**	*R 175.14*	**R 35.53**	*R 40.50*
> 1 MVA	**R 153.63**	*R 175.14*	**R 65.93**	*R 75.16*
Key customers	**R 3,010.96**	*R 3,432.49*	**R 65.93**	*R 75.16*

Voltage	Ancillary service charge [c/kWh]		Network demand charge [c/kWh] [All time of use periods]	
		VAT incl		*VAT incl*
< 500V	**0.33**	*0.38*	**21.19**	*24.16*
≥ 500V & < 22kV	**0.33**	*0.38*	**18.57**	*21.17*

Reactive energy charge [c/kVArh]			
High season		Low season	
	VAT incl		*VAT incl*
7.16	*8.16*	**0.00**	*0.00*

Source: Eskom (2015/16)

In light of this, irrigation farmers who use this tariff plan are bound to incur variable electricity costs that differ not only because of the total kilowatts consumed but also according to the time of the day they irrigate. Furthermore, those who exploit the low tariff charged during the late and early hours of the day are rewarded with lower variable electricity costs though the value of fixed costs component will be similar for all users of this tariff plan. Considering the ascending trend of electricity tariff in the recent years, the Ruraflex TOU tariff can contribute to lessening the impact of these hikes.

3.2.3.2 Landrate

The Landrate tariff structure is utilized by irrigation farmers and consists of both fixed and variable charges. The tariff is characterized by a single active charge in contrast to the Ruraflex tariff structure. The tariff is however divided into six ranges which mainly differ according to the metered supply phase and the corresponding kilovolt-amperes. Rural consumers with single, dual and three phase supplies that a conventionally metered with Landrate Dx being the only exception without metering (Eskom, 2015/16). The approved Landrate tariffs for the 2015/16 period are represented below.

Table 3. 2: Non – Local authority Landrate tariff option

Landrate tariffs — Non-local authority

	Energy charge [c/kWh]		Ancillary service charge [c/kWh]		Network demand charge [c/kWh]		Network capacity charge [R/POD/day]		Service charge [R/POD/day]	
		VAT incl		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*
Landrate 1	**84.82**	*96.69*	**0.33**	*0.38*	**21.19**	*24.16*	**R 22.65**	*R 25.82*	**R 18.81**	*R 21.44*
Landrate 2	**84.82**	*96.69*	**0.33**	*0.38*	**21.19**	*24.16*	**R 34.82**	*R 39.69*	**R 18.81**	*R 21.44*
Landrate 3	**84.82**	*96.69*	**0.33**	*0.38*	**21.19**	*24.16*	**R 55.67**	*R 63.46*	**R 18.81**	*R 21.44*
Landrate 4	**183.19**	*208.84*	**0.33**	*0.38*	**21.19**	*24.16*	**R 18.04**	*R 20.57*	**R 0.00**	*R 0.00*
Landlight	**313.23**	*357.08*								
Landrate Dx									**R 40.35**	*R 45.99*

Source: Eskom (2015/16)

Table 3.2 illustrates the 2014/15 Landrate tariff as approved by NERSA. It is noteworthy to realize that this tariff structure is way more simplified than the complex Ruraflex tariff structure. The variable energy charge component is neither dependent on the transmission zone nor the demand season. As noted above, the Landrate tariff energy charged is determined by the tariff range. A Value Added tax (VAT) inclusive energy charge of 96.69c/kWh is applicable for Landrate 1, 2 and 3 whilst 208.84c/kWh is applicable for Landrate 4 regardless of the demand seasons. The Landrate Dx tariff range is non-metered thus the variable charges are not applicable and only the fixed charges are applicable. Similar to the Ruraflex tariff plan, the network access, the service and the administration charges constitute the fixed cost component of the tariff plan. Nevertheless, the network access charge for the Ruraflex tariff option is charged according to the supply voltage per month (R/kVA/m) while for Landrate is charged in Rand per point of delivery per day (R/POD/day) as illustrated in Table 3.1 and 3.2 respectively. Irrigation farmers who utilize this tariff, their electricity bills will only vary due to the total amount of kilowatts consumed. The table below shows how the Landrate tariff ranges differ.

Table 3. 3: Landrate tariff charge ranges

Landrate 1	single-phase **16 kVA** (80 A per phase) dual-phase **32 kVA** (80 A per phase) three-phase **25 kVA** (40 A per phase)
Landrate 2	dual-phase **64 kVA** (150 A per phase) three-phase **50 kVA** (80 A per phase)
Landrate 3	dual-phase **100 kVA** (225 A per phase) three-phase **100 kVA** (150 A per phase)
Landrate 4	single-phase **16 kVA** (80 A per phase)
Landrate Dx	single-phase **5 kVA** (limited to 10 A per phase)

Source: Eskom (2015/16)

The Landrate tariff ranges vary with the metered supply phases, the NMD and the amperes supplied per phase as illustrated in Table 3.3. Supplies that constantly utilize at least 1000kWh monthly are closely associated with Landrate 1, 2 and 3 while Landrate 4 is suitable for those that utilize below 1000kWh on a monthly basis (Burger et al., 2003). Landrate Dx is more suitable for non-metered low usage supplies.

3.2.3 SUMMARY

Figure 3.4 provides a summary of the variables that influence variable electricity costs. The variables are arranged according to the main focus areas for energy management. These variables formed the basis for developing the conceptual framework of the variables that determine the financial benefit of alternative electricity energy management interventions.

TECHNOLOGY

$$P_i = \frac{\rho \times gr \times q \times H}{36000 \times \eta_{\mathrm{pump}} \times \eta_{\mathrm{motor}}}$$

X

MANAGEMENT

$$PH = \frac{\frac{\sum_c IR}{\eta_{system}} \times A \times 10}{q}$$

X

TARIFF

$$k_e \ (R/kWh)$$

Q (discharge)

- Gross irrigation requirement
    - Crop
    - Climate
    - System efficiency
    - Leaching fraction
- Time available
    - Management (Tariff)
    - Automated/Manual system
    - Soil characteristics
- Size of the system (ha)

H (pressure requirement)

- System working pressure
- Static Height
    - Topography
    - Boreholes
- Friction loss
    - Type of pipe, Length
    - Flow rate (q)

Pump station

- Single pumps
- Multiple pumps
- VSD
- Pump and motor efficiencies

How much water and when?

- Crop choice
- Irrigation scheduling practices
    - Soil water holding capacities
    - Climate
    - Irrigation intervals
    - Deficit irrigation
- Irrigation system
    - Size (ha)
    - Application rate
    - Labour (move sprayers)
    - Repair and maintenance
- Energy source availability
    - Eskom tariff structure
    - Alternative energy
- Water supply restrictions
- Pump station/Distribution network
    - Boreholes
    - Single / Multiple pumps
    - VSD
    - Balancing dams

Electricity tariffs

- Ruraflex
- Landrate
- Nightsave
- Distance from Johannesburg

Alternative sources of energy

- Solar
- Wind
- Water

Figure 3. 4: Schematic showing variables influencing variable electricity costs

An important observation from Figure 3.4 is that the flow rate (q) under “Technologies” cancels out the q under “Management”. Thus, the irrigation system discharge (q) does not influence variable electricity costs per se. However, the discharge will determine the water application rate which may influence decision-making. The remaining variables that shows that pumping cost (TEC) is a function of the following:

$$TEC = f(H, NIA, A, \eta_{pump}, \eta_{motor}, \eta_{system}, k_e) \quad (7)$$

Where:

TEC	Total electricity costs (R)
H	Pressure requirement (m)
NIA	Net irrigation applied (mm)
A	Area irrigated (ha)
η_{pump}	Pump efficiency (%)
η_{motor}	Motor efficiency (%)
η_{system}	Irrigation system application efficiency (%)
k_e	Electricity tariff (R/kWh)

These variables were evaluated to determine the variables that influence them. Table 3.4 provides the results of the analysis:

Table 3. 4: Variables affecting pumping costs

	Specific variables								
	Climate	Crops	Irrigation system	Water supply	Tariff	Topography	Distance pumped	Soils	Technologies
H			X			X	X		
NIA	X	X						X	
A				X	X			X	
η_{pump}									X
η_{motor}									X
η_{system}			X						
k_e	X	X			X				

The table should be read for example that variable, H, is influenced by the irrigation system, the topography and the distance pumped. Cognisance should be taken that the “environmental” or “geographical” variables are fixed and therefore beyond the control of the irrigator.

3.3 CONCEPTUAL FRAMEWORK OF FACTORS AFFECTING THE FINANCIAL BENEFIT OF ALTERNATIVE ENERGY MANAGEMENT INTERVENTIONS

A conceptual framework was developed to show the factors that need to be accounted for when evaluating any intervention or strategy to lower total electricity costs. The framework is presented in Figure 3.5. The framework is developed using the planning and design process as the basis to distinguish between strategies that will focus on the demand side, conveyance or at the power supply side. The planning and design process establishes the irrigation technology and also determines the investment or initial costs of the system.

The second part of the framework is concerned with operating the system and therefore represents the variable cost of operating the system. The most important variable cost component is the variable electricity costs. The initial investment has a significant impact on the electricity costs since it will determine the kW that is used to sustain the flow and pressure requirement at the demand side. An important part of reducing variable electricity costs is therefore to ensure that the design of the pumping station, distribution network and infield irrigation system design is appropriate. The infield design of the irrigation system will furthermore place important restriction on the manner the system can be used e.g. the impact of irrigation system discharge on the maximum amount of water that can be applied within a specific time period. Thus, it is impossible to manage variable electricity costs without considering the investment in irrigation technology. The last cost component includes other variable costs such as labour and maintenance costs.

The pumping manufacturing industry advocates that all the costs involved during the whole life cycle of the system (or the so-called Life Cycle Costs, LCC) must be taking into consideration when designing economical pumping systems (Grundfos, 2009). The LCC of a pump is an expression of how much it costs to purchase, install, operate, maintain and dispose of a pump during its lifetime. Failure to recognise all the costs during the life cycle of the investment may bias results as it is also well documented that the operational cost of a pump over its lifetime far exceeds the initial purchase price (ARC-IAE, 2003; Grundfos, 2009). In almost all cases the most prominent component of the operational cost is the electricity cost the user pays to operate the pump. Figure 3.6 shows the life cycle costing of a pump system which demonstrates the importance of variable electricity costs.

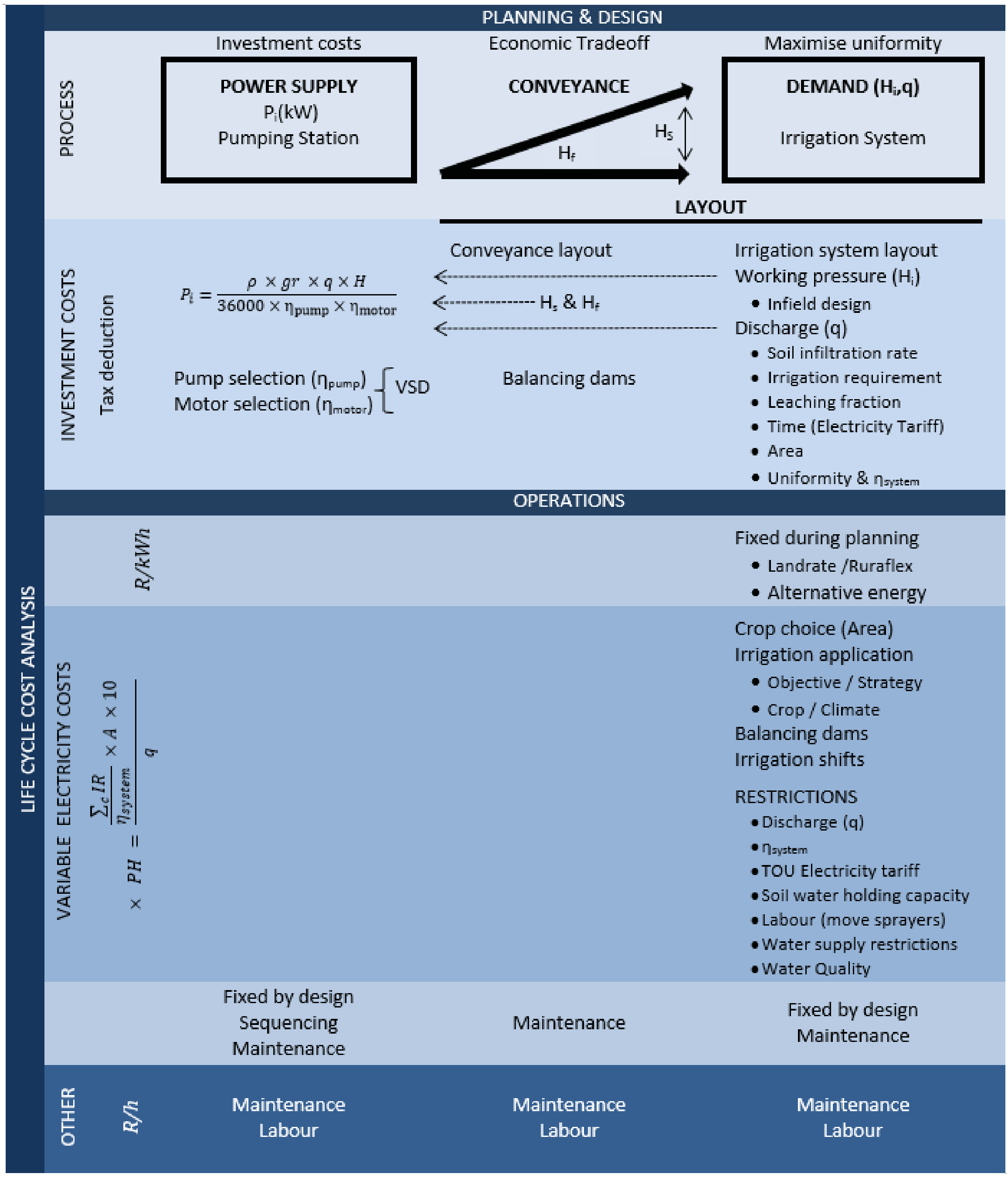

Figure 3. 5: Conceptual framework of variables affecting the life cycle costs of alternative electricity energy management interventions

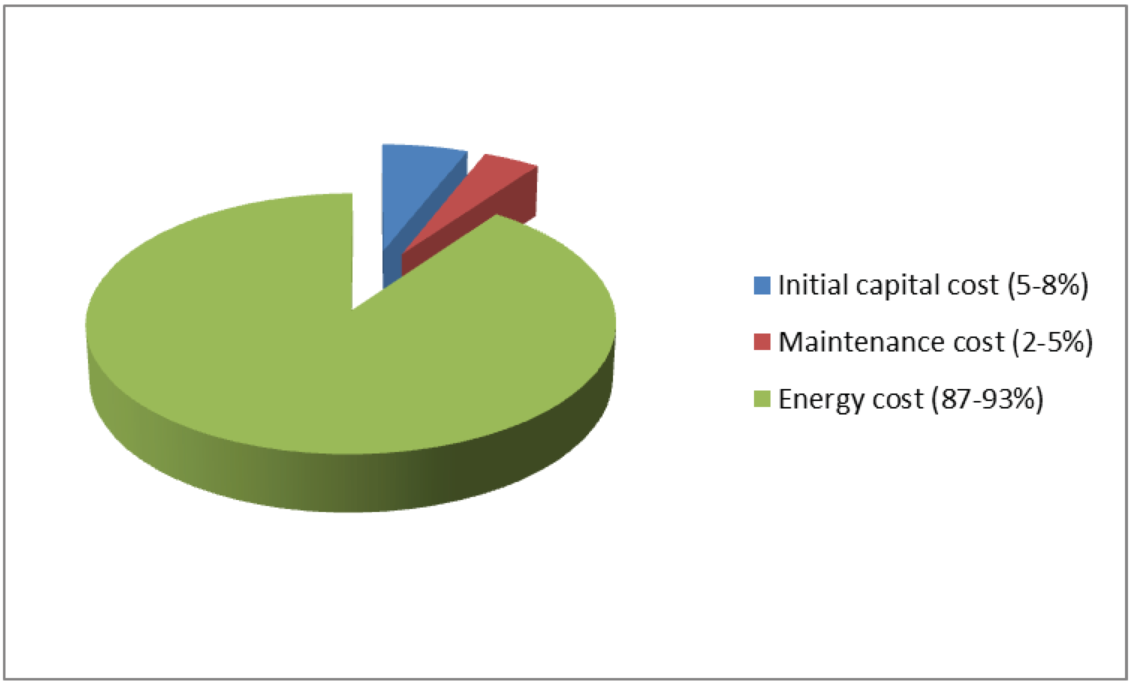

Figure 3. 6: Life cycle costs of a pumping system

Source: Grundfos (2009)

Figure 3.6 shows that the energy cost of pumping water is the most significant cost of a pumping system. The variable electricity cost may amount to as much as 90% of the LCC of the pumping system. The LCC cost shows the importance of correctly quantifying the electricity costs over the life cycle of the equipment.

3.4 APPLICATION OF CONCEPTUAL FRAMEWORK FOR COMPARING THE FINANCIAL BENEFIT OF ALTERNATIVE ENERGY MANAGEMENT INTERVENTIONS

Application of the conceptual framework for calculating the financial benefit of alternative strategies to lower electricity costs are complicated because of the interactions between the different components of the irrigation system design process and actual operation of the designed irrigation system (Jumman, 2009). None of the focus areas for energy management can be evaluated as an independent system without making assumptions about the other. Independent analyses of for instance the impact of electricity tariffs on pumping costs is common (BEFAB, 2010; Troskie, 2012). The only way to make a meaningful comparison between alternative design parameters is if the designed system is operated optimally within the constraints set of the designed technology set.

The development of procedures for determining the life cycle costs of alternative energy interventions needs to include a model to optimise irrigation water use using continuous water budget calculations. SAPWAT (Crosby and Crosby, 1999) is commonly used for irrigation planning by irrigation system designers. The model includes a simple daily water budget which may serve as the basis for the development of the Soil Water Irrigation Planning optimisation model (SWIP). With such an optimisation system irrigation hours could be optimised for a predefined scenario. Comparing different interventions with optimally derived energy demands will ensure that differences are due to the intervention under question and not because of assumed energy demands that may favour a specific intervention. Figure 3.7 shows the proposed conceptual framework with which the infield design, mainline design, electricity tariff structure and optimal irrigation planning/ energy use are integrated within an optimisation framework.

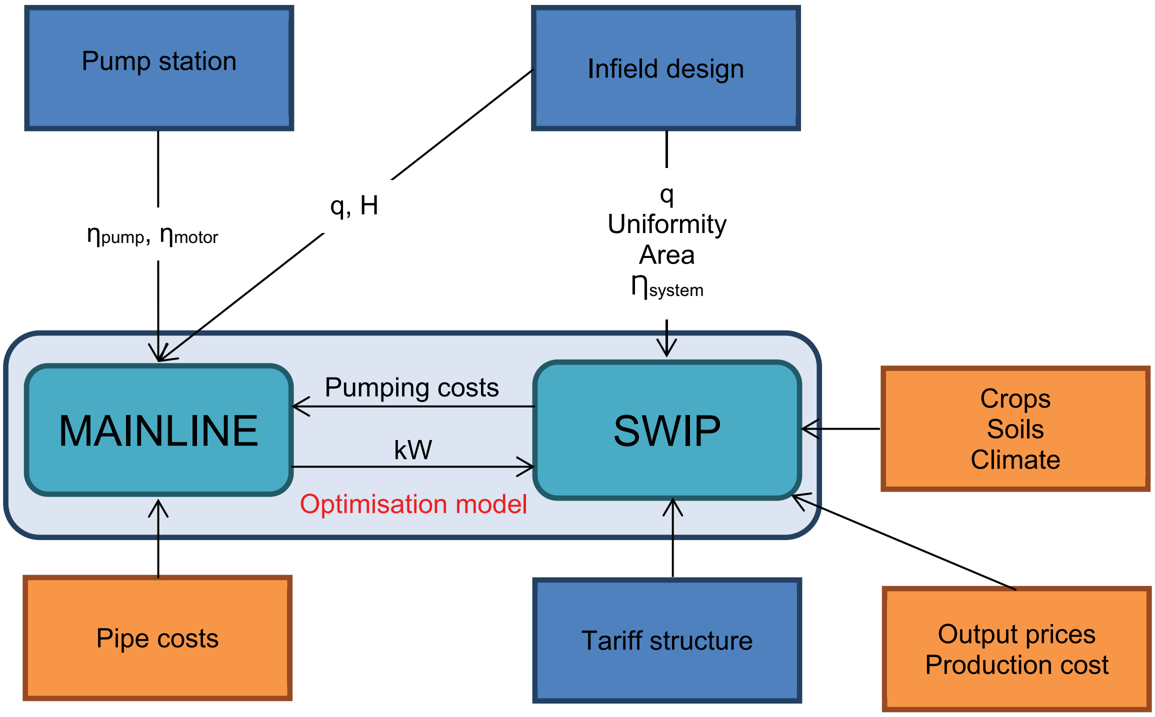

Figure 3. 7: Conceptual framework for optimising the impact of infield design and tariff structure on mainline design

Procedures and methods are available to optimise the pipe sizes of the water distribution network (Radley, 2000). Unfortunately the procedure needs to make assumptions regarding the operating hours, a flat rate energy charge and the efficiencies of the pump and motor. Integrating the optimal mainline design procedure with SWIP will allow for the design of the mainline distribution network with optimally distributed derived demand for energy for a given electricity tariff structure, Infield design and assumed motor and pump efficiencies.

Given optimised parameters for H and q a model is necessary to assist irrigation designers to estimate the impact of alternative technologies (high efficient motors and pumps, VSD) on the pump curve and resulting pumping efficiencies to ensure cost saving combination of technologies at the pumping station.

Chapter 4

METHODS AND MODELS FOR ELECTRICITY COST MANAGEMENT

4.1 INTRODUCTION

Chapter 4 provides a detail description of the methods and models as part of this research to evaluate alternative energy management strategies.

4.2 RADLEY LINEAR PROGRAMMING MODEL FORMULATION

Several methods are available to determine the best pipe diameter for the mainline of the water distribution network. Some methods like the maximum percentage friction loss does not consider economics. The “Design Manual” (Burger et al*.,* 2003) propose two methods that take cognisance of economics. The first approach is based on the trade-off between investment costs and variable electricity costs while the other method is based on an approximation of the trade-off between investment and energy costs. The first approach could be implemented through the use of linear programming (LP) (Radley, 2000). Important to note is that the LP formulation uses the actual pipe diameters and it is argued that such a method is preferred since the method avoids answers in terms of pipe diameters that does not exists. Next the Radley (2000) mathematical programming model for determining optimal pipe diameters is discussed. The convention is followed whereby variables are indicated with capital letters and data parameters with small letters.

The model specification is based on the LP formulation provided by Radley (2000):

$$Min: NPV = INV + \sum_{y} \frac{TEC(1-t)}{(1-d_y)^{y-1}} \quad (8)$$

$$INV = \sum_p PRO_p\, r_p\, l - \sum_{ty,p} \frac{(PRO_p \times r_p \times l)ty\_per_{ty}}{(1-d_{ty})^{ty-1}}) \quad (9)$$

$$TEC = \sum_t (ta_t + rc_t + dc_t)\, P_i\, PH_t + \sum_t tra_t\, kvar\, PH_t \quad (10)$$

$$P_i = \frac{\rho \times gr \times H \times q}{36000 \times \eta_{motor} \times \eta_{pump}} \quad (11)$$

$$TPF = \sum_p PRO_p\, h_{fp} \quad (12)$$

$$\sum_p PRO_p = 1 \quad (13)$$

Where:

INV	After tax investment costs for the mainline (R)
TEC	Total electricity costs for pumping water (R)
t	Marginal tax rate (%)
d_y	Real discount rate in year *y* (fraction)
y	Lifetime (years)
PRO_p	Proportion of pipe *p* used (fraction)
r_p	Costs of the pipe *p* (R/m)
l	Length of the main pipeline (m)
ty_per_{ty}	Tax deduction in tax year *ty* (%)
d_{ty}	Real discount rate in tax year *ty* (fraction)
ta_t	Active energy charge in timeslot *t* (R/kWh)
rc_t	Reliable energy charge (R/kWh)
dc_t	Demand energy charge (R/kWh)
tra_t	Reactive energy charge in timeslot *t* (R/kVARh)
P_i	Input power requirement of the electrical motor (kW)
PH_t	Pumping hours in timeslot *t* (hours)
$kvar$	Kilovar (kVAR)
ρ	Constant
gr	Gravity (m/s)
H	Pressure requirement at the pump station (m)
q	System discharge (m^3/h)
η_{motor}	Motor efficiency (%)
η_{pump}	Pump efficiency (%)
TPF	Total friction loss for a given flow rate (m)
h_{fp}	Friction loss in each of the pipe diameters for a given flow rate (m)

The main objective of the programming model is to minimise the present value of pipe investments and the associated operating costs over the lifetime of the investment. The decision variable is the proportion of a specific pipe diameter that should be bought. The length of the pipe, the flow rate of the system and the distribution of pumping hours within a specific time-of-use timeslot need to be specified beforehand for the situation for which the optimal pipe diameter must be optimised. Apart from these inputs the model also requires the friction loss over the length of the pipe for the specified flow rate.

Friction loss is calculated with the Darcy-Weisbach friction loss equation where the Darcy-Weisbach friction factor is determined with the Jain formula (Radley, 2000). The Jain formula for calculating the Darcy-Weisbach friction factor is given by the following equation:

$$\frac{1}{\sqrt{f_p}} = 1.14 - 2\log\left(\frac{k}{d} + \frac{21.25}{Re^{0.9}}\right) \qquad (14)$$

Where:

f_p	Darcy-Weisbach friction factor for pipe *p*
k	Pipe roughness (mm)
d	Inside pipe diameter (mm)
Re	Reynolds number

Figure 4.1 shows the relationship between flow rate and the optimised pipe diameter.

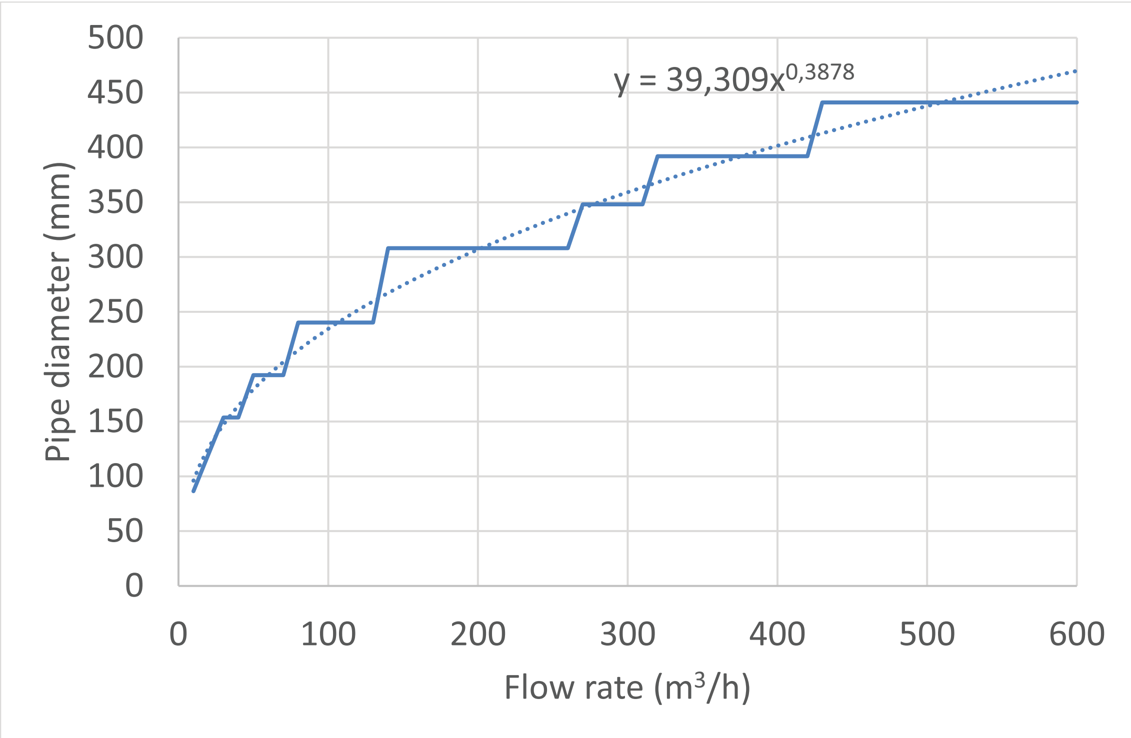

Figure 4. 1:Relationship between flow rate and optimal pipe diameter

The relationship between flow rate and optimal pipe diameter shows that there are ranges over which the optimal pipe diameter does not change. The estimated exponential function shows a continuous relationship which results in pipe diameter that does not exist. However, any two pipes with different diameters could be combine to give the same friction (kW) that results from the theoretical pipe diameter.

The results from the Radley model specification is critically dependent on the assumption with respect to time of use pumping hours. The Radley model was augmented to include irrigation hour planning based on daily soil water budget calculations to overcome the need to specify the distribution of irrigation hours beforehand.

4.3 SOIL-WATER IRRIGATION PLANNING AND ENERGY MANAGEMENT PROGRAMMING MODEL

The following section describes the Soil Water Irrigation Planning and Energy management programming model (SWIP-E) that is used to model the trade-off between pipeline investments and energy operating costs. The SWIP-E programming model is based on the SAPWAT optimisation (SAPWAT-OPT) (Grové, 2008) model that optimises a daily soil water budget for a single crop. The SAPWAT-OPT model was further developed to facilitate inter seasonal crop water use optimisation. Detail electricity cost calculations and a mainline pipe optimisation model (Radley, 2000) were included in the model to facilitate electricity energy management in an integrated way.

Next the SWIP-E model specification is described following the convention whereby variables are indicated with capital letters and data parameters with small letters.

4.3.1 OBJECTIVE FUNCTION

The objective function maximise the Net Present Value (NPV) of an irrigation system investment. Equation 15 represents the objective function used in the SWIP-E model:

$$MAX{:}\ NPV = \sum_{c,y}\frac{PI_c\,(1-t)}{(1-d_y)^{y-1}} - \sum_{c,y}\frac{YDC_c\,(1-t)}{(1-d_y)^{y-1}} - \sum_{c,y}\frac{ADC_c\,(1-t)}{(1-d_y)^{y-1}} - \sum_{c,y}\frac{IDC_c(1-t)}{(1-d_y)^{y-1}} - INV \qquad (15)$$

Where:

NPV	Net Present Value (R)
PI_c	Total production income for crop *c* (R)
YDC_c	Total yield dependant costs for crop *c* (R)
ADC_c	Total area dependant costs for crop *c* (R)
IDC_c	Total irrigation dependant costs for crop *c* (R)
INV	After tax investment costs for an irrigation system (R)
t	Marginal tax rate (%)
d_y	Real discount rate in year *y* (fraction)
y	Amount of years (years)

The first four terms of the objective function calculate the net present value of the margin above specified costs for a specified crop rotation. The margin above specified costs (cash flow) is calculated by subtracting the yield, area and irrigation dependant costs from the production income. The cash flow with an exception of electricity costs is calculated by using constant tariffs, thus, real tariffs are used. Electricity costs are increased by using a real increase electricity tariffs (increase rate above inflation). The real discount rate is calculated using the formula proposed in Boelhje and Eidman (1984). The NPV is calculated by subtracting the after tax investment costs of an irrigation system from the margin above specified costs.

The following sections describe the calculation procedures to calculate each of the components of the objective function in more detail.

4.3.1.1 Production Income

Production income is a function of yield and area planted for each crop and the price of the crop. The following equation is used to calculate the production income for each crop considered in the model:

$$PI_c = \frac{\sum_{wb} Y_{wb,c}}{num\_wb} \times p_c \times A_c \qquad (16)$$

Where:

PI_c	Total production income for crop *c* (R)
$Y_{wb,c}$	Yield for water budget *wb* for crop *c* (ton/ha)
p_c	Crop price for crop *c* (R/ton)
A_c	Area planted for crop *c* (ha)
num_wb	Number of water budgets

Production income is calculated by multiplying the crop yield with the crop price and area planted. The crop price is an input in the model while the crop yield and area planted are endogenously determined in the model. Crop yield is estimated for each of the water budgets that were included in the model to model the impact of non-uniform water applications. The sum of the yields obtained in each water budget is divided by the number of water budgets to calculate the average crop yield that is used to calculate production income.

4.3.1.2 Yield Dependant Costs

The calculation of yield dependant costs is based on a cost reduction method (Grové, 1997). Equation 17 is used to calculate yield dependant costs:

$$YDC_c = vym_c - \left(ym_c - \frac{\sum_{wb} Y_{wb,c}}{num\_wb}\right) vy_c \qquad (17)$$

Where:

YDC_c	Total yield dependant costs for crop *c* (R)
vym_c	Total yield dependant costs for crop *c* at maximum yield (R/ha)
ym_c	Maximum yield for crop *c* (ton/ha)
vy_c	Scaling factor for a less than proportional reduction in yield dependant costs for crop *c* (R/ton)
num_wb	Number of water budgets

The first part of the equation represents total yield dependant costs at maximum crop yield. The second part of the equation calculates the less than proportional reduction in yield dependant costs for the difference between the maximum and actual yield by multiplying the difference with a scaling factor (vy_c). The scaling factor for a less than proportional reduction in yield dependant costs for each crop included in the model are calculated in Excel©. The following example is used to explain Equation 17. Suppose the yield dependant costs to produce 17 ton/ha of maize is R13 506.66, thus the yield dependant cost per ton is R794.51 (13 506.66/17). Suppose the cost to produce 13 ton/ha is R9 123.18/ha, therefore the yield decrease with 4 ton/ha resulting in a cost saving of R4 383.52/ha, but due to the non-proportional decrease, the yield dependent costs decrease with R9 123.18/ha (Equation 17).

4.3.1.3 Area Dependant Costs

Area dependant costs include all input costs which will change with a change in the area planted. The area dependant costs are calculated for each crop considered in the model using Equation 18:

$$ADC_c = A_c \times va_c \quad (18)$$

Where:

ADC_c	Total area dependant costs for crop *c* (R)
A_c	Area planted to crop *c* (ha)
va_c	Area dependent cost for crop *c* (R/ha)

4.3.1.4 Irrigation Dependant Costs

The following section explains the calculation of irrigation dependant costs which is a function of the pumping hours or irrigation water applied. Equation 19 represents the formula to calculate irrigation dependant costs:

$$IDC_c = TEC_c + LC_c + RMC_c + WC_c \quad (19)$$

Where:

IDC_c	Total irrigation dependant costs for crop c (R)
TEC_c	Total electricity costs for crop *c* (R)
LC_c	Total labour costs for crop *c* (R)
RMC_c	Total repair and maintenance costs for crop *c* (R)
WC_c	Total water costs for crop *c* (R)

Irrigation dependant costs (IDC) include electricity costs, labour costs, repair and maintenance costs and water costs of the irrigation system. Total electricity costs depend on the type of electricity tariff. All tariff options include a fixed cost and variable cost. Fixed costs have to be paid every month irrespective of whether electricity was used or not while variable costs have to be paid for the electricity consumption. Variable electricity costs are a function of management (hours pumped), electricity tariffs and irrigation system design (kW). The following equation is used to calculate total electricity costs:

$$TEC = \sum_{i,t}\left(ta_{i,t} + rc_{i,t} + dc_{i,t}\right) P_i PH_{i,t} + \sum_{i,t} tra_{i,t} kvar PH_{i,t} + fec \tag{20}$$

Where:

$PH_{i,t}$	Pumping hours on day *i* in timeslot *t* (hours)
TEC_c	Total electricity costs for crop *c* (R)
P_i	Input power requirement of the electrical motor (kW)
$PH_{i,t}$	Pumping hours in timeslot *t* (hours)
$ta_{i,t}$	Active energy charge on day *i* in timeslot *t* (R/kWh)
$tra_{i,t}$	Reactive energy charge on day *i* in timeslot *t* (R/kVARh)
$rc_{i,t}$	Reliable energy charge (R/kWh)
$dc_{i,t}$	Demand energy charge (R/kWh)
$kvar$	Kilovar (kVAR)
fec	Fixed electricity costs (R)

The electricity tariffs are divided into different charges, active, reliable and demand energy charge which is dependent on the product of the kW requirement of an irrigation system and the pumping hours. The kW requirement is closely linked to irrigation system layout and design. Pumping hours (PH) is determined by irrigation management and the limits that are placed on irrigation hours during the irrigation cycle when using time-of-use electricity tariffs. The reactive energy charge is dependent on the kilovar (kVAR) and pumping hours of an irrigation system. The kVAR is calculated from the power factor (PF) of the pump (kVAR = $\cos^{-1}$ PF). Each pump has a unique power factor which can be obtained from the manufacturer. The user pays for 70% of the kVARh used. The fixed electricity costs (fec) are an input parameter in the model and depend on the type of electricity tariff.

Equation 21 and 22 represent the formulas to calculate labour costs and repair and maintenance costs of the irrigation system, respectively. The calculation procedures for labour and repair and maintenance costs are based on formulas proposed by Meiring (1989).

$$LC_c = \sum_{i,t} \frac{PH_{i,t}}{24}\, lh\, lw \tag{21}$$

Where:

LC_c Total labour costs for crop *c* (R)

$PH_{i,t}$ Pumping hours on day *i* in timeslot *t* (hours)

lh Labour hours needed per 24 hours irrigation for a given size centre pivot (hours)

lw Labour wage (R/hour)

Labour costs for permanent labourers can be considered as a fixed cost. However, labour costs obtain a variable character once labour is employed in a specific enterprise because labour costs can then be allocated between different enterprises. Labour costs for centre pivot irrigation is variable because the amount of labour hours required is determined by the hours that the system is operated. The amount of labour that is required per operating hour is influenced by the size of the system and the type of task being performed. The model calculates the labour demand for every 24 hours that the system is operated. The calculated labour demand is multiplied with the total pumping hours and the labour wage to calculate total labour costs.

Repair and maintenance costs depend on the conditions (climate) under which the system operates. The pump's repair and maintenance cost is directly linked to the use of the pump, through expressing the repair and maintenance tariff as a percentage per 1000 hours pumped. The repair and maintenance costs of the motor, pivot and pipe are not included in the model since it is independent of the use of the system and will decrease the profit linearly (Meiring, 1989).

$$RMC_c = \sum_{i,t} PH_{i,t}\, rt \tag{22}$$

Where:

RMC_c Total repair and maintenance costs for crop *c* (R)

$PH_{i,t}$ Pumping hours on day *i* in timeslot *t* (hours)

rt Repair and maintenance tariff per 1000 hours pumped for an irrigation system (R/1000hours)

Equation 23 represents the formula to calculate water costs:

$$WC_c = \sum_{c,i} IR_{c,i}\; A_c wt \tag{23}$$

Where:

WC_c	Total water costs for crop *c* (R)
$IR_{c,i}$	Irrigation for crop *c* on day *i* (mm)
A_c	Area planted to crop *c* (ha)
wt	Water tariff (R/mm)

Water charges are a function of the irrigation water applied, area planted and the water tariff charged by the water user association. The water tariff includes the totality of payments that an irrigator makes for the irrigation service and is calculated on a volumetric basis. The volumetric-based charges is a fixed rate per unit water received, where the charge is related directly to and proportional to the volume water received. The charge per millimetre water was calculated by dividing the total charge by the volume water allocated and a charge per millimetre was used in this research.

4.3.1.5 Investment Costs

The section describes the calculation procedures used to calculate the net after tax investment costs of an irrigation system. The calculation procedure of the main pipeline is based on the formulas used in the linear programming pipe optimisation model developed by Radley (2000). The pivot and pump investment costs are collected from a manufacturer and are inputs in the model. The following equation represents the calculation procedure for investment costs of an irrigation system:

$$INV = \sum_p PRO_p \, r_p \, l - \sum_{ty,p} \frac{(PRO_p \times r_p \times l) ty\_per_{ty}}{(1 - d_{ty})^{ty-1}} + i\_pivot + i\_pump - \sum_{ty} \frac{(i\_pivot + i\_pump) ty\_per_{ty}}{(1 - d_{ty})^{ty-1}} \quad (24)$$

Where:

INV	After tax investment costs for an irrigation system (R)
PRO_p	Proportion of pipe *p* used (fraction)
r_p	Cost of the pipe *p* (R/m)
l	Length of the main pipeline (m)
ty_per_{ty}	Tax deduction in tax year *ty* (%)
d_{ty}	Real discount rate in tax year *ty* (fraction)
ty	Tax year (years)
i_pivot	Investment costs of the pivot (R)
i_pump	Investment costs of the pump (R)

The main pipeline can be designed by choosing the pipe diameter such that the sum of the operating and investment costs are minimised. Calculations are done with consideration of the investment of the pipe, the tax benefit that the irrigator will receive from investing in a new pipeline and electricity costs (operating costs). Investment costs are depended on the pipe costs, length of the pipe and can be considered as a lump sum. The costs of the pipes and the length of the main pipeline are inputs in the model. The tax benefit that the irrigator will receive from investing in a new irrigation system was included in the calculation of the investment costs of the main pipeline, centre pivot and pump. The tax benefit calculations are based on a 50%, 30% and 20% in year one, two and three, respectively tax deduction. The present value of the tax benefit was calculated by using the same procedure as in the objective function. The tax benefit for the centre pivot and pump investment is calculated in Excel© and is an input parameter in the model.

Equation 25 is included in the model to ensure that sum of the proportions of the pipes used must be equal to one:

$$\sum_p PRO_p = 1 \qquad (25)$$

Where:

PRO_p	Proportion of pipe *p* used (fraction)

4.3.2 CONSTRAINT SET

The following section describes the constraint set of the SWIP-E model. The section is divided into crop yield and water budget calculations, pumping hours, kilowatt requirement calculation and resource constraints.

4.3.2.1 Crop Yield and Water Budget Calculations

Crop yield is calculated with the use of crop yield response factors (ky) which relate relative yield decrease (1-Y/Ym) to relative evapotranspiration deficit (1-ETA/ETM). The Stewart multiplicative (De Jager, 1994) relative evapotranspiration formula was used to calculate crop yield taking the effect of water deficits in different crop growth stages into account. Equation 26 is used to calculate crop yield:

$$Y_{wb,c} = ym_c \times \prod_{g=1}^{4}\left(1 - ky_{c,g}\left(1 - \left(\frac{\sum_i ETA_{wb,c,i}}{\sum_i etm_{c,i}}\right)\right)\right) \qquad (26)$$

Where:

$Y_{wb,c}$	Yield for water budget *wb* for crop *c* (tons/ha)
ym_c	Maximum yield for crop *c* (ton/ha)
$ky_{c,g}$	Yield response factors for crop *c* in growth stage *g*

$ETA_{wb,c,i}$ Actual evapotranspiration in water budget *wb* for crop *c* on day *i* (mm)

$etm_{c,i}$ Maximum evapotranspiration for crop *c* on day *i* (mm)

Crop yield were estimated for each of the water budgets included in the model. Actual evapotranspiration is based on simple cascading water budget calculations in SAPWAT (Crosby and Crosby, 1999). SAPWAT uses the basic methodology proposed in FAO-56 (Allen, Pereira, Raes and Smith. 1998) to calculate crop water requirements based on a reference evapotranspiration rate. The basic idea is that while the crop does not experience any water deficits the actual evapotranspiration is equal to the potential.

Irrigation systems do not apply water with perfect uniformity. Due to the lack of the uniformity a part of the field is adequately irrigated while others are not. An excess amount of water can increase the costs of pumping, lower yields and water logging of soils in inadequately irrigated areas. In contrast a shortage of water decrease yields, which result in a decrease in profit. Various researchers (Hamilton, Green and Holland, 1999, Grové, 2008 and Lecler, 2004) modelled the impact of non-uniformity by dividing the irrigation field in different water budgets. The relationship between applied water and crop yield was explicitly incorporated in the water budget calculations by modelling several different water budgets simultaneously in GAMS (Brooke et al.,1998). Thus, all the water budget formulas are defined in terms of wb.

The water budget routine included in the SWIP-E model distinguishes between water in the root zone and below the root zone. The Total Available Moisture (TAM) in the soil that potentially can be used by the crop is a function of the Water Holding Capacity (WHC) of the soil and the Rooting Depth (RD) of the crop. Only a portion of TAM is readily available for crop consumption (RAM). RAM is a function of RD, WHC and the P-value, which indicates the proportion of the water that is readily available for crop consumption. The P-value calculation is based on a formula proposed in Dominguez, De Juan, Tarjelo, Martinez and Martinez-Romera (2012). If Soil Moisture Deficits (SMD) are greater than RAM, the rate at which the crop consumes water is reduced from its potential level and ETA is only a fraction of ETm. Given these conditions ETA is calculated using Equation 27 where the min | notation indicates that the answer will the minimum of the two calculations (Grové and Oosthuizen, 2010).

$$ETA_{wb,c,i} = min \left| \begin{array}{l} etm_{c,i} \\ etm_{c,i}\left(\frac{RWC_{wb,c,i}}{TAM_{wb,c,i} - RAM_{wb,c,i}}\right) \end{array} \right. \quad (27)$$

Where:

$ETA_{wb,c,i}$ Actual evapotranspiration in water budget *wb* for crop *c* on day *i* (mm)

$etm_{c,i}$ Maximum evapotranspiration for crop *c* on day *i* (mm)

$RWC_{wb,c,i}$	Root water content in water budget *wb* for crop *c* on day *i* (mm)
$TAM_{wb,c,i}$	Total available moisture in water budget *wb* for crop *c* on day *i* (mm)
$RAM_{wb,c,i}$	Readily available moisture in water budget *wb* for crop *c* on day *i* (mm)

Soil moisture deficit defines the difference between the water holding capacity in the root zone (RWCAP) and the actual water content in the root zone (RWC). RWCAP is a function of the WHC of a specific soil and the RD of the crop. RWC is a function of the RWC of the previous day, ETA, rainfall, irrigation and any additions made to RWC due to root growth (TR). The irrigation amount is calculated for the average water budget and multiplied with a scaling factor (cu_scale) to calculate an irrigation amount for each of the water budgets included in the model. Water that drains below the root zone is not explicitly accounted for in the calculation of RWC but indirectly because it is capped to a maximum of TAM. Equation 28 is used to determine RWC:

$$RWC_{wb,c,i} = min \left| \begin{matrix} RWC_{wb,c,i-1} - ETA_{wb,c,i-1} + r_{c,i-1} + IR_{c,i-1} cu_{scale_{wb}} + TR_{wb,c,i} \\ rwcap_{wb,c,i} \end{matrix} \right. \quad (28)$$

Where:

$RWC_{wb,c,i}$	Root water content in water budget *wb* for crop *c* on day *i* (mm)
$ETA_{wb,c,i}$	Actual evapotranspiration in water budget *wb* for crop *c* on day *i* (mm)
$r_{c,i}$	Rainfall for crop *c* on day *i* (mm)
$IR_{c,i}$	Irrigation for crop *c* on day *i* (mm)
cu_scale_{wb}	Scaling factor for water budget *wb*
$TR_{wb,c,i}$	Additions made to RWC due to root growth in water budget *wb* for crop *c* on day *i* (mm)
$rwcap_{wb,c,i}$	Water holding capacity in the root zone in water budget *wb* for crop *c* on day *i* (mm)

The water content of water below the root zone (BRWC) is determined by:

$$BRWC_{wb,c,i} = min \left| \begin{matrix} BRWC_{wb,c,i-1} + BR_{wb,c,i} - TR_{wb,c,i} \\ (rd_{max} - rd_i)whc \end{matrix} \right. \quad (29)$$

Where:

$BRWC_{wb,c,i}$	Water below the root zone in water budget *wb* for crop *c* on day *i* (mm)
$BR_{wb,c,i}$	Water that drain below the root zone in water budget *wb* for crop *c* on day *i* (mm)

$TR_{wb,c,i}$	Additions made to RWC due to root growth in water budget *wb* for crop *c* on day *i* (mm)
rd_i	Root development on day *i* (m)
rd_{max}	Maximum root depth (m)
whc	Water holding capacity (mm/m)

Where BR and TR are calculated as:

$$BR_{wb,c,i} = max \left| \begin{matrix} RWC_{wb,c,i-1} + BR_{wb,c,i} - TR_{wb,c,i} \\ 0 \end{matrix} \right. \quad (30)$$

Where:

$BR_{wb,c,i}$	Water that drain below the root zone in water budget *wb* for crop *c* on day *i* (mm)
$RWC_{wb,c,i}$	Root water content in water budget *wb* for crop *c* on day *i* (mm)
$TR_{wb,c,i}$	Additions made to RWC due to root growth in water budget *wb* for crop *c* on day *i* (mm)

$$TR_{wb,t} = \left| \begin{matrix} (rd_{c,i} - rd_{c,i-1})/(rd_{max} - rd_{c,i-1})BRWC_{wb,c,i-1} & if\ rd_{c,i} = rd_{g=2} \\ 0 & if\ rd_{c,i} \neq rd_{g=2} \end{matrix} \right. \quad (31)$$

Where:

$TR_{wb,c,i}$	Additions made to RWC due to root growth in water budget *wb* for crop *c* on day *i* (mm)
rd_i	Root development on day *i* (m)
rd_{max}	Maximum root depth (m)
$BRWC_{wb,c,i}$	Water below the root zone in water budget *wb* for crop *c* on day *i* (mm)

The last equation indicates that TR is directly attributed to root growth and the availability of water below the root zone (BRWC). Thus, TR will only occur in the crop development growth stage and TR will be zero in the initial, mid-season and late-season growth stages.

To initialize the whole water budget the user has to specify the water holding capacity (WHC) and the water content in percentage terms. RWC and BRWC are then adjusted accordingly to give the same water content in terms of a percentage.

4.3.2.2 Pumping Hours

According the Burger et al. (2003) pumping hours can be calculated on an annual basis for all the fields or systems supplied from one pumping station with Equation 32.

$$PH_{i,t} = \frac{\frac{\sum_c IR_{c,i}}{\eta_{system}} \times A_c \times 10}{q} \tag{32}$$

Where:

$PH_{i,t}$	Pumping hours on day *i* in timeslot *t* (hours)
$IR_{c,i}$	Irrigation requirement for crop *c* on day *i* (mm)
η_{system}	Irrigation system application efficiency (%)
A_c	Irrigated area for crop *c* (ha)
q	Flow rate (m^3/h)

The irrigation amount is calculated in the model, while the flow rate and system efficiency is input parameters in the model. The irrigation amount is based on the average irrigation of the water budgets included in the model. The system efficiency is based on the spray losses of the irrigation system (wind drift).

Eskom's time-of-use electricity tariffs are designed to create the incentive for irrigation farmers to use electricity during low demand season and off-peak hours. The time-of-use tariffs are divided in three time slots with different rates applicable to each time-slot. Pumping hours needs to restrict to the available hours within an irrigation cycle and time-of-use. Equation 33 illustrates the equation used to restrict the pumping hours within the available hours in an irrigation cycle.

$$PH_{i,t} \leq thc_{i,t} \tag{33}$$

Where:

$PH_{i,t}$	Pumping hours on day *i* in timeslot *t* (hours)
$thc_{i,t}$	Available irrigation hours within each irrigation cycle on day *i* in timeslot *t* (h)

The basic idea is that pumping hours in a specific time-slot cannot exceed the available irrigation hours in that specific time-slot.

4.3.2.3 Kilowatt Requirement

Kilowatt (kW) is determined endogenously in the model and quantifies the kilowatts required to drive the water through the system. Kilowatt is a function of the flow rate of the pump, total pressure required by the system and the efficiency of the pump and motor (Burger et al., 2003). Equation 34 is used to calculate the kilowatt requirement at the pumping station:

$$P_i = \frac{\rho \times gr \times H \times q}{36000 \times \eta_{motor} \times \eta_{pump}} \quad (34)$$

Where

P_i	Input power requirement of the electrical motor (kW)
ρ	Constant
gr	Gravity (m/s)
H	Pressure requirement at the pump station (m)
q	Flow rate (m^3/h)
η_{motor}	Motor efficiency (%)
η_{pump}	Pump efficiency (%)

Total pressure in the system is the sum of the operating pressure of the pivot, static head and friction in the main pipeline. The pivot pressure represents the required pressure at the centre of the pivot in order to apply a designed irrigation amount per day. Static head is a constant which represents the height difference between the water source and the irrigation system. Equation 35 is used to determine the total operating pressure of the system which the pump must supply:

$$H = cp + hs + \sum_p PRO_p \, h_{fp} \quad (35)$$

Where:

H	Pressure requirement at the pump station (m)
cp	Centre pressure (m)
hs	Static head (m)
h_{fp}	Friction loss in each of the pipe diameters for a given flow rate (m)
PRO_p	Proportion of pipe p used (fraction)

Friction in the mainline is a function of the proportion of the pipe diameter that has been used in the mainline and the friction that was calculated through the use of the Darcy-Weisbach (Burger et al., 2003) equation for a given flow rate.

4.3.2.4 Area

The following equation is used to restrict the area planted of a certain crop to the pivot size:

$$A_c \leq Pivot\ Size \quad (36)$$

Where:

A_c	Irrigated area for crop *c* (ha)
$Pivot\ Size$	Size of the centre pivot (ha)

The model is developed for a crop rotation system consisting of maize and wheat. Thus, the available area for each crop must be equal or smaller than the designed centre pivot size. Important to note is that the model does not model intra seasonal competing crops since the crop rotation consist of maize and wheat only.

4.3.2.5 Water

The maximum water allocation depends on the area and the allocation of water determined by the water user association. The basic idea of the equation is that the amount of irrigation applied (average water budget) for the total area planted cannot exceed the allocation of the total area available.

$$\frac{\sum_c IR_{c,i}}{\eta_{system}} A_c \leq Alloc \times Pivot\ Size \quad (37)$$

Where:

$IR_{c,i}$	Irrigation requirement for crop *c* on day *i* (mm)
η_{system}	Irrigation system application efficiency (%)
A_c	Irrigated area for crop *c* (ha)
$Alloc$	Allocation of water (m^3/ha)
$Pivot\ Size$	Size of the centre pivot (ha)

Equation 38 represents the maximum irrigation application within an irrigation cycle. The user has to specify the length of an irrigation cycle. Thus, the irrigation cycle determine the day an irrigator can decide to apply irrigation. Furthermore the assumption is made that the maximum irrigation application within an irrigation cycle cannot exceed the maximum irrigation amount per irrigation cycle. The irrigation amount is based on the average irrigation applications of the water budgets.

$$\frac{\sum_c IR_{c,i}}{\eta_{system}} \leq irc_i \quad (38)$$

Where:

$IR_{c,i}$	Irrigation requirement for crop *c* on day *i* (mm)
η_{system}	Irrigation system application efficiency (%)
irc_i	Irrigation amount per cycle for crop *c* on irrigation day *i* (mm/cycle)

The above resource constraints are explicitly included into the modelling process.

4.4 MATHEMATICAL MODEL FOR EVALUATING PUMP PERFORMANCE

Modelling the performance of pumps is done through the development of methods and procedures to estimate the change in flow rate, pressure requirement and pump efficiency. Changes in flow rate and pressure is straight forward if the pump curve is available. However, estimating changes in efficiency due to shifts in the pump curve is not so obvious. The following section includes a proposed methodology to determine the changes in flow rate, pressure requirement and efficiency (Moreno, Medina, Ortega and Tarjuelo, 2012).

Affinity laws can be used to determine the change in flow rate and pressure requirement due to a change in speed. The speed of a pump is determined as a percentage of the full speed of the pump (Equation 39). The flow rate change directly if there is a change in speed (Equation 40) and pressure requirement change as a square of speed which is illustrated with Equation 41.

$$N_2 = N_1 \times VSD\_Speed \tag{39}$$

Where:

N_1	Full pump speed (rpm)
N_2	Pump speed with VSD (rpm)
VSD_speed	Percentage pump speed change (%)

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{40}$$

Where:

N_1	Full pump speed (rpm)
N_2	Pump speed with VSD (rpm)
Q_1	Flow rate at full pump speed (m^3/h)
Q_2	Flow rate after a change in pump speed (m^3/h)

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{41}$$

Where:

H_1	Pressure requirement at full pump speed (m)
H_2	Pressure requirement after a change in pump speed (m)
N_1	Full pump speed (rpm)
N_2	Pump speed with VSD (rpm)

$$\eta_2 = 1 - \left[(1 - \eta_1)\left(\frac{N_1}{N_2}\right)^{0.1}\right] \tag{42}$$

Where:

η_1	Pump efficiency at full pump speed (%)
η_2	Pump efficiency after a change in pump speed (%)
N_1	Full pump speed (rpm)
N_2	Pump speed with VSD (rpm)

Moreno et al*.,* 2012 proposed formulas to approximate the pump and efficiency curves of a pump if the speed of the pump changes. Equation 43 and 44 represents the pump and efficiency curves, respectively.

$$H = a + cQ^2 \tag{43}$$

Where:

H	Pressure requirement of an irrigation system (m)
Q	Flow rate of an irrigation system (m^3/h)
a	Calculated coefficient
c	Calculated coefficient

$$\eta = eQ + fQ^2 \tag{44}$$

Where:

Q	Flow rate of an irrigation system (m^3/h)
e	Calculated coefficient
f	Calculated coefficient
η	Pump efficiency of an irrigation system (%)

The coefficients *a, c, e* and *f* determine the shape of the curves and Equation 45 to 48 represents the formulas to calculate the coefficients. Coefficients *a* and *c* is written as a function of *e* and *f*, while coefficient *f* is a function of *e*.

$$e = \frac{2\eta_1}{Q_1} \tag{45}$$

$$f = \frac{-e^2}{4\eta_1} \tag{46}$$

$$a = \frac{H_1 e^2}{e^2 - f^2 Q^2} \tag{47}$$

$$c = \frac{-f^2 a}{e^2} \tag{48}$$

Where:

a	Calculated coefficient
c	Calculated coefficient

e	Calculated coefficient
f	Calculated coefficient
η	Pump efficiency of an irrigation system (%)
Q	Flow rate of an irrigation system (m^3/h)
H	Pressure requirement of an irrigation system (m)

The coefficients are calculated from the pressure (Hd) and flow rate (Qd) at a pump best efficiency point (BEP). Thus, different pumps will have different coefficients. These coefficients are calculated beforehand in the model and are used to calculate the pressure requirement and pump efficiency at each flow rate.

Table 4. 1: Coefficients used in the example of static head and zero static head

	Operating Point	
	1	**2**
Hd (m)	42.2	30.4895
Qd (m^3/h)	167	141.95
BEP (%)	77.5%	77.131%
N (rpm)	1450	1232.5
VSD Speed (%)	100%	85%
a	56.26666667	40.65266667
c	-0.00050438	-0.00050438
e	0.009281437	0.010867396
f	-0.0000278	-0.00003828

The coefficients in Table 4.1 were applied to approximate the pump and efficiency curve for an irrigation system with a static head and a zero static head. The coefficients of operating point 1 are if the pump operates at 100% speed, while the coefficients of operating point 2 are at 85% speed. Figure 4.2 and 4.3 illustrate an example of a centre pivot irrigation system operating at two points with a static head of 20m. Operating point 1 represents the point at which the pump operates at 100%. The flow rate and pressure at operating point 1 is 160 m^3/h and 43 m, respectively. The efficiency of the pump is 77% and the kilowatt requirement is 49 kW. Assume the flow rate decrease to 120 m^3/h, thus the operating point of the irrigation system will shift. If a VSD is used the pump curve will shift down and the new operating point will be operating point 2, with a flow rate of 120 m^3/h and a pressure of 33 m and at an efficiency of 75%, resulting in a kilowatt requirement of 29 kW. If a throttle valve was used instead of a VSD, the pump would have operated at a flow rate of 120 m^3/h and a pressure of 49 m, with an efficiency of 71%, resulting in a kilowatt requirement of 38 kW. Thus, the VSD require 9 kW less than the throttle valve. However, careful analysis needs to be done to determine if the VSD will be financially feasible in terms of the cost of the VSD and the energy cost savings.

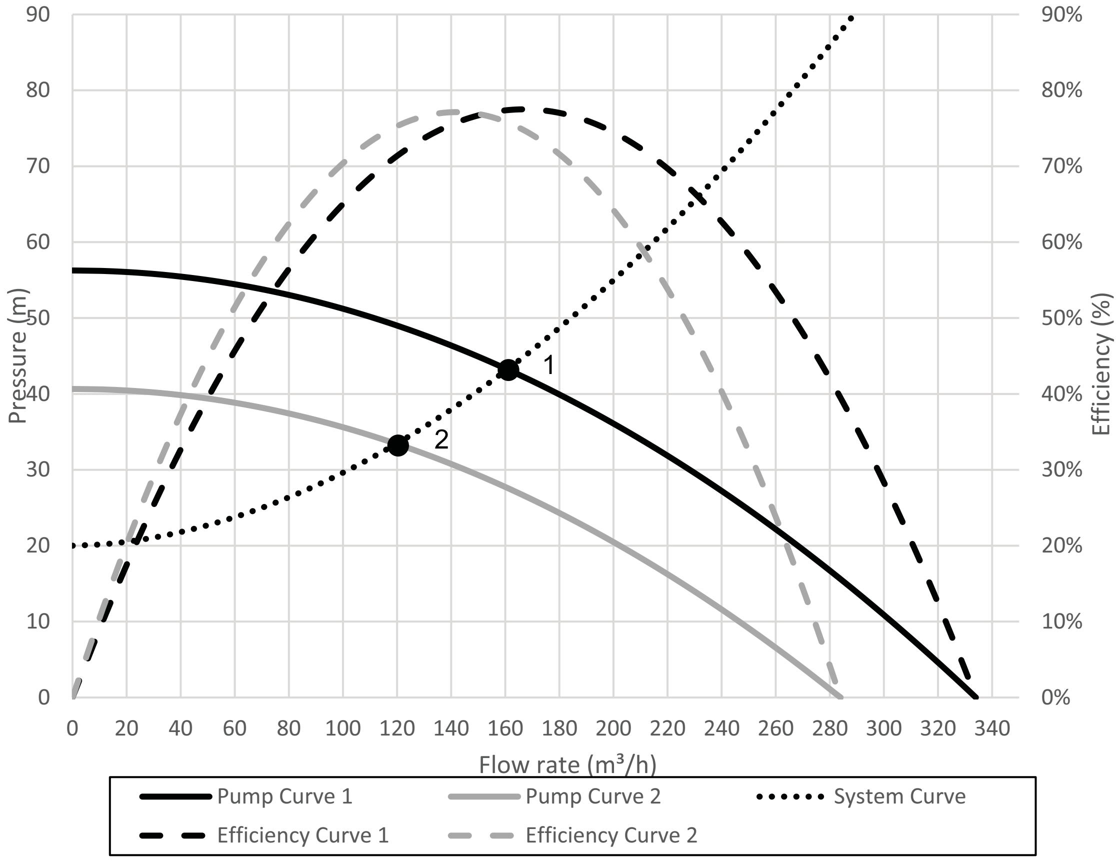

Figure 4. 2:System, pump and efficiency curves for an irrigation system with a static head

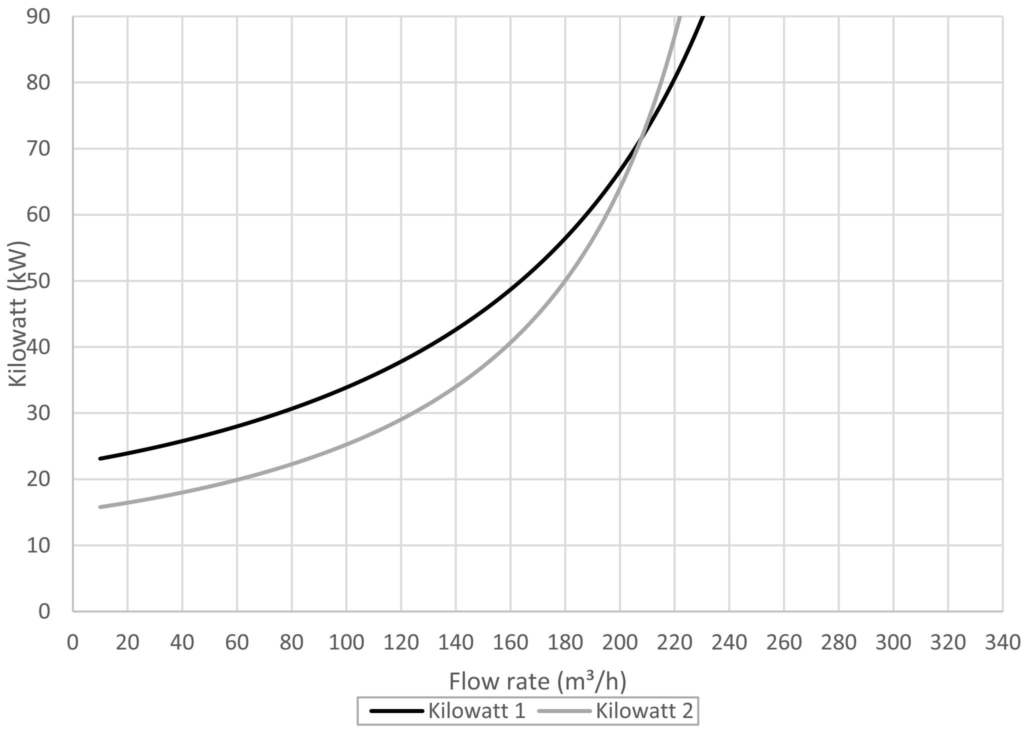

Figure 4. 3:Kilowatt requirement curves for an irrigation system with a static head

Figure 4.4 and 4.5 represents the pump, efficiency and kilowatt curves for an irrigation system with a zero static head. Operating point 3 is at a flow rate of 200 m^3/h and a pressure of 36 m with an efficiency of 74% and a kilowatt requirement of 52 kW. Suppose the flow rate decrease to 170 m^3/h, the pressure will be 26 m with efficiency of 74% and a kilowatt requirement of 32 kW if a VSD is used (operating point 4). If a throttle valve is used to obtain a flow rate of 170 m^3/h, the pressure will increase to 42 m with an efficiency of 77% and a kilowatt usage of 40 kW. Although the use of a throttle valve results in a higher efficiency, the kilowatt requirement is higher compared to the use of a VSD due to the higher pressure.

The change in efficiency for a system with a static head is more significant than a system with zero static head. The change in efficiency has a direct impact on the amount of kilowatt required which will influence the energy costs of the system. Thus, each irrigation system should be analyses individually to determine if a VSD will be profitable.

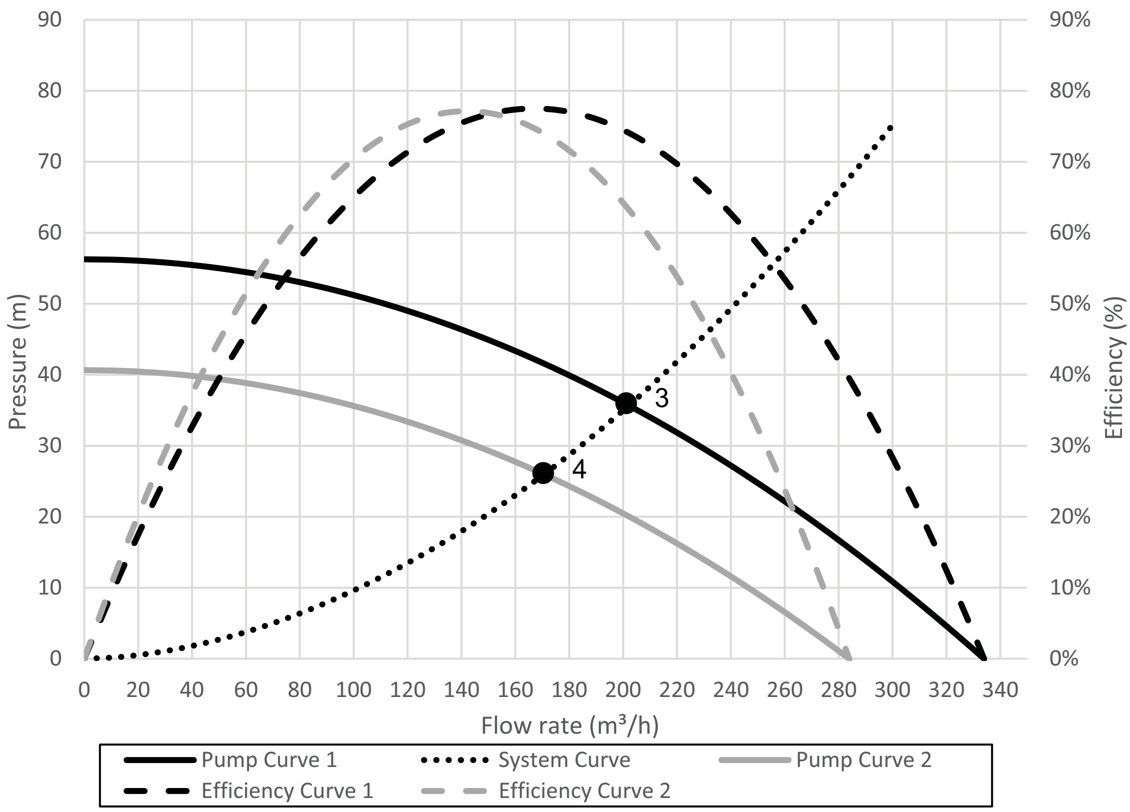

Figure 4. 4: System, pump and efficiency curves for an irrigation system with a zero static head

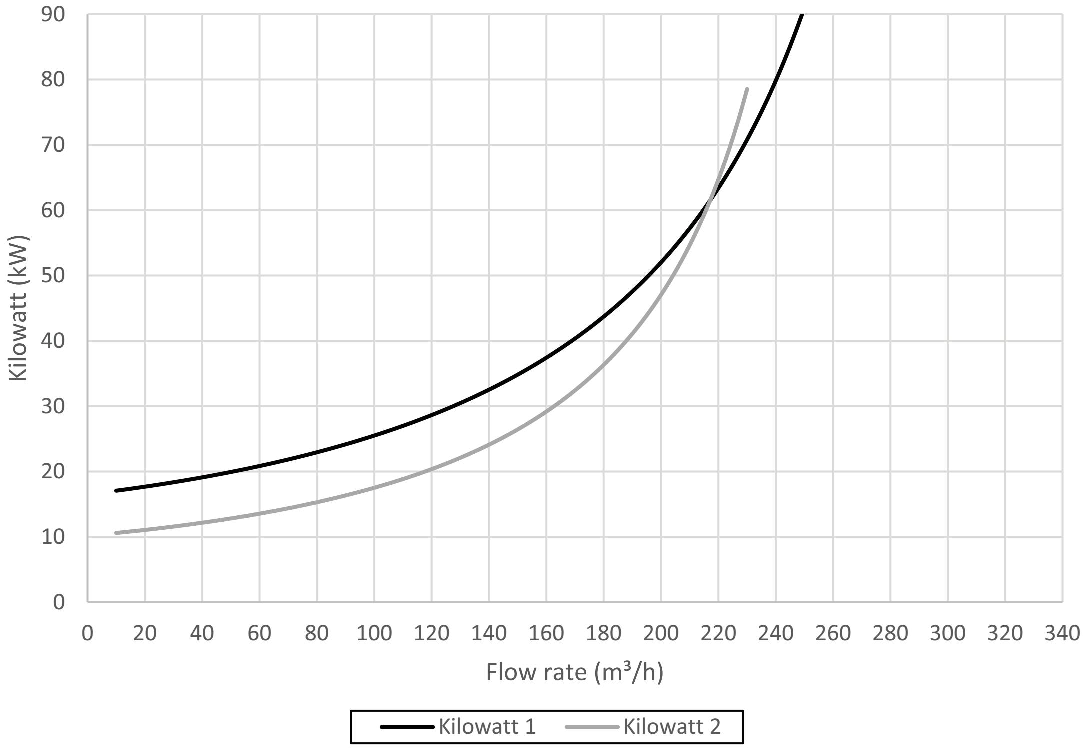

Figure 4. 5: Kilowatt requirement curves for an irrigation system with a zero static head

4.5 *APPLICATION OF VARIABLE SPEED DRIVES WITH A DYNAMIC HEAD*

A dynamic head is present when the pressure is changing while the system is operating. Such a situation is for example present in cases where a centre pivot irrigation system is operating at a gradient. The design of the system is done such that enough pressure is supplied to overcome the highest static head. The system will produce too much pressure at the lowest static head. Energy could be saved if the speed of the motor is reduced to generate the correct pressure.

In order to calculate the energy use as the pivot is rotating, it is necessary to know how the static head is changing. Given a constant slope and pivot size the changes in the static height can be calculated using standard trigonometry equations. Figure 4.6 shows the location of eight different operating points used in the calculations while Figure 4.7 shows how the static head changes as the pivot rotates.

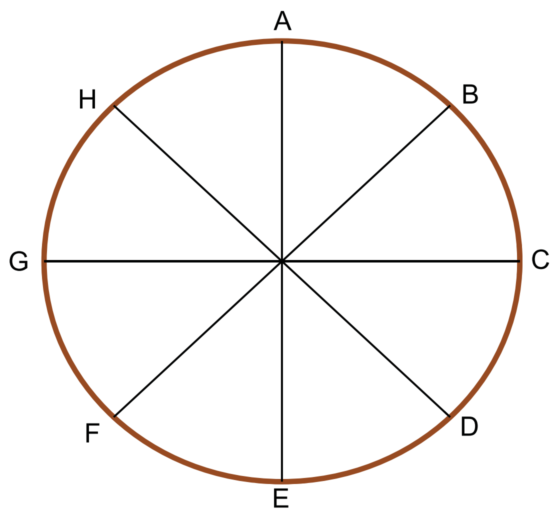

Figure 4. 6: Operating points of a centre pivot irrigation system

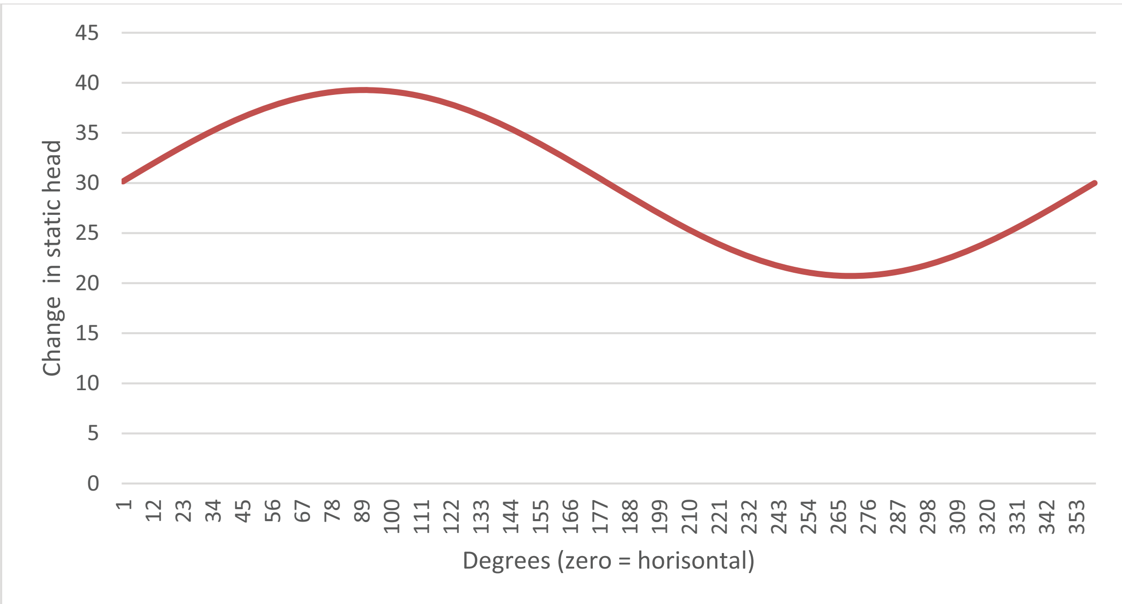

Figure 4. 7: Changes in static head while rotating

The 30.11 ha centre pivot has a gradient of 3%, which results in different static heads for the operating points shown in Figure 4.6. The differences in static head at the operating points will change the pressure requirement of the system, but flow rate will stay constant at each operating point. The static head at the middle of the centre pivot is 20 m (Operating point C and G). The highest point is at point A with a static head of 29.28 m. Given the before mentioned information, the dynamic changes in the head was calculated.

The speed of the VSD was determined to ensure that the flow rate (Q) and pressure (H) at each operating point was obtained. The pump efficiency was calculated for each operating point and the resulting kilowatt requirement.

Table 4.2 represents the coefficients used in the calculation and the resulting efficiencies and kilowatt usage for the different operating points for a 30.11 ha centre pivot operating at a gradient of 3%. Operating points F, G and H are excluded in the calculation since it has the same operating point as point D, C and D, respectively.

Table 4. 2: Calculation coefficients for different operating points and resulting kilowatt usage and efficiencies

	A	B	C	D	E
VSD Speed (%)	90.9%	89.2%	84.9%	80.3%	78.3%
Static Head (m)	29.28	26.57	20	13.43	10.71
H (m)	59.8	58.6	51	44.4	41.6
Q (m^3/h)	150.5	150.5	150.5	150.5	150.5
Efficiency (%)	75%	75%	76%	77%	77%
Kilowatt (kW)	52.2	50	41.7	34.3	31.3
a	71.686344	70.58288733	62.949954	56.31331933	53.543106
c	-0.00052982	-0.00052982	-0.00052982	-0.00052982	-0.00052982
e	0.008458307	0.008522278	0.009009371	0.009510148	0.009745918
f	-0.00002299	-0.00002335	-0.00002614	-0.00002917	-0.00003066

Figure 4.8 and 4.9 represents the pump, efficiency and kilowatt curves for the pump at the different operating points. The changes in efficiency was not significant which indicated that a VSD can be potential beneficial for a centre pivot operating at a gradient. However, as mentioned above it is of utmost importance to calculate the energy savings through the use of a VSD and the costs of a VSD.

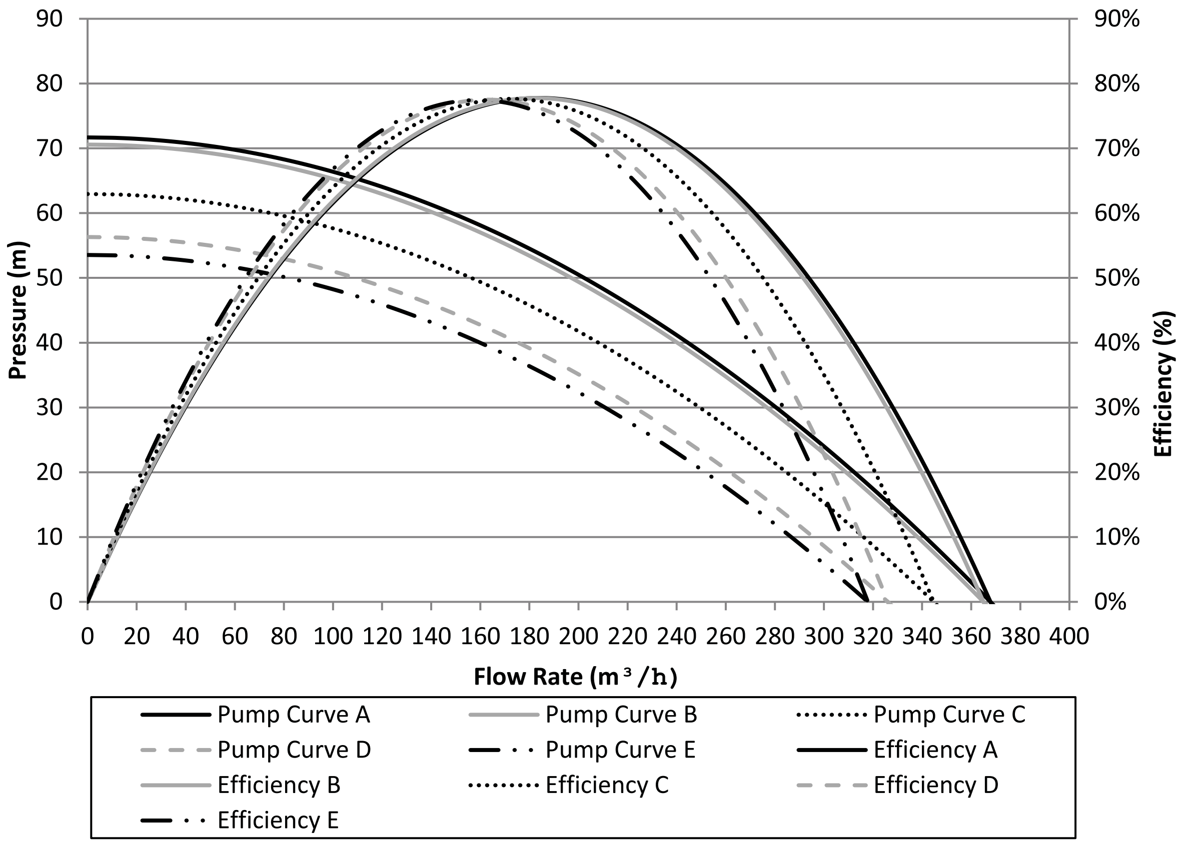

Figure 4. 8: Pump and efficiency curves for a centre pivot operating at a gradient

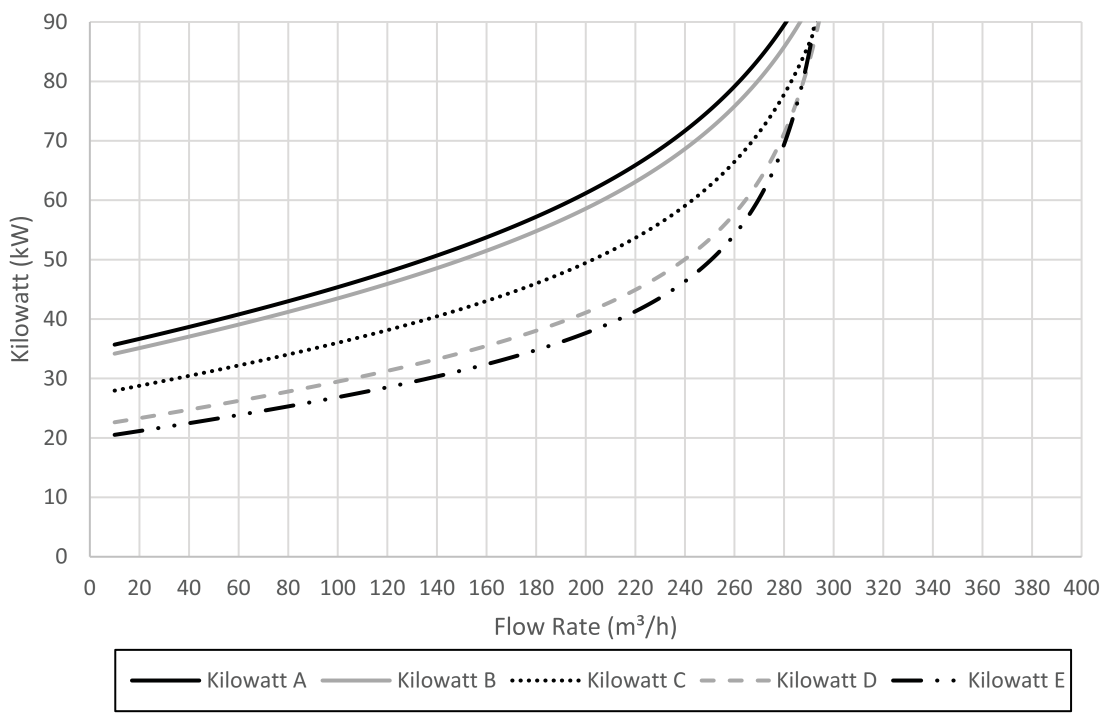

Figure 4. 9: Kilowatt curves for the different operating points for a centre pivot operating at a gradient

Chapter 5

RESULTS AND SENSITIVITY ANALYSES OF IRRIGATION COSTS FOR SELECTED CASE STUDIES

5.1 INTRODUCTION

Case study M1 to M5 include moveable irrigation systems. Case study M1 is based on a maize wheat crop rotation system in Douglas, Northern Cape. The case study include two centre pivot sizes of 30.1ha and 47.7ha and application capacities of 8 mm/day, 10 mm/day, 12 mm/day and 14 mm/day. Ruraflex and Landrate were included in the case study. The economic trade-off between mainline investment costs and operating costs were analysed. Case study M2 include a 20ha centre pivot. The original irrigation design consisted of water being pumped from the boreholes into a reservoir, and thereafter water was pumped with a booster pump to the irrigation systems. The case study compares Ruraflex and Landrate as well as the effect of the correct design, operation and maintenance of the system. Case study M3 include a 7.4 ha centre pivot that was irrigated during the 2015 winter season using Ruraflex. A number of boreholes are used to fill a reservoir. Water is then pumped with a booster pump to the centre pivot. The case study is used to demonstrate the impact of correct design, planning and mainline design on electricity costs. Case study M4 include a potato farm in the Limpopo province. Water is pumped out of the river to two balancing dams and then to the irrigation system. All pumps are fitted with a VSD and the electricity supply point is Landrate. The case study was used to demonstrate the impact of using variable speed technology with various pumping sections on an irrigation system. Case study M5 include a 20ha and 30.1ha centre pivot. The operating slope of the centre pivot was changed from 1% to 15% to analyse the suitability of a VSD for an irrigation system operating at a slope.

Case study S1 to S3 include static system such as micro irrigation and sprinkler irrigation. Case study S1 was done on a 22.26ha sprinkler irrigation system with a gross application rate of 5 mm/day and an application efficiency of 75%. A limitation of 18 hours per day and no irrigation on Sundays are applicable for the irrigation system. The case study was done for Ruraflex and Landrate. Case study S2 include a 22.26ha drip irrigation system with a gross application rate of 1.3 mm/h and with an application rate of 95%. A limitation of maximum of 15 hours per day are applicable to the system and it is possible to irrigate seven days per week. The case study was used to evaluate the electricity savings between a sprinkler and drip system for the same situation. Landrate and Ruraflex was also compared, both with and without VSDs. Case study S3 include an 18.83ha micro-sprinkler irrigation system for avocados in the Limpopo province with a gross application rate of 5.5 mm/h and with an application rate of 85%. The case study was used to illustrate electricity costs for both Landrate and Ruraflex, for a system with and without a VSD. Case study S3 was also used to evaluate the impact of optimal mainline design when using Landrate or Ruraflex. The results are discussed in Case study S4.

5.2 MOVABLE IRRIGATION SYSTEMS

5.2.1 CASE STUDY M1: ECONOMIC TRADE-OFF BETWEEN MAINLINE INVESTMENT COSTS AND OPERATING COSTS

The results obtained from the economic evaluation for pipe investments are presented in this section. The section includes the results obtained for Ruraflex and Landrate as well as a comparison between Ruraflex and Landrate.

5.2.1.1 Ruraflex

Table 5.1 shows the design parameters, investment and electricity costs as well as the profitability of Ruraflex for the eight different irrigation systems included in the analysis for a low water holding capacity of 100mm/m. The irrigation systems include a small (30.1ha) and large (47.7ha) centre pivot with irrigation system delivery capacities ranging from 8mm/day to 14mm/day. If irrigation system delivery capacities increase from 8mm/day to 14mm/day the flow rates increase from 100.5m^3/h to 178m^3/h for the small centre pivot and from 158.9m^3/h to 278m^3/h for the large centre pivot. Low system delivery capacities (8mm/day and 10mm/day) resulted in thinner optimal pipe diameters when compared to higher system delivery capacities (12mm/day and 14mm/day). For example, the most economical pipe diameter for the low system delivery capacities for the small centre pivot is 200mm while a 250mm pipe diameter is optimal for the higher system delivery capacities. Larger pipe diameters are optimal for the large centre pivot compared to the small centre pivot when comparing systems with the same delivery capacities. The optimal pipe diameters increase to 250mm and 315mm respectively for low and high system delivery capacities when increasing centre pivot size. These changes in pipe diameters are a direct result of the higher flow rates associated with larger pivots.

Changes in pipe diameter and flow rate (delivery capacity) have a direct impact on the kilowatt requirement to drive the water through the system and therefore operating costs. If the pipe diameter stays the same friction increases as the flow rates increase, resulting in an increase in the kilowatt requirement. Friction increases from 2.974m to 4.475m if the flow rates increase from 100.5m^3/h to 125.5m^3/h resulting in an increase in the kilowatt requirement of 5kW. The optimal pipe diameter increases when flow rate increased from 125.5m^3/h to 150.5m^3/h which resulted in a decrease in friction even though the flow rates increase. Larger pipe diameters reduce friction loss and therefore total pressure with lower kilowatt requirements while increases in flow rate will cause an increase in kilowatt requirement. The direction of change in kilowatt requirement is therefore not self-evident if pipe diameter is increased in conjunction with an increase in flow rate. The results show that the kilowatt requirement will increase, but less proportional. For example, if the flow rate is increased from 125.5m^3/h to 150.5m^3/h for the small centre pivot the friction decreases from 4.475m to 2.107m resulting in an increase in kilowatt requirement of 2kW due to pipe size increase. The same observation is made for the large centre pivot. The percentage friction followed the same trend as the friction loss since the length of the main pipeline (750m) is constant. Important to note is that the percentage friction loss is much less than the norm of 1.5%. The results show that friction loss as a percentage of the length of the pipe never exceeds 0.6%. The implication of using the 1.5% norm is that thinner pipe diameters would be used which decrease investment cost but at the same time operating cost (electricity costs) is increased. Thus, increasing electricity costs will have a significant effect on profitability of irrigation systems if thinner pipes are used.

The results show that variable electricity costs increase as flow rate increases if the optimal pipe diameter stays the same. However, variable electricity costs decrease if the optimal pipe diameter increases in conjunction with flow rate increases. For example, if the flow rate increases from 158.9m^3/h to 198.6m^3/h, variable electricity costs increase from R 849 125 to R 865 063 when pipe diameter is constant and decrease from R 865 063 to R 832 717 if the flow rate increases to 239m^3/h and the optimal pipe diameter increases. Generalisations are, however, not possible since variable electricity costs decreased between the 12mm/day and 14mm/day irrigation system delivery capacities for the small centre pivot even though pipe diameter stayed the same. The reason for the decrease in variable electricity costs is that the increase in kilowatt requirement is less than the decrease in irrigation pumping hours associated with irrigating with higher system delivery capacities which resulted in a decrease in kilowatt hours (kWh). The kilowatt hours decreased with 397kWh (40 436kWh – 40 039kWh) which caused a decrease in variable electricity costs of R 14 597 (R 508 959 – R 494 362) between the 12mm/day and 14mm/day irrigation system delivery capacities for the small centre pivot. The interaction between kilowatt requirement and the pumping hours emphasises the importance of appropriately modelling the interaction between irrigation system design and management. Fixed electricity costs are the same (R 307 099) for all the irrigation systems except for the high irrigation system delivery capacities (12mm/day and 14mm/day) for the large centre pivot due to a higher kilovolt-ampere point. The fixed electricity cost for the high system delivery capacity for the large centre pivot is R 394 056 due to a 75KVA point. Total electricity costs for the large centre pivot increase as flow rates increase due to the increase in fixed electricity costs.

Table 5. 1: Optimised design parameters, investment and electricity costs for different irrigation systems using Ruraflex for a 100mm/m water holding capacity

	Centre Pivot Size (ha)							
	Small (30.1)				Large (47.7)			
	Irrigation System Delivery Capacity (mm/day)				Irrigation System Delivery Capacity (mm/day)			
	8	10	12	14	8	10	12	14
	DESIGN PARAMETERS							
Flow Rate (m^3/h)	*100.5*	*125.5*	*150.5*	*178*	*158.9*	*198.6*	*239*	*278*
Outside Diameter (mm)	*200*	*200*	*250*	*250*	*250*	*250*	*315*	*315*
Friction (m)	*2.974*	*4.475*	*2.107*	*2.869*	*2.328*	*3.511*	*1.316*	*1.738*
Friction percentage (%)	*0,4*	*0,6*	*0,28*	*0,38*	*0,31*	*0,47*	*0,18*	*0,23*
Total pressure (m)	*36*	*39*	*38*	*38*	*37*	*41*	*41*	*45*
Kilowatt (kW)	*13*	*18*	*20*	*23*	*21*	*28*	*33*	*42*
Kilowatt hours (kWh)	*39 610*	*42 234*	*40 436*	*40 039*	*62 197*	*66 395*	*65 975*	*71 335*
	INVESTMENT AND ELECTRICITY COSTS							
Pipe Investment (R)	*112 853*	*112 853*	*179 895*	*179 895*	*179 895*	*179 895*	*276 158*	*276 158*
Pivot Investment (R)	*638 483*	*669 000*	*723 186*	*739 654*	*815 452*	*835 239*	*842 405*	*930 818*
Pump Investment (R)	*14 368*	*21 655*	*20 661*	*20 661*	*20 661*	*22 216*	*22 216*	*22 216*
Total Investment Costs (R)	*765 704*	*803 518*	*923 742*	*940 210*	*1 016 008*	*1 037 350*	*1 122 779*	*1 229 192*
Total Variable Electricity Costs (R)	*541 411*	*549 204*	*508 959*	*494 362*	*849 125*	*865 063*	*832 717*	*883 347*
Total Fixed Electricity Costs	*307 099*	*307 099*	*307 099*	*307 099*	*307 099*	*307 099*	*394 056*	*394 056*
Total Electricity Costs (R)	*848 510*	*856 303*	*816 058*	*801 461*	*1 156 224*	*1 172 162*	*1 226 773*	*1 277 404*
Net Present Value (R)	*4 858 514*	*4 857 930*	*4 852 137*	*4 905 564*	*8 304 887*	*8 356 438*	*8 330 847*	*8 198 284*
Net Present Value (R/ha)	*161 412*	*161 393*	*161 201*	*160 838*	*174 107*	*175 187*	*174 651*	*171 872*

Net present value (NPV) decreases as flow rate increases for the small centre pivot with an exception for an increase between the 12mm/day and 14mm/day delivery capacities. The increase is due to a slightly larger irrigated area (ha) which causes total NPV to increase. However, NPV per hectare decreases as flow rate increases for the small centre pivot. Increasing investment costs resulted in a decrease in NPV per hectare. The 8mm/day delivery capacity resulted in the most profitable irrigation system delivery capacity for the small centre pivot. The NPV of the large centre pivot increased between the 8mm/day and 10mm/day irrigation system delivery capacities and decreases for delivery capacities above 10mm/day. The 10mm/day delivery capacity resulted in the highest NPV for the large centre pivot. Even though electricity costs and investment costs increased between the 8mm/day and 10mm/day delivery capacity, the NPV is highest for the 10mm/day delivery capacity because the crop yield for wheat was slightly higher resulting in higher gross margins. Again the increase in total investment costs is responsible for the decreasing trend in NPVs for irrigation system delivery capacities above 10mm/day for the large centre pivot.

5.2.1.2 Landrate

Table 5.2 shows the design parameters, investment and electricity costs for Landrate for the eight different irrigation systems included in the analyses for a low water holding capacity of 100mm/m. The smallest irrigation system delivery capacity (8mm/day) resulted in a thinner optimal pipe diameter as compared to higher irrigation system delivery capacities (10, 12, 14mm/day) for both the centre pivot sizes. Increasing the irrigation system delivery capacity above 8mm/day increased the optimal pipe diameter to 250mm and 315mm respectively for the small and large centre pivot. The larger centre pivot resulted in a larger optimised pipe diameter compared to a smaller centre pivot with the same delivery capacity. The larger pipe diameters of the large centre pivot directly contributed to the result of higher flow rates associated with larger centre pivots. For example, the optimal pipe diameter for the 8mm/day irrigation system delivery capacity is 200mm while the optimal pipe diameter for the larger centre pivot with the same irrigation system delivery capacity is 250mm.

The impact of pipe diameter and flow rate on the kilowatt requirement of an irrigation system is discussed next. If an increase in the pipe diameter occurs, friction decreases even though flow rate increases irrespective of centre pivot size. However, a less than proportional increase in kilowatt requirement occurs due to a decrease in friction. For example, the friction loss decreased from 2.974m to 1.51m even though flow rate increased from 100.5m^3/h to 125.5m^3/h. The reduction in friction is because of the increase in pipe diameter. The net effect of the reduction in friction and the increase in flow rate causes kilowatt to increase with only 3kW for the small centre pivot. Notwithstanding, the size of the centre pivot friction in the main pipeline increases if flow rate increases when the pipe diameter is kept constant which causes an increase in the kilowatt requirement of an irrigation system. Increasing the flow rate from 125.5m^3/h to 150.5m^3/h increases the friction to 2.869m which increased the kilowatt requirement to 20kW. The percentage friction in all the cases considered is more than one percentage point lower than the norm of 1.5%.

The results for the large centre pivot show that the variable electricity costs are constant for an increase in irrigation system delivery capacity between 8mm/day and 10mm/day whereas variable electricity costs show an increasing trend for irrigation system deliveries above 10mm/day. Changes in variable electricity costs are the direct result of the interaction between kilowatt requirement and pumping hours as measured by kilowatt hours (kWh). Increasing delivery capacity will reduce pumping hours but at the same time increase kilowatt requirement due to higher friction given the pipe diameter is not changed. The increasing trend in variable electricity cost is observed because kilowatt changes are the dominant factor affecting variable electricity costs for the large centre pivot. Contradictory to the results of the large pivot the variable electricity costs of the small pivot decrease if the optimal pipe diameter increases when irrigation system delivery capacity increases to 10mm/day. Furthermore, no trend is observable if irrigation delivery capacities are increased above 10mm/day and the optimal pipe diameter is 250mm. The changes in kilowatt due to changes in flow rate are much smaller for the small pivot due to the relatively lower flow rates of the smaller pivots. As a result, the interaction between reduced pumping hours and increasing kilowatts associated with increasing irrigation system delivery capacities is much more important in determining the impact thereof on variable electricity costs. Fixed electricity costs stayed the same between the irrigation systems included in the analyses because the fixed electricity costs are independent of the size of an irrigation system.

The results of the NPVs indicate that the larger centre pivot is more profitable than the smaller centre pivot. The pivot with the 8mm/day delivery capacity is, however, the most profitable of the alternative delivery capacities considered. The net present value decreases if irrigation system delivery capacity increases above 8mm/day for both centre pivot sizes with an exception for an increase between the 12mm/day and 14mm/day delivery capacity for the small centre pivot. The increase in net present value is due to 0.4ha larger irrigated area for the 14mm/day irrigation system delivery capacity. Increasing investment costs are the major factor affecting the decrease in profitability of the irrigation system with higher delivery capacities.

Table 5. 2: Optimised design parameters, investment and electricity costs for different irrigation systems using Landrate for a 100mm/m water holding capacity

	Centre Pivot Size (ha)							
	Small (30.1)				Large (47.7)			
	Irrigation System Delivery Capacity (mm/day)				Irrigation System Delivery Capacity (mm/day)			
	8	10	12	14	8	10	12	14
	DESIGN PARAMETERS							
Flow Rate (m^3/h)	*100.5*	*125.5*	*150.5*	*178*	*158.9*	*198.6*	*239*	*278*
Outside Diameter (mm)	*200*	*250*	*250*	*250*	*250*	*315*	*315*	*315*
Friction (m)	*2.974*	*1.510*	*2.107*	*2.869*	*2.328*	*0.937*	*1.316*	*1.738*
Friction percentage (%)	*0.4*	*0.2*	*0.28*	*0.38*	*0.31*	*0.12*	*0.18*	*0.323*
Total pressure (m)	*36*	*36*	*38*	*38*	*37*	*38*	*41*	*45*
Kilowatt (kW)	*13*	*16*	*20*	*23*	*21*	*26*	*33*	*42*
Kilowatt hours (kWh)	*39 610*	*39 012*	*40 436*	*40 039*	*62 197*	*62 197*	*65 975*	*71 335*
	INVESTMENT AND ELECTRICITY COSTS							
Pipe Investment (R)	*112 853*	*179 895*	*179 895*	*179 895*	*179 895*	*276 158*	*276 158*	*276 158*
Pivot Investment (R)	*638 483*	*669 000*	*723 186*	*739 654*	*815 452*	*835 239*	*842 405*	*930 818*
Pump Investment (R)	*14 368*	*21 655*	*20 661*	*20 661*	*20 661*	*22 216*	*22 216*	*22 216*
Total Investment Costs (R)	*765 704*	*870 550*	*923 742*	*940 210*	*1 016 008*	*1 133 613*	*1 122 779*	*1 229 192*
Total Variable Electricity Costs (R)	*652 227*	*642 380*	*665 826*	*659 281*	*1 024 147*	*1 024 146*	*1 086 340*	*1 174 613*
Total Fixed Electricity Costs	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*
Total Electricity Costs (R)	*1 032 220*	*1 022 373*	*1 045 819*	*1 039 275*	*1 404 140*	*1 404 139*	*1 466 334*	*1 554 607*
Net Present Value (R)	*4 796 388*	*4 724 886*	*4 643 845*	*4 730 731*	*8 141 881*	*8 055 133*	*7 973 632*	*7 769 924*
Net Present Value (R/ha)	*159 348*	*156 973*	*154 281*	*155 106*	*170 689*	*168 871*	*167 162*	*162 891*

5.2.1.3 Comparison, Discussion and Conclusion

Electricity tariffs increase between Ruraflex and Landrate. Ruraflex is a time-of-use tariff which provides lower tariffs when the demand for electricity is low whereas Landrate has a flat rate which is relatively high. The results show that the higher electricity tariff of Landrate causes optimal pipe diameters to increase more rapidly when increasing irrigation system delivery capacity. For both the centre pivot sizes the increase in optimal pipe diameters occurred when increasing delivery capacities to 10mm/day for Landrate while the change occurred at 12mm/day for Ruraflex. The larger pipe diameters of the 10mm/day systems cause friction loss to decrease resulting in a decrease in kilowatt requirement of 2kW for both centre pivot sizes when comparing Landrate to Ruraflex. The conclusion is that failure to consider electricity tariffs when designing irrigation mainlines may result in suboptimal designs which will increase electricity costs.

SABI accredited designers are allowed to design irrigation systems such that the friction as a percentage of the length of the pipeline does not exceed 1.5%. In order to test the norm, the friction percentages were calculated while assuming that it is not optimal to increase pipe diameter between the 10mm/day and 12mm/day systems for Ruraflex and 8mm/day and 10mm/day systems for Landrate. The results of the calculations are shown in Table 5.3. The percentage friction increased from 0.6% to 0.83% and from 0.47% to 0.66% respectively for the small and large centre pivot if the flow rates were increased while the pipe diameter remained constant for Ruraflex. The breakeven percentage friction that will cause pipe diameter to increase is therefore between 0.6% and 0.66%. With Landrate the percentage friction increased from 0.4% to 0.6% and from 0.31% to 0.47% respectively for the small and large centre pivot if the flow rates were increased from 8mm/day to 10mm/day. The range in which the breakeven percentage friction will be is 0.4% to 0.6% which is lower when compared to Ruraflex. Such a result is expected because Landrate electricity charges are relatively higher than Ruraflex and therefore it is optimal to increase pipe diameters more quickly. The conclusion is that electricity tariffs have a significant impact on breakeven percentage friction. The breakeven point is furthermore much lower than the norm of 1.5%.

An important factor that determines total variable electricity costs is the product of kilowatt and pumping hours. Pumping hours are reduced if the irrigation system delivery capacity is increased. The degree of reduction is almost the same between the small and large centre pivots. However, significant differences exist between the small and large centre pivot in terms of increasing kilowatt requirements associated with increasing delivery capacities. Kilowatt requirements increase with 10kW and 21kW respectively for the small and large centre pivot. The magnitude of the increase in kilowatt requirement for the large pivot causes the kilowatt hours to increase even though pumping hours are reduced with increasing delivery capacities. The relatively small change in kilowatt requirements necessary to increase delivery capacity for the small pivot causes kilowatt hours not to increase significantly with increasing delivery capacity. The direction of change in the kilowatt hours for the small centre pivot depends more on the interaction between increasing kilowatt requirement and decreasing pumping hours resulting from increasing delivery capacities. Thus, the conclusion is that the interaction between kilowatt requirement and irrigation management (hours) becomes more significant for smaller irrigated areas in determining variable electricity costs.

Table 5. 3: Friction losses from not using optimal pipe diameters for a small and large centre pivot

	Centre Pivot Size (ha)			
	30.1		47.7	
	Ruraflex			
Flow Rate (m^3/h)	*125.5*	*150.5*	*198.6*	*239*
Outside Diameter (mm)	*200*	*200*	*250*	*250*
Friction (m)	*4.475*	*6.259*	*3.511*	*4.946*
Friction percentage (%)	*0.6*	*0.83*	*0.47*	*0.66*
	Landrate			
Flow Rate (m^3/h)	*100.5*	*125.5*	*158.9*	*198.6*
Outside Diameter (mm)	*200*	*200*	*250*	*250*
Friction (m)	*2.974*	*4.475*	*2.328*	*3.511*
Friction percentage (%)	*0.4*	*0.6*	*0.31*	*0.47*

The total variable electricity costs of Landrate are higher for all the alternatives when compared to Ruraflex even though the kilowatt requirement of the 10mm/day irrigation systems is 2kW less with Landrate. Higher total variable electricity costs are a direct result of the higher electricity tariff rate associated with Landrate. However, it is important to include fixed electricity costs since the fixed electricity costs differ between electricity tariff structures. Fixed electricity costs for Landrate are higher compared to Ruraflex, except for the 12mm/day and 14mm/day delivery capacity for the large centre pivot. Landrate's fixed electricity tariffs are greater than Ruraflex's tariff. However, Ruraflex's network access tariff depends on the size of kilovolt-ampere (KVA), thus, higher kilovolt-amperes will result in higher fixed electricity costs. The fixed electricity costs for the 8mm/day delivery capacity for the large centre pivot using Landrate is R 379 993 and R 307 099 for Ruraflex, while the fixed electricity costs for Ruraflex increase to R 394 056 for the 12mm/day and 14mm/day delivery capacity for the large centre pivot. The increase is due to a kilovolt-ampere increase of 25KVA between the 10mm/day and 12mm/day delivery capacity for the large centre pivot using Ruraflex.

The conclusion is that Ruraflex is more profitable than Landrate irrespective of pivot size and irrigation system delivery capacity since all the irrigation systems included in the analyses resulted in higher net present values using Ruraflex which is a direct result of lower electricity costs associated with Ruraflex. Furthermore, the larger centre pivot resulted in higher NPVs per hectare compared to the small centre pivot because as the centre pivot size increases the total investment costs per hectare decrease since the total investment costs are divided by a larger number (hectares). Smaller delivery capacities (8mm/day) are the most profitable for both of the centre pivot sizes and electricity tariff structures, except for the large centre pivot using Ruraflex where the 10mm/day delivery capacity had the highest NPV.

5.2.1.4 Management implications

The section include the results obtain for management implications. The research was done in Douglas for two electricity tariffs, two centre pivot sizes and four irrigation system capacities. Table 5.4 shows the optimised pumping hours for the alternative irrigation system designs using either Ruraflex or Landrate electricity tariffs. Total optimal pumping hours decrease as flow rate increases between irrigation system delivery capacities for both the centre pivot sizes. Higher flow rates can apply more water in one hour, thus, less irrigation hours are necessary to apply the same amount of irrigation water.

Small variations in total irrigation hours are present between the centre pivot sizes for a given irrigation system delivery capacity. Total irrigation hours for the 8mm/day delivery capacity using Ruraflex is 2 995hours for the small centre pivot and 3 002hours for the large centre pivot. The total irrigation hours for a given irrigation system delivery capacity and pivot size is exactly the same for the two electricity tariffs because the full water allocation was used for irrigation. However, the distribution of total pumping hours between maize and wheat is different between the two electricity tariffs for irrigation system delivery capacities smaller than 12mm/day. With Ruraflex the total pumping hours for maize is more while the pumping hours for wheat are less when compared to the pumping hours of these two crops under Landrate. The shift in irrigation hours towards maize is to reduce pumping of water during the portion of wheat's growing season that falls in the high energy demand season when the Ruraflex electricity tariff is very high. The results further show that the pumping hours in each of the time-of-use timeslots are less than the available pumping hours in a specific timeslot. The last mentioned is because the timing and magnitude of water applications are dictated by the status of the crop which is related to the soil water availability. The distribution of pumping hours within each of the time-of-use timeslots shows that maize is mostly irrigated during off-peak and standard time, while wheat needs to be irrigated during peak times when considering irrigation system delivery capacities below 12mm/day. The value of the marginal product is much higher than the marginal factor cost of applying irrigation water, therefore it is profitable to irrigate during peak timeslots. For irrigation system deliveries above 10mm/day the capacities are such that enough water could generally be applied to minimise irrigation during peak timeslots.

Table 5. 4: **Optimised irrigation hours for different irrigation systems using a 100mm/m water holding capacity for Ruraflex and Landrate**

			Centre Pivot Size (ha)							
			Small (30.1)				Large (47.7)			
			Irrigation System Delivery Capacity (mm/day)							
			8	10	12	14	8	10	12	14
Irrigation Hours	*Maize*	*OP*	*880*	*880*	*827*	*749*	*880*	*880*	*827*	*749*
		ST	*599*	*285*	*140*	*81*	*608*	*287*	*138*	*82*
		PE	*5*	*9*	*2*	*0*	*0*	*9*	*2*	*0*
	Wheat	*OP*	*855*	*783*	*728*	*677*	*855*	*784*	*727*	*678*
		ST	*510*	*419*	*301*	*206*	*510*	*420*	*299*	*207*
		PE	*146*	*22*	*3*	*0*	*149*	*22*	*3*	*0*
Total Irrigation Hours (Ruraflex)	*Maize*		*1 484*	*1 174*	*969*	*830*	*1 488*	*1 176*	*967*	*831*
	Wheat		*1 511*	*1 224*	*1 032*	*883*	*1 514*	*1 226*	*1 029*	*885*
	Total (Season)		*2 995*	*2 398*	*2 001*	*1 713*	*3 002*	*2 402*	*1 996*	*1 716*
Total Irrigation Hours (Landrate)	*Maize*		*1 449*	*1 159*	*969*	*829*	*1 453*	*1 162*	*966*	*831*
	Wheat		*1 546*	*1 239*	*1 032*	*884*	*1 549*	*1 240*	*1 030*	*885*
	Total (Season)		*2 995*	*2 398*	*2 001*	*1 713*	*3 002*	*2 402*	*1 996*	*1 716*

*OP: Off-Peak

*ST: Standard

*PE: Peak

The conclusion is that careful consideration of the economics is necessary since smaller delivery capacities require much more intensive management, because longer irrigation hours are needed in order to avoid a decrease in crop yield. The timing of irrigation is of utmost importance since it has a direct effect on electricity costs and crop yield. The assumption made by various researchers and irrigation designers that all available off-peak hours will be used first before irrigation will take place in more expensive time-of-use timeslots is void by the fact that the water budget and the status of the crop will determine irrigation timing and amounts.

5.2.2 Case Study M2: Correct Design, Operation and Maintenance

The original irrigation design consisted of water being pumped from the boreholes into a reservoir, and thereafter water was pumped with a booster pump to the irrigation systems. The farmer decided to modify the system so that water can pumped directly from the boreholes to the irrigation system, with the intention to reduce pumping costs since the booster pump will no longer be required.

The system lay-out of the 20 ha centre pivot that was used for irrigation during the 2015 winter season is shown in Figure 5.1. Two strong boreholes supply water directly to the mainline. Unfortunately these boreholes are fitted with positive displacement pumps (“Mono” pumps) which are not suitable for pumping directly into the irrigation system but the farmer did not want to replace them with submersible pumps because of the investment cost. The pumps were however fitted with VSDs and the farmer is using Ruraflex. Table 5.5 illustrate a summary of the system parameters for the case study.

Table 5. 5: Designed and measured system parameters of an irrigation system

System parameter	Design	Measured
Pressure required at pump:	71.4m	61.3m
Flow required at pump:	100 m^3/h	63 m^3/h
Power factor (cos φ)	0.99	0.99
Input power (drawn from transformer)	31.5 kW	22 kW
Apparent power	31.8 kVA	22.2 kVA
Reactive power	4.5 kVAr	3.13 kVAr
Sprinkler package	12 mm/day	8 mm/day

Figure 5. 1: Lay-out of a 20ha centre pivot

The irrigation system was evaluated and it was found that the boreholes were unable to supply the required pressure to the irrigation system, which implicate that the flow and application rates were less than the design values. This effectively reduced the system capacity to 8 mm/day (63 m^3/h) from the design value of 12 mm/day (100 m^3/h). The implications thereof were that the farmer now had to irrigate longer hours to apply the water that the crop was requiring. Since irrigation had to take place during Ruraflex's peak timeslots when the electricity tariff is high the higher irrigation hours resulted in higher electricity cost.

The effect of the reduced irrigation system capacity (8 mm/day to 12 mm/day) resulted in higher irrigation hours. The irrigation hours increased from 1 040 to 1 651 hours. This resulted in the total variable electricity cost to increase from R 22 036 to R 25 483 for the season as shown in table 5.6.

Variable electricity costs for Ruralfex and Landrate is shown in table 5.6. Variable electricity costs is significantly higher for Landrate compared to Ruraflex, variable electricity costs is R 34 837 and R 22 036 for Landrate and Ruraflex for the 12 mm/day system capacity, respectively. Thus, Ruraflex offer an advantage to irrigators compared to Landrate.

Table 5. 6: Irrigation, pumping hours and variable electricity costs for two irrigation system capacities for Ruraflex and Landrate

		Ruraflex		Landrate	
Irrigation		**100m3/h**	**63/m3/h**	**100m3/h**	**63/m3/h**
Total	mm.ha	10400	10401	10400	10401
	mm	520	520	520	520
Pumping hours					
Total	hours/20ha	1040	1651	1040	1651
VARIABLE ELECTRICITY					
Active	R/20ha	14214	16818	27787	30808
Reactive	R/20ha	772	849	0	0
Reliability	R/20ha	108	120	108	120
Demand	R/20ha	6942	7697	6942	7697
Total	**R/20ha**	**22036**	**25483**	**34837**	**38625**
	R/ha	**1102**	**1274**	**1742**	**1931**
	R/mm	**2.12**	**2.45**	**3.35**	**3.71**
	R/kWh	**0.67**	**0.70**	**1.06**	**1.06**
	kW/ha	**1.58**	**1.10**	**1.58**	**1.10**
	kWh/ton	**655.20**	**726.44**	**655.20**	**726.44**

The recommendations from this study following the evaluation of the system are to either reinstate the booster pump, or to reduce the size of the pivot, or to replace the Mono pumps with the correct size of submersible pumps.

5.2.3 CASE STUDY M3: CORRECT DESIGN, PLANNING AND MAINLINE DESIGN

The farm has a shortage of water and the producer redevelop the water supply system to make better use of available water. A number of boreholes are used to fill a reservoir. Water is then pumped with a booster pump to the centre pivot. The lay-out of the system to the 7.4 ha centre pivot that was used for irrigation during the 2015 winter season is shown in Figure 5.2. The electricity supply point was on Ruraflex.

After evaluation of the system, it was observed that the boreholes are located at an elevation higher than the centre pivot. If the reservoir had been placed near the boreholes, it would have been possible to supply water to the pivot from the reservoir under gravity, thereby eliminating the need for the booster pump and approximately 1500m of pipeline. This alternative scenario was modelled using the parameters shown in Figure 5.7. The main implication of eliminating the booster pump was that the pressure requirement was 25m less.

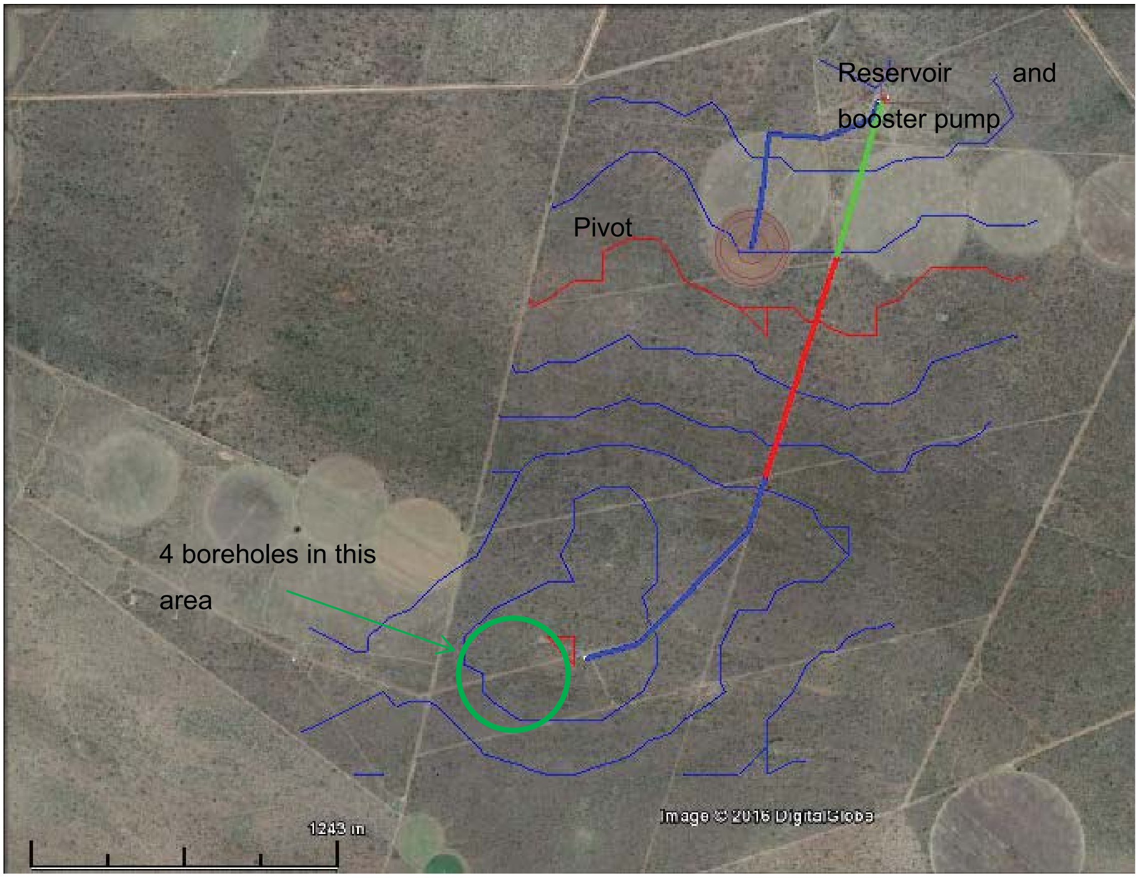

Figure 5. 2: Lay-out of the system to the 7.4 ha centre pivot

Table 5. 7: Designed and alternative system parameters for the irrigation system

System parameter	Design	Alternative
Pressure required at pump:	100.5m	76m
Flow required at pump:	32 m^3/h	32 m^3/h
Power factor (cos φ)	0.75	0.86
Input power (drawn from transformer)	23.6 kW	20.1 kW
Apparent power	31.5 kVA	23.4 kVA
Reactive power	20.8 kVAr	11.9 kVAr

The results of modelling both scenarios are shown in Table 5.8. The variable electricity costs for the alternative scenario (optimal scenario) would have been R 16 483 for the 7.4ha centre pivot compared to R 19 679 for the system with the booster pump (current scenario). However, the fixed electricity costs should also be considered as the alternative scenario eliminates the second electricity point (transformer) and all its associated fixed costs.

Table 5. 8: Irrigation amount, pumping hours and variable electricity costs for the current and optimal scenario using Ruraflex

		Ruraflex	
Irrigation		**Optimal**	**Current**
Total	mm.ha	3923	3923
	mm	530	530
Pumping hours			
Total	hours/7.4ha	1226	1226
VARIABLE ELECTRICITY			
Active	R/7.4ha	10610	12458
Reactive	R/7.4ha	569	995
Reliability	R/7.4ha	81	95
Demand	R/7.4ha	5222	6131
Total	**R/7.4ha**	**16483**	**19679**
	R/ha	**2227**	**2659**
	R/mm	**4.20**	**5.02**
	R/kWh	**0.67**	**0.68**
	kW/ha	**2.72**	**3.19**
	kWh/ton	**410.71**	**482.23**

5.2.4 CASE STUDY M4: USE OF VARIABLE SPEED TECHNOLOGY WITH VARIOUS PUMPING SECTIONS ON AN IRRIGATION SYSTEM

The results of this section is based on a potato farm in the Limpopo province where water is pumped out of the river to the first balancing dam, and then to the second balancing dam and the finally to the irrigation system. All the pumps are fitted with VSDs but the farmer uses the Landrate tariff option.

The producer pumps water from the river via a servitude to the farm which is located approximately 3km from the river as shown in Figure 5.3. Although only one 13 ha centre pivot is shown, the whole area of the farm has been developed with mainlines and pivot centres so that the pivots can be moved to different positions according to the rotational requirements of potato production.

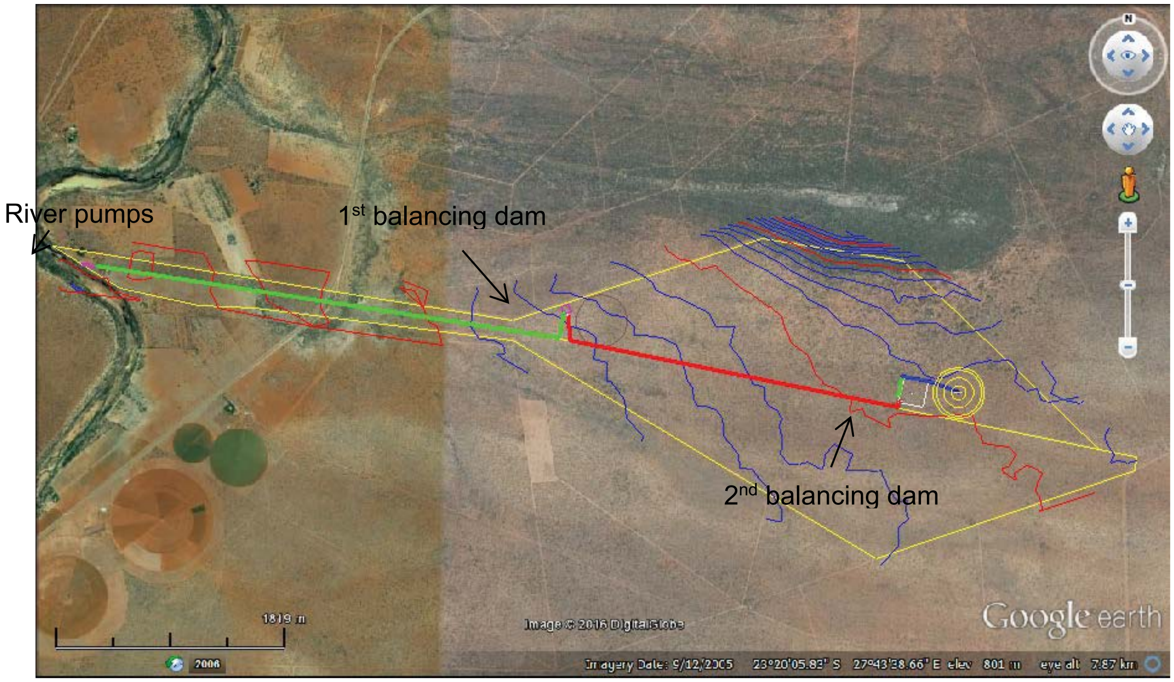

Figure 5. 3: Lay-out of the 13 ha centre pivot

The system parameters for the design scenario as well as a scenario without a VSD are shown in Table 5.9. Without the VSD, the last pump at the second balancing dam will have to be throttled to supply the right flow rate. The effect thereof would be that it would be working at a higher pressure than required, increasing the total pressure requirement from 112 m to 141 m. As the pressure is direct input in the power (kW) calculation, the input power of the motor is significantly higher without the VSD.

Table 5. 9: **Designed and without VSD system parameters for an irrigation system**

System parameter	Design	Without VSD
Pressure required (3 pumps combined):	112 m	141m
Flow required:	50 m^3/h	50 m^3/h
Power factor (cos φ)	0.99	0.7
Input power (drawn from transformer)	23.4 kW	32 kW
Apparent power	26 kVA	45.7 kVA
Reactive power	11.3 kVAr	32.6 kVAr

The results of modelling the two scenarios are shown in Table 5.10. The savings incurred by using the VSD on Landrate is approximately R 12 000 on the 13 ha pivot over the season. A further R 3 800 can be saved if the producer uses Ruraflex instead of Landrate. The farmer use Landrate because it is a complicated pumping system and it will be difficult to manage the three pump stations all within the favourable Ruraflex time slots.

Table 5. 10: Irrigation amount, pumping hours and variable electricity costs for two scenarios for Ruraflex and Landrate

		Ruraflex		Landrate	
Irrigation		**No VSD**	**VSD**	**No VSD**	**VSD**
Total	mm.ha	6975	6975	6975	6975
	mm	537	537	537	537
Pumping hours					
Total	hours/13ha	1395	1395	1395	1395
VARIABLE ELECTRICITY					
Active	R/13ha	19630	14354	37864	27688
Reactive	R/13ha	1692	587	0	0
Reliability	R/13ha	147	108	147	108
Demand	R/13ha	9459	6917	9459	6917
Total	**R/13ha**	**30929**	**21966**	**47470**	**34713**
	R/ha	**2379**	**1690**	**3652**	**2670**
	R/mm	**4.43**	**3.15**	**6.81**	**4.98**
	R/kWh	**0.69**	**0.67**	**1.06**	**1.06**
	kW/ha	**2.46**	**1.80**	**2.46**	**1.80**
	kWh/ton	**811.64**	**593.51**	**811.64**	**593.51**

5.2.5 *CASE STUDY M5: IRRIGATION SYSTEMS OPERATING AT A SLOPE*

Irrigation systems operating at slopes result in different operating points due to static head changes. A VSD can be used to deliver the exact flow rate and pressure of each operating point. Without the use of a VSD the desired flow rate and pressure can be obtained through the use of a throttle valve which result in lower efficiency and higher energy costs. The use of a VSD result in lower energy costs due to higher efficiencies and lower pressure requirements. However, a proper analysis needs to be done before installing a VSD on an irrigation system to calculate the economic benefit of a VSD since the investment costs of a VSD needs to be taken into consideration.

This case study for hypothetical pivots illustrates the economic benefit that can be obtained through the use of a VSD for irrigation systems operating at different slopes. Figure 5.4 and Figure 5.5 illustrate an example of applying a method to calculate the economic benefit from using a VSD.

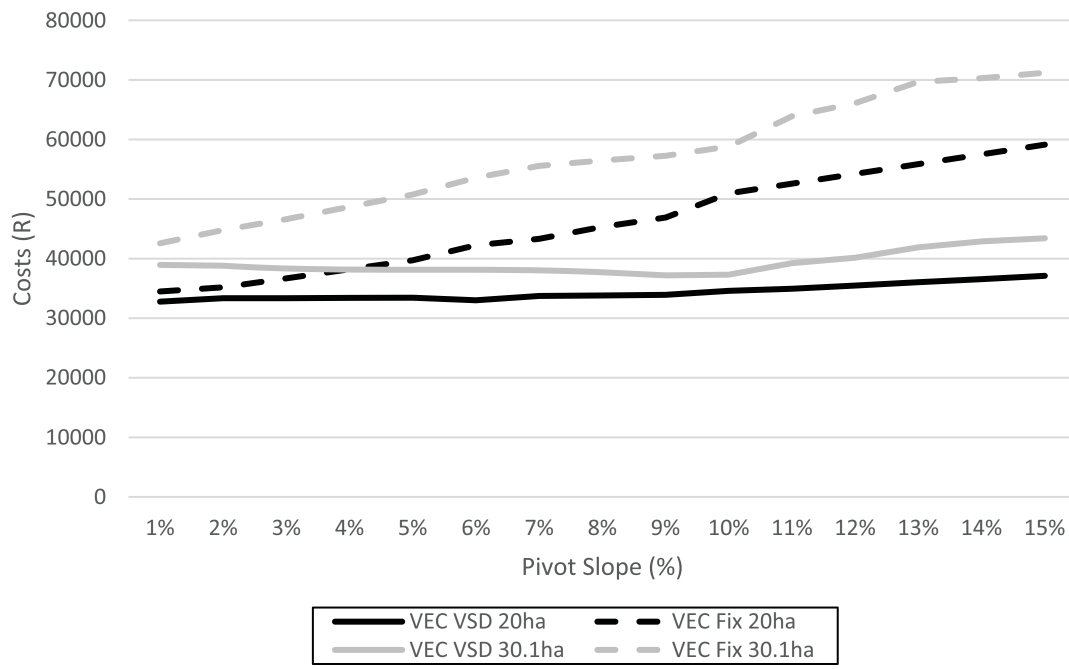

Figure 5. 4: Variable electricity costs of a variable speed drive and a fix speed pump for a 20ha and a 30.1ha centre pivot operating at slopes ranging from 1% to 15%

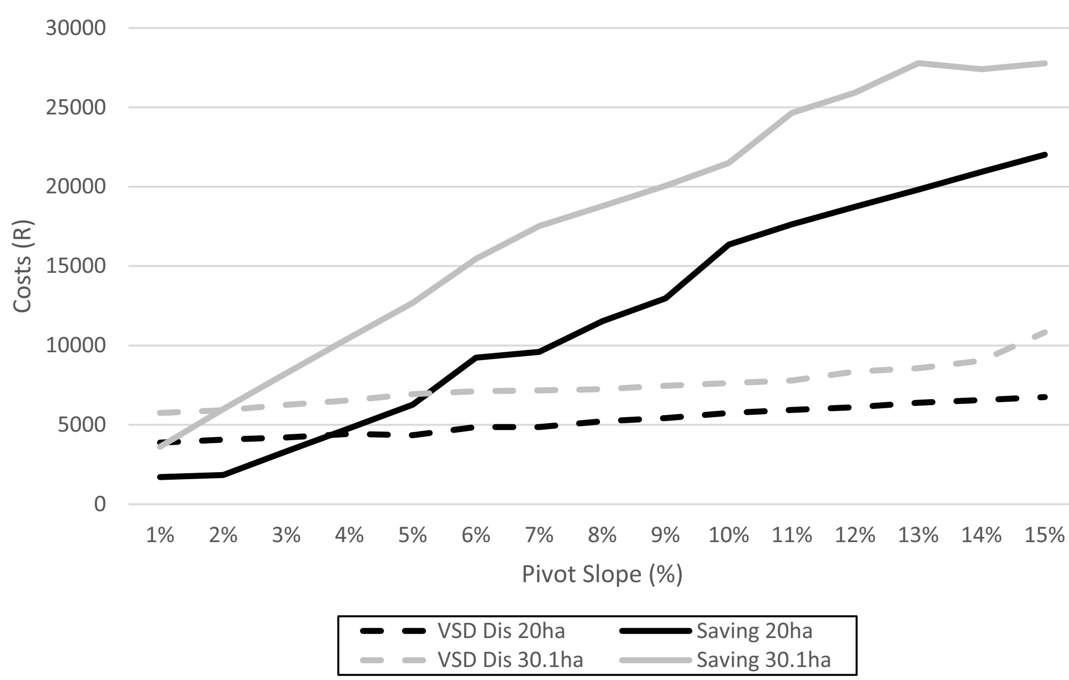

Figure 5. 5: Discounted variable speed drive investment costs and the energy saving costs for a 20ha and a 30.1ha centre pivot operating at slopes ranging from 1% to 15%

Figure 5.4 illustrate variable electricity costs for using a VSD and a fix speed pump for a 20ha and 30.1ha centre pivot operating at a slope ranging from 1% to 15%. Variable electricity costs using a VSD is lower than using a fix speed pump irrespective of the slope of the centre pivot. The use of a VSD result in higher efficiencies at a specific operating point which result in lower kilowatt usage and therefore lower variable electricity costs. Although lower variable electricity is realized from using a VSD it is important to compare the saving in electricity costs to the discounted cost of a VSD. Figure 5.5 illustrate the discounted VSD investment costs and energy savings for a 20ha and 30.1ha centre pivot operating at a slope ranging from 1% to 15%.

The economic benefit from a VSD is only realized from a slope higher than 4% for a 20ha centre pivot and 2% for a 30.1ha centre pivot. The static head at a 4% slope on a 20ha centre pivot is 30.08m and at a slope of 2% on a 30.1ha 26.192m. The static head is calculated from the pump to the highest operating point of the centre pivot. Thus, the breakeven static head for using a VSD depends on the size of the pivot since the length of the pivot will determine the static head at the highest operating point. The highest operating point will determine the choice of the pump which will determine the kilowatt requirement of the irrigation system and thus the investment cost of the VSD. Furthermore, the factors that influence the variable electricity costs will also determine the economic benefit of a VSD since energy savings is calculated from variable electricity costs. Factors that influence variable electricity costs differ between irrigation systems. The conclusion is that every irrigation system is unique and needs to be evaluated individually since various factors will have an influence on the economic benefit of a VSD. These factors include the following:

- Static head
- Operating pressure
- Pipe diameter (friction)
- Flow rate (irrigation system capacity)
- Type of pump and motors (manufacturer)
- Efficiency of pump and motors
- Field size
- Management
- Electricity tariff choice

5.3 STATIC SYSTEMS

Static irrigation systems such as sprinkler and micro irrigation differ from centre pivots in both lay-out and management. The effect of block-based lay-outs and differences in scheduling approaches was investigated through 3 case studies on sprinkler, drip and micro-sprinkler irrigation systems. All three case studies is based on sugarcane at Pongola.

5.3.1 *CASE STUDY S1: SPRINKLER IRRIGATION SYSTEM*

This case study was done on a sprinkler irrigation system (semi-solid set). The size of the sprinkler irrigation system is 22.26 ha. The growing period starts 1 November and the length of the growing period is twelve months. The gross application rate is 5 mm/day with an application efficiency of 75%. A limitation of 18 hours per day and no irrigation on Sundays are applicable for the irrigation system.

The lay-out of the system is shown in Figure 5.6. Water is pumped from the river into a central mainline, from which laterals branch off to both the left and right side. The elevation change over the length of the mainline from the river to the highest point is 26m.

Figure 5. 6: Lay-out of the sprinkler irrigation system

The study was done for Ruraflex and Landrate. Table 5.11 show the system parameters for the sprinkler irrigation system.

Table 5. 11: System parameters for a sprinkler irrigation system

Pressure required at pump: Valve inlet pressure = 52m Elevation difference = 25.59m Mainline head loss = 6.32m Secondary losses = 7.2m Safety factor = 5%		96m
Flow required at pump: Including 10% safety factor		130 m^3/h
Output power (required by pump)		47 kW
Power factor (cos φ)		0.87
Motor efficiency		92%
Input power (drawn from transformer)		51.1 kW
Apparent power		85.7 kVA
Reactive power		28.9 kVAr
Irrigation scheduling:	Net Irrigation Requirement per month (mm)	Irrigation hours required per month:
Nov	35	93
Dec	66	176
Jan	93	248
Feb	90	240
Mar	73	195
Apr	56	149
May	54	144
June	49	131
Jul	55	147
Aug	65	173
Sept	71	189
Oct	73	195
Total	780	2080

The results of modelling the situation while operated under Landrate and Ruraflex are shown in table 5.12. The total electricity costs for Ruraflex is R 96 513 for the whole season compared to R 130 008 for Landrate. Thus the producer can save R 33 495 per year on 22.26ha simply by using Ruraflex instead of Landrate.

Table 5. 12: Kilowatt requirement and electricity costs for Landrate and Ruraflex for a 22.26 ha sprinkler irrigation system

	Landrate	Ruraflex
Motor input power, kW	51.1	51.1
Energy consumption, kWh	106237	106237
Variable electricity costs, R	110433	75470
R/ha	4961	3390
R/mm	4.09	2.79
R/kWh	1.04	0.71
Total electricity costs, R	130008	96513
R/kWh	1.22	0.91
kW/ha	2.30	2.30

5.3.2 CASE STUDY S2: DRIP IRRIGATION SYSTEM

The case study include a drip irrigation system. The intention was to evaluate the electricity savings between a sprinkler and drip system for the same situation. Landrate and Ruraflex was also compared, both with and without VSDs. The size of the field is 22.26 ha. The growing period start the 1st of November at last 12 months. The gross application rate of the drip irrigation system is 1.3 mm/h with an application rate of 95%. A limitation of maximum of 15 hours per day are applicable to the system and it is possible to irrigate seven days per week. The system parameters for a drip irrigation system without a VSD and with a VSD are shown in table 5.13 and table 5.14, respectively.

Table 5. 13: System parameters for a drip irrigation system without a VSD

Pressure required at pump: Valve inlet pressure = 20m Elevation difference = 25.24m Mainline head loss = 10.37m Secondary losses = 6.14m Safety factor = 5%		65m
Flow required at pump: Including 10% safety factor		106 m^3/h
Output power (required by pump)		26 kW
Power factor (cos φ)		0.8
Motor efficiency		90%
Input power (drawn from transformer)		28.9 kW
Apparent power		36.1 kVA
Reactive power		21.6 kVAr
Irrigation scheduling:	Net Irrigation Requirement per month (mm)	Irrigation hours required per month:
Nov	35	60
Dec	66	114
Jan	93	161
Feb	90	156
Mar	73	126
Apr	56	97
May	54	93
June	49	85
Jul	55	95
Aug	65	112
Sept	71	123
Oct	73	126
Total	780	1348

Table 5. 14: System parameters for a drip irrigation system with a VSD

	Setpoint 1	Setpoint 2	Setpoint 3
Pressure required at pump: (m)	55	60	65
Flow required at pump: (m3/h)	95	97	106
Pump efficiency (%)	70.5	71	72
Output power (required by pump)	20.3	22.4	26.1
Power factor (cos φ)	0.99	0.99	0.99
Motor efficiency	90%	90%	90%
Frequency (Hz)	46	48	50
Motor speed (rpm)	2668	2784	2900
Input power (drawn from transformer)	22.6	24.9	29.0
Apparent power	22.8	25.1	29.3
Reactive power	3.0	3.3	3.9
Irrigation hours required per month:			
Nov	20	20	20
Dec	38	38	38
Jan	54	54	54
Feb	52	52	52
Mar	42	42	42
Apr	32	32	32
May	31	31	31
June	28	28	28
Jul	32	32	32
Aug	37	37	37
Sept	41	41	41
Oct	42	42	42

The lay-out of the blocks is shown in Figure 5.7. Laterals of all the blocks run roughly east-west (parallel to the mainline cutting across the area). The area is divided into six blocks which are irrigated in three shifts (according to the colours shown in the lay-out).

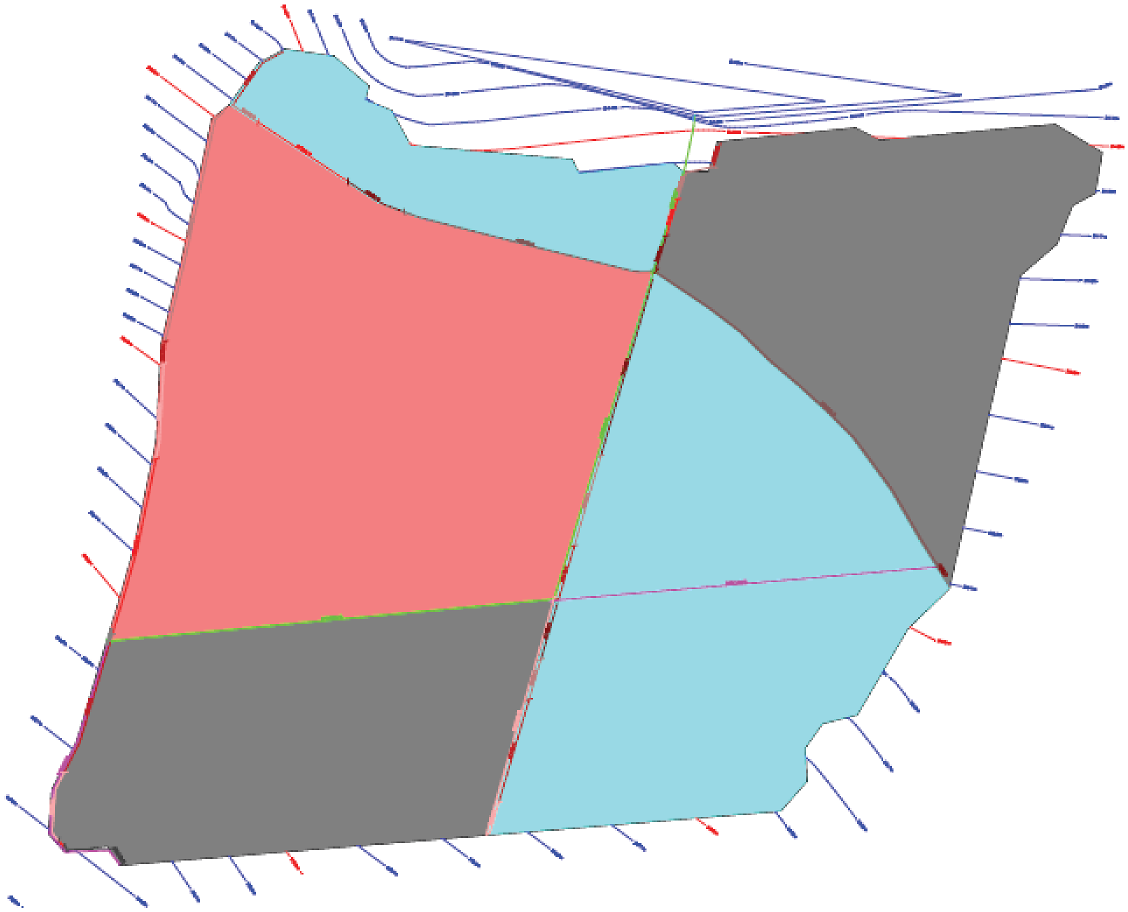

Figure 5. 7: Lay-out of the drip irrigation system

The results of modelling the different scenarios are shown in Table 5.15, and indicate that the producer will save electricity costs if using Ruraflex. Furthermore, if a VSD is fitted to the motor, another R 4000 per year can be saved with the current block lay-out and allocation to shifts. On a 30 kW motor the cost of the VSD will be between R 30 000 and R 40 000 – to justify this investment cost, the rate of return may have to be better and this could possibly be achieved through a more careful lay-out of the system and placement of the block valves.

Table 5. 15: Kilowatt requirement and electricity costs for a drip irrigation system with a VSD and without a VSD for Ruraflex and Landrate

	No VSD		VSD	
	Landrate	Ruraflex	Landrate	Ruraflex
Motor input power, kW	28.9	28.9	25.5	25.5
Energy consumption, kWh	38957	38957	34349	34349
Variable electricity costs, R	40496	23466	35705	20759
R/ha	1819	1054	1604	933
R/mm	2.83	1.64	2.67	1.55
R/kWh	1.04	0.60	1.04	0.60
Total electricity costs, R	60071	36301	55280	32288
R/kWh	1.54	0.93	1.61	0.94
kW/ha	1.30	1.30	1.15	1.15

5.3.3 *CASE STUDY S3: MICRO - SPRINKLER IRRIGATION SYSTEM*

The case study was done on a micro-sprinkler irrigation system for avocados in the Limpopo province. It was used to illustrate electricity costs for both Landrate and Ruraflex, for a system with and without a VSD. The field size is 18.83 ha and the growing period start on the 1st of April and lasts 12 months. The gross application rate of the micro – sprinkler irrigation system is 5.5 mm/h with an application rate of 85%. A limitation of maximum 18 hours per day are applicable and irrigation can take place seven days per week. Table 5.16 and table 5.17 represent the system parameters for a micro – sprinkler irrigation system without a VSD and with a VSD, respectively.

Table 5. 16: System parameters for a micro – sprinkler irrigation system without a VSD

<table>
<tr><td colspan="2">Pressure required at pump:
Valve inlet pressure = 20m
Elevation difference = 25.24m
Mainline head loss = 10.37m
Secondary losses = 6.14m
Safety factor = 5%</td><td>72m</td></tr>
<tr><td colspan="2">Flow required at pump:
Including 10% safety factor</td><td>87 m^3/h</td></tr>
<tr><td colspan="2">Output power (required by pump)</td><td>24 kW</td></tr>
<tr><td colspan="2">Power factor (cos φ)</td><td>0.8</td></tr>
<tr><td colspan="2">Motor efficiency</td><td>90%</td></tr>
<tr><td colspan="2">Input power (drawn from transformer)</td><td>26.7 kW</td></tr>
<tr><td colspan="2">Apparent power</td><td>33.3 kVA</td></tr>
<tr><td colspan="2">Reactive power</td><td>19.9 kVAr</td></tr>
<tr><td>Irrigation scheduling:</td><td>Net irrigation requirement per month, mm</td><td>Irrigation hours required per month:</td></tr>
<tr><td>Apr</td><td>42</td><td>245</td></tr>
<tr><td>May</td><td>43</td><td>249</td></tr>
<tr><td>Jun</td><td>37</td><td>211</td></tr>
<tr><td>Jul</td><td>41</td><td>238</td></tr>
<tr><td>Aug</td><td>50</td><td>290</td></tr>
<tr><td>Sept</td><td>61</td><td>351</td></tr>
<tr><td>Okt</td><td>57</td><td>329</td></tr>
<tr><td>Nov</td><td>60</td><td>346</td></tr>
<tr><td>Des</td><td>67</td><td>387</td></tr>
<tr><td>Jan</td><td>36</td><td>205</td></tr>
<tr><td>Feb</td><td>12</td><td>70</td></tr>
<tr><td>Mar</td><td>17</td><td>99</td></tr>
<tr><td></td><td>524</td><td>3020</td></tr>
</table>

Table 5. 17: System parameters for a micro – sprinkler irrigation system with a VSD

	Setpoint 1	Setpoint 2	Setpoint 3	Setpoint 4	Setpoint 5	Setpoint 6	Setpoint 7	Setpoint 8
Flow required at pump: (m3/h)	62.81	87.13	67.78	86.42	85.81	77.70	84.10	83.24
Pressure required at pump:(m)	72	72	70	66	59	64	54	56
Pump efficiency (%)	63	70.5	68	70.5	70.5	69	68	70
Output power (required by pump, kW)	19.56	24.25	19.01	22.05	19.57	19.64	18.20	18.15
Power factor (cos φ)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Motor efficiency	90%	90%	90%	90%	90%	90%	90%	90%
Frequency (Hz)	50	50	49	48	45	47	43	44
Motor speed (rpm)	2900	2900	2859	2777	2625	2734	2511	2558
Input power (from transformer, kW)	21.7	26.9	21.1	24.5	21.7	21.8	20.2	20.2
Apparent power (kVA)	27.2	33.7	26.4	30.6	27.2	27.3	25.3	25.2
Reactive power (kVAr)	16.2	20.1	15.8	18.3	16.2	16.3	15.1	15.0
Transformer size	40 kVA							
Irrigation hours required per month:								
Apr	31	31	31	31	31	31	31	31
May	31	31	31	31	31	31	31	31
Jun	26	26	26	26	26	26	26	26
Jul	30	30	30	30	30	30	30	30
Aug	36	36	36	36	36	36	36	36
Sept	44	44	44	44	44	44	44	44
Okt	41	41	41	41	41	41	41	41
Nov	43	43	43	43	43	43	43	43
Des	48	48	48	48	48	48	48	48
Jan	26	26	26	26	26	26	26	26
Feb	9	9	9	9	9	9	9	9
Mar	12	12	12	12	12	12	12	12

The lay-out of the system is shown in Figure 5.8. Laterals run north-south (the preferred planting direction of the crop), and the area is divided into nine blocks. The two small blocks at the top are irrigated simultaneously, while the other blocks are all irrigated one at a time (therefore eight shifts). Water is pumped from the river to the blocks, with the highest valve being located 40 m above the river.

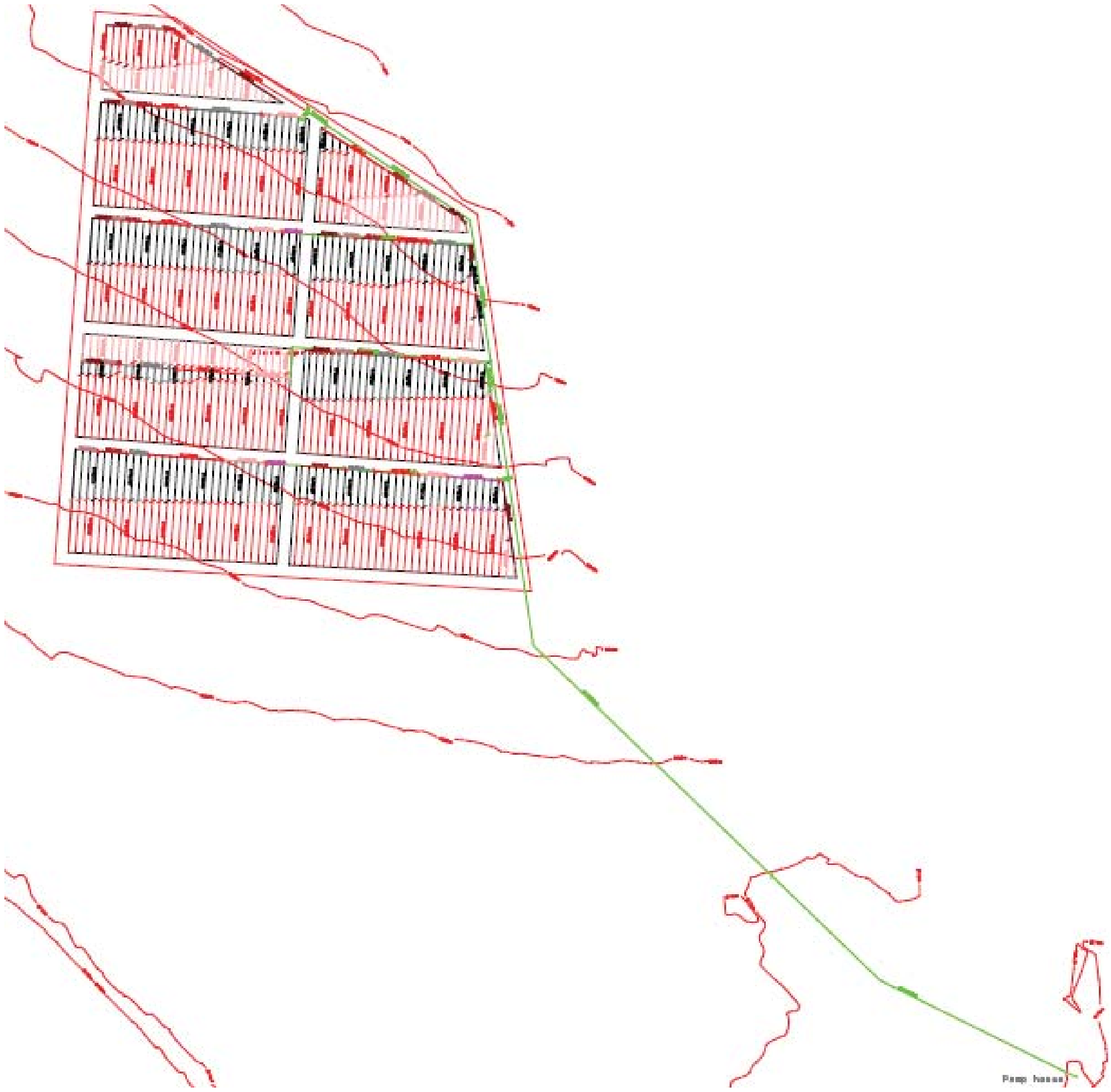

Figure 5. 8: Lay-out of the micro – sprinkler irrigation system

The results of modelling the different scenarios are shown in Table 5.18. The results yet again confirm that the largest amount of savings can be achieved through using Ruraflex instead of Landrate. In this case, the use of a VSD (which will cost the producer between R 30 000 and R 40 000 for the 30 kW motor) could reduce the electricity costs by R 9 000 per year, which means that the producer could recover the cost of his investment after about 3 years.

Table 5. 18: **Kilowatt requirement and electricity costs for a micro-sprinkler irrigation system without a VSD and with a VSD for Landrate and Ruraflex**

	No VSD		VSD	
	Landrate	Ruraflex	Landrate	Ruraflex
Motor input power, kW	26.7	26.7	22.2625	22.2625
Energy consumption, kWh	80527	80527	67144	67144
Variable electricity costs, R	83708	49633	69796	41581
R/ha	4445	2636	3707	2208
R/mm	3.19	1.89	2.92	1.74
R/kWh	1.04	0.62	1.04	0.62
Total electricity costs, R	103283	62005	89371	53054
R/kWh	1.28	0.77	1.33	0.79
kW/ha	1.42	1.42	1.18	1.18

5.3.4 *CASE STUDY S4: MICRO - SPRINKLER IRRIGATION SYSTEM WITH OPTIMISED MAINLINE*

The case study uses the data and layout of the mainline of case study S3 to show the impact of optimising the pipe diameters on electricity costs. The results of the analyses are shown in Table 5.19. The results were generated without the consideration of a VSD.

Table 5. 19: **Optimised kilowatt requirement and electricity costs for a micro-sprinkler irrigation system without a VSD for Landrate and Ruraflex**

	Landrate	Ruraflex
Motor input power, kW	25.83	26.58
Energy consumption, kWh	77893	80180
Variable electricity costs, R	80969	49419
R/ha	4300	2624
R/mm	3.09	1.88
R/kWh	1.04	0.62
Total electricity costs, R	100544	61780
R/kWh	1.29	0.77
kW/ha	1.37	1.41
Initial pipe costs, R	222037	157776

The optimisation results for Ruraflex show a very close resemblance with the results obtained for Ruraflex in case study S3 because the difference in the motor input requirement is only 0.12 kW less. As a result the difference in total electricity costs is only R225. The optimised electricity costs for Landrate is also comparable to case study S3, however, the total electricity costs is R2739 less when compared to the results for Landrate in case study S3. The main reason why the input kilowatt requirement and therefore the electricity costs for case study S4 is less is because it is optimal to increase the pipe diameters of the mainline in order to decrease variable electricity costs low. The decrease in variable electricity costs, however, comes at an increase in initial pipe investment costs that is R 64 261 higher when compared to the mainline design when using Ruraflex to optimise the mainline pipe diameters. The higher electricity tariff associated with Landrate justifies the higher investment costs to reduce electricity costs in the long-run.

Chapter 6

GUIDELINES FOR FARMER ADVISORY SERVICES FOR IMPROVED ELECTRICITY COST MANAGEMENT

6.1 INTRODUCTION

The amount of energy, usually in the form of electricity, used by an irrigation system is the direct result of decisions made during the planning, design and implementation of the system.

These decisions include the application of design norms, the selection of reliable equipment, the installation of the system according to plan, as well as the efficient management and maintenance of such a system by the producer.

It is disconcerting how many producers select a new irrigation system solely on the grounds of its capital costs and not according to the design specifications and running costs. Producers should be more aware of the irrigation development process and how the decisions made influence the running costs of the system. This section is based on guidelines provided in the ARC's Manual for the Evaluation of Irrigation Systems (Koegelenberg and Breedt, 2002).

The development process for an irrigation system should include the following steps:

- The client (producer) decides to develop an irrigation system.
- The producer determines the design specifications by means of multi-disciplinary cooperation for the required irrigation system and decides on a designer. These specifications should include:
    - Climatic requirements (to determine the peak irrigation requirement)
    - Managerial requirements (such as hours available for irrigation and labour limitations)
    - Crop information (type, cultivar, planting date, planting density / spacing, etc.)
    - Soil information (type, depth, water holding capacity, infiltration rate, etc.)
- The designer does a feasibility study for the proposed crop and irrigation system.
- Preliminary costs of the irrigation system are presented to the producer in a preliminary technical report, which forms part of the feasibility study (This study can be extended to include a master plan, where development will take place inn more than one phase).
- The feasibility study is used to apply for finance.

- If the finance has been arranged, the designer can continue with a detailed design. The first step of design is the compilation of a design report. This design report includes the scheduling planning, detail design, plans and costing.
- The design report is discussed with the client (producer) and if accepted, the client will purchase and install the equipment.
- After installation, any deviations from the design made during the installation are noted and attached to the design report.
- An evaluation is done at strategic places in the irrigation system to determine whether the system was installed according to the specifications in the design report and whether the pressure, delivery and water distribution of the system is correct.
- If the evaluation shows any problems, it is recommended that a detail evaluation is executed and the solutions for the problems which occur are reported to the producer.

For smaller developments, the preliminary technical report and design report can be combined.

6.2 INFORMATION THAT MUST BE PROVIDED BY THE IRRIGATION CONSULTANT TO THE PRODUCER

It is disconcerting that many producers are not aware of the requirements which have to be met when an irrigation consultant makes a presentation for the design of an irrigation system. The idea is not that the producer should be an expert in the field of irrigation, but that he/she should ask the relevant questions to ensure that he/she is aware of the design specifications of the system which will enable him/her to install the irrigation system correctly.

If the producer has the need to have the design evaluated theoretically, it is suggested that an independent irrigation expert be approached for the evaluation of the design according to relevant design norms for irrigation systems. The South African Irrigation Institute (SABI) is the custodian of irrigation design norms in South Africa, and SABI Approved Designers have passed a written exam on irrigation design practices and the design norms. More information on the norms and Approved Designers is available on SABI's website – www.sabi.co.za.

It is highly recommended that irrigation designer charge a design fee and if so, the producer should insist that the following information appears in the design report:

- SABI peak design form

This is a concise form containing all the technical design specifications that the design meets. The producer can use this information to decide if the design satisfies the set design specifications.

- Final technical report

This report describes the resources that form part of the irrigation development as well as a short description of the operation of the irrigation system.

- Pump curve

The pump curve on which the duty point(s) are indicated is used to easily read off the efficiency and power requirement of the pump. The pump curve is also needed in case the existing irrigation scheme is expanded in the future.

- Layout plan

This should comprise of the layout of the irrigation system and mainline, and detailed plans of each block in the case of permanent irrigation systems. Two copies are required, one for installation purposes and one for the producer's records.

- Detailed drawings of equipment to make installation easier, including:
    - Valve connections: Drawings of the valves with the desired accessories.
    - Filter banks: Drawings of the complete filter installation with manifolds and valves.
    - Pumps: Drawings of the pump station lay-out with necessary equipment.

- Maintenance and management manuals

A thorough manual is required to ensure that the performance of the installed irrigation system is not adversely affected by incorrect practices.

- List of quantities

A list of the items required for each block is needed so that quotations can be obtained from irrigation equipment suppliers. The list of quantities can also be used as a checklist for the equipment that is delivered by the irrigation equipment supplier.

- Cost estimation

An estimate of the cost for the whole project must be made and for each phase, if applicable. This should include capital as well as running costs.

It is suggested that all this information is placed in a file to keep it for the future. The name of the producer, system name or number and contact details of the designer can be displayed on the cover of the file.

6.3 INTERPRETATION OF THE DESIGN REPORT

It is important that the designer discusses the design with the producer to make him aware of the specifications that the proposed irrigation system design satisfies. The questions that need to be answered will depend on the specific irrigation system and the answers will, in the most cases, be answered in the final technical report.

The producer should ask the following general questions and answers should be contained in the design report:

Table 6. 1: Questions to be ask by the producer to the designer

Subject	Question	Where in design report can answer be found
Expertise level of designer	What is the expertise level of the designer, eg. Is the designer an approved SABI designer, or a professional registered engineer/ technician?	Peak design form Title block of the lay-out plan
General system information	What is the expected lifespan of the system? What safety factors are built into the system? Is expansion of the system possible? What assumptions were made regarding equipment and resources available on the farm?	Technical report
Description of proposed irrigation system	What are the soil water characteristics of the soil to be irrigated? What type of irrigation systems are used for the irrigation of the different crops? What type of emitter is proposed and what is its recommended working pressure, spacing and discharge?	Technical report

Subject	Question	Where in design report can answer be found
	What is the capacity and quality of the water source available for the development? Is the water suitable for irrigation of the specific crop?	
Design parameters	What design parameters were used to size the different pipes in the system? What is the flow velocity in the main line? What is the recommended working pressure at the block inlet? What are the design CU / DU_{lq} /EU? Is the gross application rate of the system less than the infiltration rate of the soil?	Peak design form, technical report
Scheduling planning	How much easily available water is available in the root zone? What is the irrigation requirement of the different crops to be irrigated? What is the cycle length and standing/revolution time of the system? For which Eskom tariff plan was the design done? What is the system capacity (mm/day) and how does it compare with the crop's peak water requirement?	Peak design form, technical report
Equipment	Is a pump curve provided on which the duty point is indicated? How long is the pumping time within the Eskom peak tariff time? What is the energy cost per year? Is filtration necessary and if so, what type is provided?	Technical report

Subject	Question	Where in design report can answer be found
	Are injection pumps provided and if so, what is the capacity thereof? Is a flow meter provided and what are the requirements for its installation? Has provision been made for sufficient air inlet and outlet valves in the system? Is water hammer a problem and what can be done to prevent it?	
Guarantees	What are the guarantees of the individual components of the system and what is included and excluded? What is the guarantee that the system will function according to the design parameters? What is the availability of the proposed irrigation equipment when faulty equipment has to be replaced? What is the easily available water in the effective root area? Who and how will it be determined whether the system complies with the design specifications - e.g. how can it be evaluated? What equipment should be kept as emergency equipment? Is a written agreement provided in which it is confirmed that the system conforms to the SABI norms and if not, where do deviations occur?	Technical report

6.4 DECISIONS DIRECTLY INFLUENCING ELECTRICITY COSTS

The points discussed in the above sections concern irrigation systems in general. The 7 points discussed below, focus on the decisions which have a direct effect on electricity costs. Producers should also refer to the guidelines for irrigation system designers (Appendix A of this report), which contains more technical specifications for irrigation systems.

6.4.1 TYPE OF ELECTRICITY TARIFF PLAN USED (RURAFLEX OR LANDRATE)

Ruraflex is more profitable than Landrate irrespective of system size and irrigation system delivery capacity since all the irrigation systems included in the analyses resulted in higher net present values using Ruraflex which is a direct result of lower electricity costs associated with Ruraflex. An important observation is also that the total annual fixed cost charge for Landrate is consistently higher than the annual fixed cost charge of Ruraflex, and that savings can be achieved through careful planning of electricity supply points' sizes and locations. Altering the maximum notified demand should be carefully considered as penalties apply if the maximum notified demand is exceeded.

6.4.2 OPERATING HOURS AVAILABLE PER DAY FOR IRRIGATION

The timing of irrigation is of utmost importance since it has a direct effect on electricity costs and crop yield. Profitability of Ruraflex is closely related to the irrigation scheduling practices. Careful consideration of the irrigation system design and irrigation scheduling practices is necessary. However, the assumption made by various researchers and irrigation designers that all available off-peak hours will be used first before irrigation will take place in more expensive time-of-use timeslots is void by the fact that the water budget and the status of the crop will determine irrigation timing and amounts. During peak irrigation demand periods, the value of the marginal product is much higher than the marginal factor cost of applying irrigation water, therefore it is profitable to irrigate during peak timeslots.

6.4.3 DESIGN CAPACITY OF THE SYSTEM (MM/DAY)

Smaller delivery capacities proved to be the most profitable for all the system sizes and electricity tariff structures investigated, as higher flow rates increased the energy demand. This increase in kW demand had a greater impact on the energy cost than the decrease in irrigation hours resulting from high system capacities. The conclusion is that careful consideration of the economics is necessary since smaller delivery capacities require much more intensive management, because longer irrigation hours are needed in order to avoid a decrease in crop yield.

6.4.4 SYSTEM SIZE (AREA)

Larger irrigation systems resulted in higher NPVs per hectare compared to the smaller systems because as the irrigated area increases, the total investment costs per hectare decrease since the total investment costs are divided by a larger number (of hectares).

However, making irrigation system investment decisions on investment cost only is flawed as the variable electricity costs may outweigh the investment costs when considering the life cycle of the investment. Incurred variable electricity costs are very much situation dependant. Investors in irrigation systems should require form their supplier to provide an estimate of variable electricity costs together with the investment costs.

6.4.5 MAIN PIPELINE SIZING

It is recommended that all irrigation designs are undertaken by a SABI approved irrigation designer or suitably qualified engineer, technologist or technician. The friction loss gradient provides a quick means of evaluating pipe diameter. Friction loss gradient should be less than 0.6%. A well-managed Ruraflex tariff plan will result in a lower average electricity charge per kWh which economically justifies the use of smaller diameter pipes resulting in lower capital costs in addition to lower electricity costs.

6.4.6 USE OF VARIABLE SPEED DRIVE TECHNOLOGY

VSD technology provides a powerful means of correcting irrigation system design inefficiencies which cannot be addressed by hydraulic design. See Appendix A for an applied procedure to evaluate the feasibility of a VSD.

Every irrigation system is unique and needs to be evaluated individually since various factors will have an influence on the economic benefit of a VSD. Systems where the duty points vary because of elevations differences between delivery points will benefit the most. These include centre pivots operating against slopes greater than 2% and static irrigation systems where block inlets are located at different elevations.

VSD technology will increase the power factor of the motor resulting in less reactive energy being used. Only good quality VSD’s with appropriate harmonic filters should be installed. Failure to do so may reduce the power factor due to harmonics resulting more reactive power being used.

6.4.7 OPERATION AND MAINTENANCE

Irrigation systems should be operated at the correct pressure – pressures higher than the minimum requirements increases the power (kW) demand and thereby increases electricity costs, while pressures below the design requirements necessitates longer irrigation hours which will also increase electricity consumption and therefore costs.

Irrigation systems need to be maintained properly in order to ensure water is applied at an acceptable uniformity – lower uniformities necessitates more irrigation to ensure that the whole field receives enough water to maintain high crop yields. Consequently more irrigation hours are required, which increase electricity costs.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

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However, making irrigation system investment decisions on investment cost only is flawed as the variable electricity costs may outweigh the investment costs when considering the life cycle of the investment. Incurred variable electricity costs are very much situation dependant. Investors in irrigation systems should require form their supplier to provide an estimate of variable electricity costs together with the investment costs.

7.1.5 MAIN PIPELINE SIZING

It is recommended that all irrigation designs are undertaken by a SABI approved irrigation designer or suitably qualified engineer, technologist or technician. The friction loss gradient provides a quick means of evaluating pipe diameter and systems with a friction loss gradient of 0.6% or less are the most economical solutions overall. A well-managed Ruraflex tariff plan will result in a lower average electricity charge per kWh which economically justifies the use of smaller diameter pipes resulting in lower capital costs in addition to lower electricity costs.

7.1.6 USE OF VARIABLE SPEED DRIVE TECHNOLOGY

VSD technology provides a powerful means of correcting irrigation system design inefficiencies which cannot be addressed by hydraulic design.

Every irrigation system is unique and needs to be evaluated individually since various factors will have an influence on the economic benefit of a VSD. Systems where the duty points vary because of elevations differences between delivery points will benefit the most. These include centre pivots operating against slopes greater than 2% and static irrigation systems where block inlets are located at different elevations.

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Irrigation systems should be operated at the correct pressure – pressures higher than the minimum requirements increase the power (kW) demand and thereby increases electricity costs, while pressures below the design requirements necessitates longer irrigation hours which will also increase electricity consumption and therefore costs.

Irrigation systems need to be maintained properly in order to ensure water is applied at an acceptable uniformity – lower uniformities necessitate more irrigation to ensure that the whole field receives enough water to maintain high crop yields. Consequently, more irrigation hours are required, which increase electricity costs.

7.2 RECOMMENDATIONS

7.2.1 IRRIGATION SYSTEM DESIGN CONSIDERATIONS

- It is recommended that the SABI design norm for the maximum allowable friction losses in main pipelines must be reduced from the current 1.5% to 0.7%, to ensure that there is a better balance between investment and operating costs. Lowering the norm will decrease operating costs while increasing the investment costs. However, applying a stricter norm will ensure that pipe diameter is closer to the optimal pipe diameter.

- Irrigation designers should apply economic principles when designing irrigation mainline designs since it will increase the overall profitability of the investment compared to applying the friction percentage design norm. Applying economic principles will automatically differentiate between electricity tariff structures (Ruraflex and Landrate) when designing an irrigation system.

- Irrigation designers should include both the investment costs and an estimate of the operating costs of the irrigation system design in order to allow farmers to make informed decisions.

7.2.2 KNOWLEDGE DISSEMINATION

- It is recommended that a number of knowledge dissemination sessions be held with irrigation designers and water users across the country to inform them of the project outcomes and proposed changes to the irrigation design norms. This can be further supported with popular articles on the project outcomes in relevant magazines.

- It is further recommended that SABI should oversee the development of software to support irrigation designers to apply economic principles when designing irrigation mainlines.

7.2.3 *FUTURE RESEARCH*

- It is recommended that risk is included in the SWIP-E model in order to evaluate the risk associated with smaller irrigation system delivery capacities in combination with load shedding.

- The SWIP-E model can be further expanded to include a combination of irrigation systems, which imply that more than one operating point will exist. Multiple operating points will have an effect on the kilowatt requirement at the pumping station, electricity costs and irrigation water management.

- The model furthermore provides a powerful basis to evaluate the profitability of new technology such as variable speed drives, energy efficient pumps and motors as well as modification of existing irrigation system designs.

- The SWIP-E model provides a powerful basis for crop water use optimisation for a given irrigation system design. The model may prove invaluable in determining the impact of compulsory licensing of agricultural water use on irrigation farming profitability.

- The model could be expanded to include intra-seasonal competing crops, such as maize and groundnuts, which implies that crops will compete for water during a growing season.

- It is recommended that the global optimality of the solutions of the model be tested with a genetic algorithm.

Lastly, it is recommend that the economic benefit of alternative energy sources, such as wind energy, hydroelectricity and solar panels be investigated.

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APPENDIX A

GUIDELINES FOR IRRIGATION SYSTEM DESIGNERS FOR REDUCING ELECTRICITY COSTS

A1. INTRODUCTION

Increasing electricity tariffs have created an awareness of the factors influencing electricity costs. Figure A1 depicts a conceptual framework of variables affecting the life cycle costs of alternative electricity energy management interventions.

The framework was developed using the irrigation planning and design process as the basis to distinguish between strategies that will focus on the demand side, conveyance or at the power supply side. The planning and design process establishes the irrigation technology and also determines the investment or initial costs of the system, as shown in the top part of the framework.

The factors that are found in the top part have a direct influence on the design of the system, and the thereby also a direct effect on the life cycle cost of the irrigation system. The producer must inform the irrigation designer their preferences regarding the following management aspects, which all have cost implications:

- System size (area)
- Quantity and quality of water available
- Type of electricity tariff plan used (Ruraflex or Landrate)
- Operating hours available per week for irrigation
- Scheduling strategy
- Design capacity of the system (mm/day)
- Preferred type of switchgear

Furthermore the producer will have to undertake adequate maintenance to ensure acceptable levels of uniformity and efficiency.

Guidelines for farmer advisory services to provide producers with a better understanding of the cost implications of their decisions were compiled as Appendix B of this project. The aim of this section is to provide the irrigation designer with more information on the effect of the management aspects listed above as well as more technical design aspects on electricity use and costs.

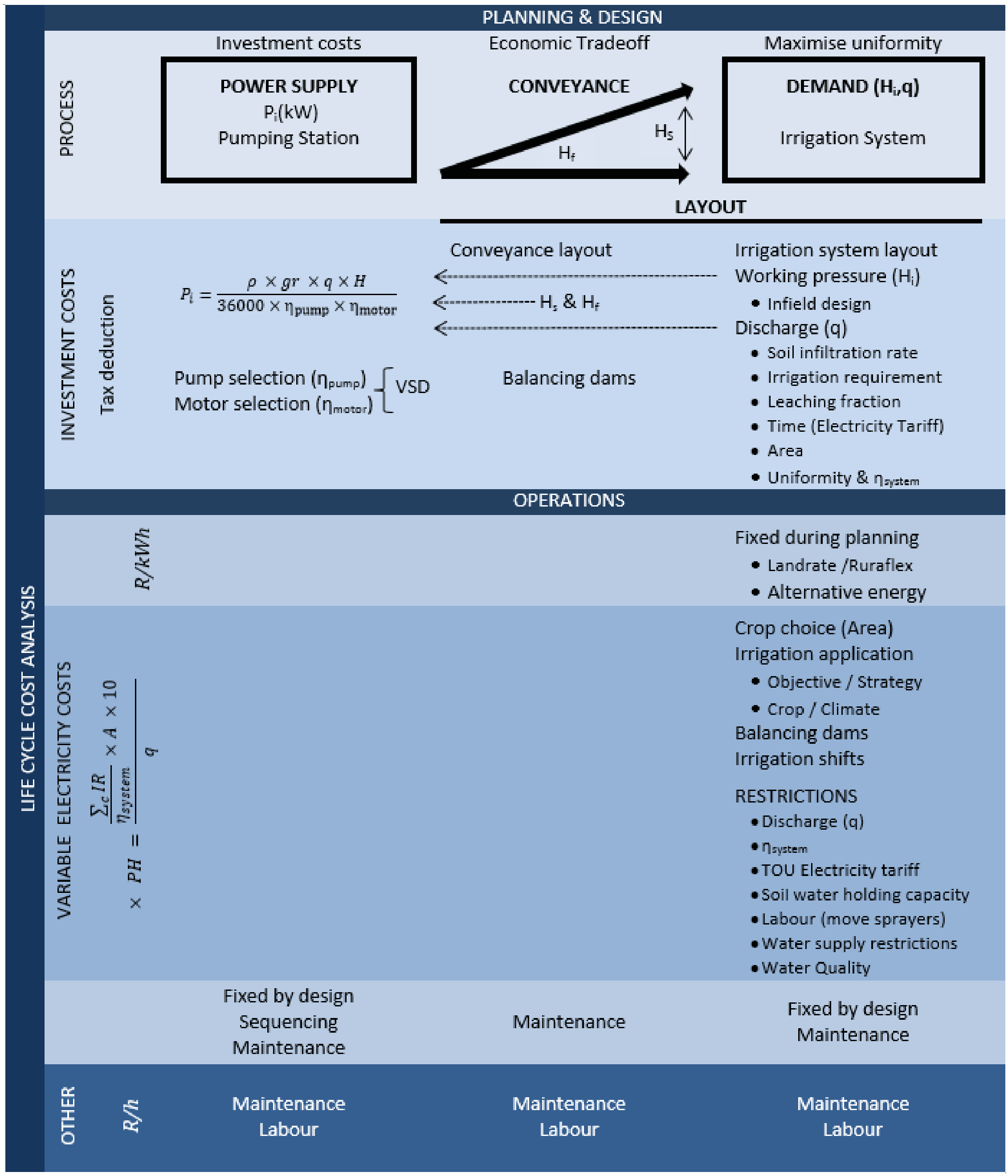


Figure A. 1: Conceptual framework of variables affecting the life cycle costs of alternative electricity energy management interventions

The total electricity costs of an irrigation system comprise of fixed and variable costs. Fixed costs are related to administrative aspects of supply and have to be paid every month irrespective of whether electricity was used or not, while variable costs offer more opportunities for optimisation as it is related to electricity consumption.

Variable electricity cost (VEC) is a function of technology (kilowatt), management (irrigation hours) and the electricity tariff. Equation 49 represents the universal equation to calculate variable electricity cost.

$$VEC = P_i \times PH \times k_e \quad (49)$$

Where:

VEC	Variable electricity costs (R)
P_i	Input power requirement (kW)
PH	Pumping hours (hours)
k_e	Electricity tariff (R/kWh)

TECHNOLOGY: $P = \frac{\rho \times gr\ q \times H}{36000 \times \eta_{\text{pump}} \times \eta_{\text{motor}}}$

P_i	Input power requirement of the electrical motor (kW)
ρ	Constant
gr	Gravity (m/s)
q	Flow rate (m^3/h)
H	Pressure requirement (m)
η_{pump}	Pump efficiency (%)
η_{motor}	Motor efficiency (%)

MANAGEMENT: $PH = \frac{\frac{\sum_c IR}{\eta_{system}} \times A \times 10}{q}$

PH	Pumping hours (hours)
IR	Irrigation requirement for a specific crop (mm)
η_{system}	Irrigation system application efficiency (%)
A	Irrigated area (ha)

TARIFF: k_e Electricity tariff (R/kWh)

Technology, management and electrcity tariffs are the three components that needs to be investigated to manage variable electricity cost. Each of the components is determined from a series of variables that must be determined for a specific situation for which the design is being done. Design norms or standards offer guidance for irrigation designers during this process.

The South African irrigation Institute (SABI) is currently the custodian of the irrigation design norms in South Africa. The norms are published for the general public on SABI's website as well as by the Agricultural Research Council's Institute for Agricultural Engineering in their Irrigation Design Manual (Burger et al., 2003), and covers all the applicable variables in the planning and design of irrigation systems. The origin and relevance of the current norms is reviewed here and benchmarked internationally where applicable.

A norm is defined as a widely accepted or required standard against which performance or achievement can be assessed. The SABI design norms serve to guide the designer in calculations and decision-making in the planning and design of agricultural irrigation systems.

The design of appropriate irrigation systems requires a balanced approach that results in both technically, financially and ethically acceptable solutions for the irrigator. Diverging from the norms is acceptable if it can be well motivated from a both a technical and an ethical perspective by the designer.

The norms are applicable to various components of the irrigation system design process, which is presented graphically in Figure A.1. The process consists roughly of the following phases:

- Irrigation planning
- Infield irrigation system design
- Water supply system design
- Pump station design

The designer takes two distinctly different approaches during the design of the infield and water supply system components of the irrigation system – when designing the infield components, the aim is to achieve a set minimum uniformity of application, while the focus of the supply system design is to convey the water as economically as possible from the source to the infield system, which implies high efficiency should be strived for. All these requirements lead the designer to produce a system that has the minimum power requirement, even though the focus is on water application and financial savings rather than energy management.

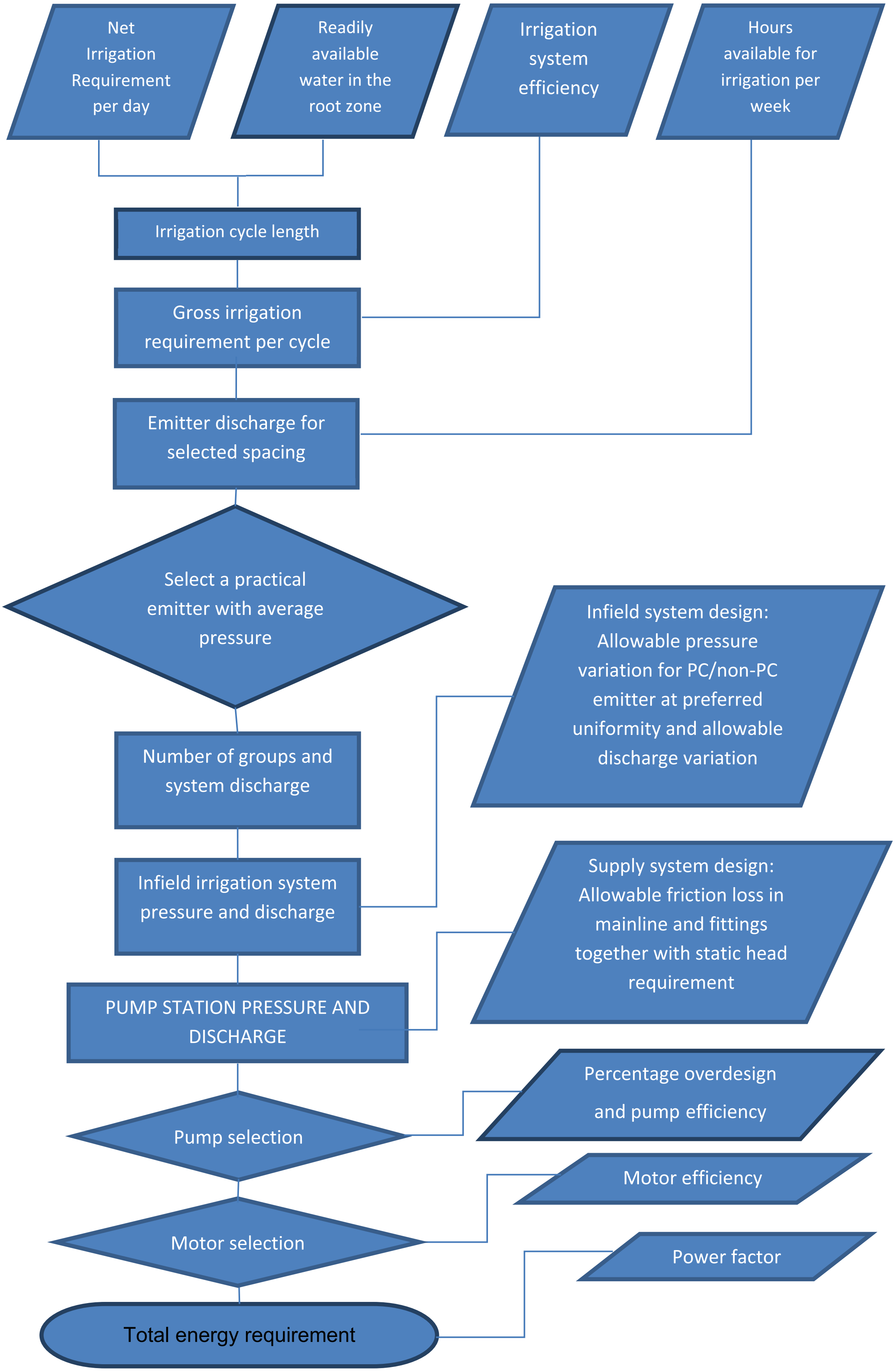


Figure A. 2: Irrigation system design process

The final power requirement of an irrigation system powered by a hydraulic pump and an electrical motor depends on the system discharge and pressure requirement, and pump and motor efficiencies, as defined in Equation 49 above.

The system discharge at the pump, Q_{pump}, depends on the Gross Irrigation Requirement (GIR) of the crop, the area to be irrigated and the time available to apply the irrigation water, which is a management input. The GIR depends on the evapotranspiration of the crop and the effective rainfall, as well the losses that occur under the specific type of irrigation system (Figure A.2).

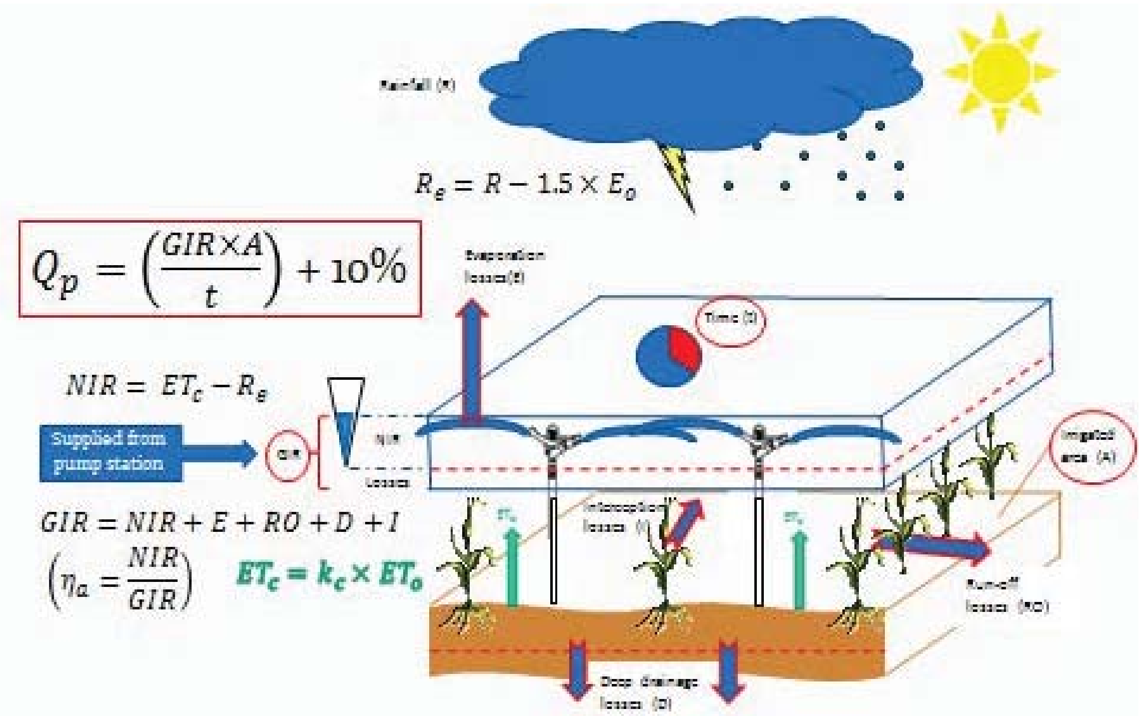


Figure A. 3: Factors influencing the system discharge at the pump station

The pressure required from the pump, H_{pump}, is the sum of the pressure requirement of the in-field system, friction losses in the main line, secondary friction losses in fittings and accessories, elevation difference between the water level at the source and the irrigation system, with a safety factor of 5% applied to the total. This is shown in a diagram in Figure A.3.

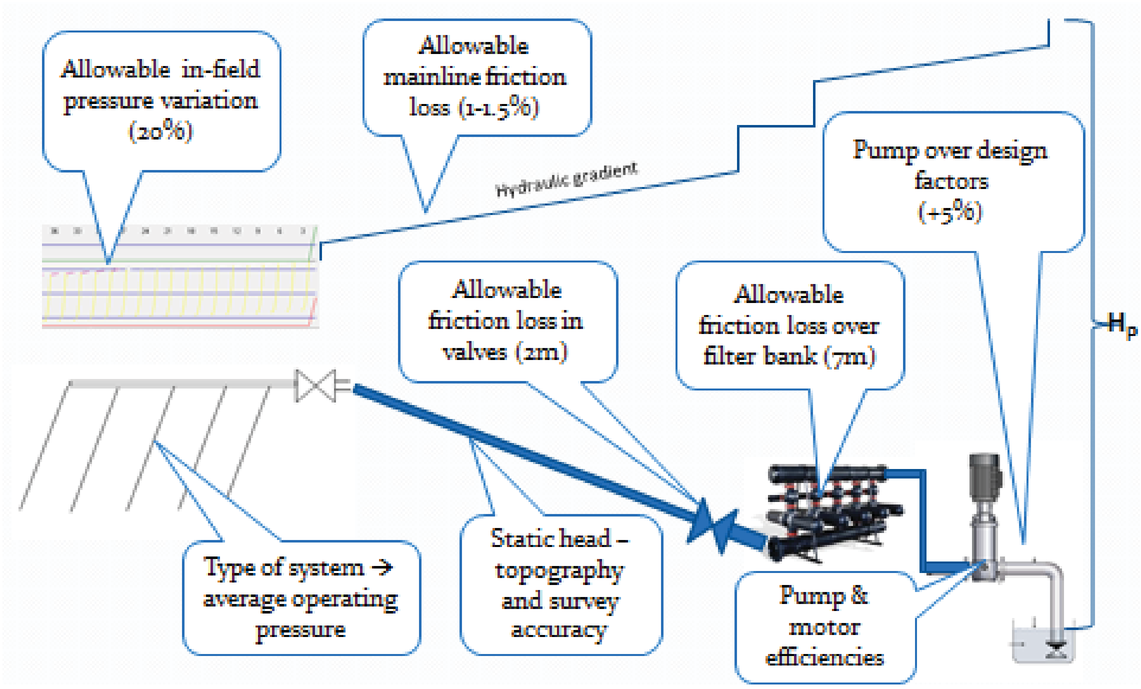


Figure A. 4: Factors influencing the pressure requirement at the pump

The pump and motor efficiencies are taken in consideration when calculating the motor input power, which is the amount of kilowatt the water user will be paying for. Finally the size of the electricity supply point in kilovolt-Ampère (kVA) is determined by applying the power factor (cos φ) of the electrical motor, as shown in Figure A.5.

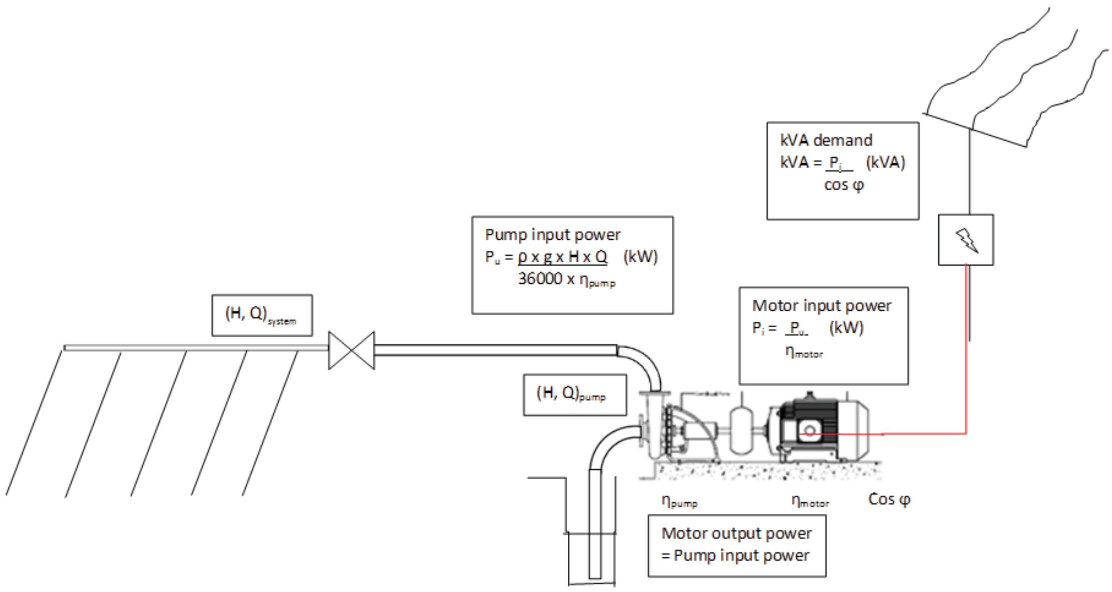


Figure A. 5: Schematic diagram of energy demand at a pump station

The total energy or pumping cost, TEC, is finally calculated as shown in Equation 50:

$$TEC = \sum_{i,t}\left(ta_{i,t} + rc_{i,t} + dc_{i,t}\right) P_i PH_{i,t} + \sum_{i,t} tra_{i,t} kvarPH_{i,t} + fec \quad (20)$$

Where:

$PH_{i,t}$	Pumping hours on day *i* in timeslot *t* (hours)
TEC_c	Total electricity costs for crop *c* (R)
P_i	Input requirement (kW)
$PH_{i,t}$	Pumping hours in timeslot *t* (hours)
$ta_{i,t}$	Active energy charge on day *i* in timeslot *t* (R/kWh)
$tra_{i,t}$	Reactive energy charge on day *i* in timeslot *t* (R/kVARh)
$rc_{i,t}$	Reliable energy charge (R/kWh)
$dc_{i,t}$	Demand energy charge (R/kWh)
$kvar$	Kilovar (kVAR)
fec	Fixed electricity costs (R)

Decisions made during every step of the process will influence the variables contributing to the electricity costs, and the design norms therefore have a direct effect on the power requirement of the system. These norms and the proposed changes are discussed in this section.

A2. SYSTEM DESIGN NORMS

This section presents an overview of the SABI design norms that have an effect on the energy demand of an irrigation system, as defined by the power required to operate the system. According to 2013 data from the Department of Water and Sanitation (Vander Stoep and Tylcoat, 2014), 80.3% of registered irrigation systems in South Africa are pressurized types of irrigation systems (centre pivots, sprinkler, drip and micro sprinkler systems), and the majority of these systems are powered by centrifugal pumps driven by electrical motors. Any practices that will reduce the power demand of such systems, will therefore have widespread application in the irrigation sector.

The indicator used in practice for power capacity of pump stations is approximately 1 kW per hectare – systems with a value lower than 1 kW/ha is considered quite energy efficient, although the total energy consumption will be influenced by management practices. The indicator depend on the irrigation system, thus the value of the indicator may change for different irrigation systems.

A2.1 GROSS IRRIGATION REQUIREMENT

The amount of water required by the crop is the most basic input when planning an irrigation system. Most systems are designed to provide adequate water during the peak irrigation requirement period of the crop's growing season, and it is at the irrigator's discretion to use the system at a reduced capacity during the rest of the season.

Although not a design norm, the most widely recognised method of determining evapotranspiration of crops in South Africa is the SAPWAT3 program (Van Heerden, Crosby, Grové, Benadé, Schulze and Tewolde, 2009). SAPWAT3 is essentially an enhanced and improved version of SAPWAT, the program that was developed with funding from the Water Research Commission (WRC) in the 1990s to establish a decision-making procedure for the estimation of crop irrigation requirements by irrigation engineers, planners and agriculturalists. Subsequent to the development of the first SAPWAT programme, the Food and Agricultural Organisation (FAO) published the Irrigation and Drainage report No. 56 (Allen, Pereira, Raes and Smith, 1998), Crop evapotranspiration Guidelines for computing crop water requirements. This intuitive and comprehensive document is highly acclaimed and is accepted internationally. SAPWAT3 has at its core the computer procedures contained in FAO 56 (Allen, Pereira, Raes and Smith, 1998). All recommendations have been applied following the procedures set out in FAO 56 (Allen et al., 1998).

A2.2 SYSTEM EFFICIENCY

Table A.1 shows the recommended and minimum values for the efficiency of different types of irrigation systems based on the results of a WRC project (Reinders et al., 2010). The assumption is that the maximum theoretical efficiency of any irrigation system should be 100%. Assumptions are then made for acceptable losses in any system that can occur and the total losses deducted from 100%, to obtain the maximum (recommended) attainable efficiency. The minimum acceptable value is based on the previous norms. Although this process makes it possible for the designer to determine an appropriate efficiency for any specific situation that is being designed for by putting together the loss percentage values, he/she must however always strive for a system designed for the maximum attainable efficiency.

The efficiency values shown in Table A.1 apply only to the physical performance of the irrigation system and it is assumed that the irrigator applies appropriate and economical management practices.

Table A. 1: Typical irrigation system efficiencies

Irrigation system	Losses				Default system efficiency (net to gross ratio) (%)	
	Non-beneficial spray evaporation and wind drift (%)	In-field conveyance losses (%)	Filter and minor losses (%)	Total Losses (%)	Min	Recommend
Drip (surface and subsurface)	0	0	5	5	90	95
Micro sprinkler	10	0	5	15	80	85
Centre Pivot, Linear move	8	0	2	10	80	90
Centre Pivot LEPA	0	0	5	5	85	95
Flood: Piped supply	0	0	2	5	80	95
Flood: Lined canal supplied	0	5	5	10	70	90
Flood: Earth canal supplied	0	12	5	14	60	86
Sprinkler (permanent)	8	0	2	10	75	90
Sprinkler (movable)	10	5	2	17	70	83
Traveling gun	15	5	2	22	65	78

Source: Adapted from Reinders et al. (2010)

In consideration of energy demand, the maximum possible system efficiency value should be used to prevent irrigation systems from being over-designed and using excessive energy.

A2.3 IRRIGATION HOURS PER WEEK

These values are used to determine the required system discharge (q). The principle has always been that the more hours available to undertake the irrigation of an area, the smaller the discharge will be and therefore the power requirement. However, it should also be kept in mind that the number of hours used for irrigation, contributes to the total number of kilowatt-hours demanded from the energy source. A designer should therefore strive to optimize the system at the point where the minimum energy demand occurs rather than the maximum number of hours.

Total electricity costs depend on the type of electricity tariff. All tariff options include a fixed cost and variable cost. Fixed costs have to be paid every month irrespective of whether electricity was used or not while variable costs have to be paid for the electricity consumption. Variable electricity costs are a function of management (hours pumped), electricity tariffs and irrigation system design (kW). The electricity tariffs are divided into different charges, active, reliable and demand energy charge which is dependent on the product of the *kW* requirement of an irrigation system and the pumping hours. The *kW* requirement is closely linked to irrigation system layout and design.

Pumping hours (*PH*) is determined by irrigation management and the limits that are placed on irrigation hours during the irrigation cycle when using time-of-use electricity tariffs (such as Ruraflex). The reactive energy charge is dependent on the kilovar (kVAR) and pumping hours of an irrigation system. The *kVAR* is calculated from the power factor (PF) of the pump (kVAR = $\cos^{-1}$ PF). Each pump has a unique power factor which can be obtained from the manufacturer. The user pays for 70% of the *kVARh* used. The fixed electricity costs (fec) are an input parameter in the model and depend on the type of electricity tariff.

By using the models developed as described in chapter 4, it was possible to investigate the optimal point where the minimum energy cost occur, and it is recommended that the norms be adjusted to the following:

A2.3.1 Selection of energy tariff

The increases in electricity tariffs have a significant impact on the profitability of irrigation farmers, due to the fact that farmers depend on electricity to pump water for irrigation. The average electricity tariff adjustments from 1998 to 2015 are shown in Table A.2.

Table A. 2: Eskom's average tariff adjustments for the last 18 years

Year	Average Tariff Adjustment (%)
1 January 1998	5.00
1 January 1999	4.50
1 January 2000	5.50
1 January 2001	5.20
1 January 2002	6.20
1 January 2003	8.43
1 January 2004	2.50
1 January 2005	4.10
1 April 2006/7	5.10
1 April 2007/8	5.90
1 April 2008/9	27.50
1 April 2009/10	31.30
1 April 2010/11	24.80
1 April 2011/12	25.80
1 April 2012/13	16.00
1 April 2013/14	8.00
1 April 2014/15	8.00
1 April 2015/16	12.08

Eskom has designed a number of tariff options for electricity users. In this report only the tariff options that are most widely used by farmers were considered. These consisted of the Ruraflex and Landrate options.

Landrate is a flat rate, dependant on the size of supply. The size of supply determines the Landrate (Landrate 1,2,3,4 and Dx – see Table A.3) option that farmers will use. The most common option is the Landrate 2 option.

Table A. 3: Landrate tariff plan options

Landrate 1	single-phase **16 kVA** (80 A per phase) dual-phase **32 kVA** (80 A per phase) three-phase **25 kVA** (40 A per phase)
Landrate 2	dual-phase **64 kVA** (150 A per phase) three-phase **50 kVA** (80 A per phase)
Landrate 3	dual-phase **100 kVA** (225 A per phase) three-phase **100 kVA** (150 A per phase)
Landrate 4	single-phase **16 kVA** (80 A per phase)
Landrate Dx	single-phase **5 kVA** (limited to 10 A per phase)

For the Landrate options, the variable electricity costs are shown in the first three columns in A.4 below; the last two columns are fixed electricity costs.

Table A. 4: Landrate costs (2015/2016)

Landrate tariffs										Non-local authority
	Energy charge [c/kWh]		Ancillary service charge [c/kWh]		Network demand charge [c/kWh]		Network capacity charge [R/POD/day]		Service charge [R/POD/day]	
		VAT incl		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*
Landrate 1	**84.82**	*96.69*	**0.33**	*0.38*	**21.19**	*24.16*	**R 22.65**	*R 25.82*	**R 18.81**	*R 21.44*
Landrate 2	**84.82**	*96.69*	**0.33**	*0.38*	**21.19**	*24.16*	**R 34.82**	*R 39.69*	**R 18.81**	*R 21.44*
Landrate 3	**84.82**	*96.69*	**0.33**	*0.38*	**21.19**	*24.16*	**R 55.67**	*R 63.46*	**R 18.81**	*R 21.44*
Landrate 4	**183.19**	*208.84*	**0.33**	*0.38*	**21.19**	*24.16*	**R 18.04**	*R 20.57*	**R 0.00**	*R 0.00*
Landlight	**313.23**	*357.08*								
Landrate Dx									**R 40.35**	*R 45.99*

Source: Eskom (2015/16)

The Ruraflex tariff plan was designed to create the incentive to use electricity during low demand season and off-peak hours. Ruraflex is available to all three phase rural clients with an installed capacity of up to 5 MVA, on rural networks in rural areas as determined by Eskom from time to time and which accept supply from 400 V to 22 kV. The variable costs for Ruraflex depend on the time of use. Time of use is divided into three time slots, namely, off-peak time, standard time and peak time. Off-peak time covers the time of the day that the demand for electricity is the lowest and comprises 82 hours/week. Peak time on the other hand covers the time of the day that electricity demand is the highest and comprises 25 hours/week. Figure A6 illustrate the different time of use periods. High demand season is from June to August.

Different rates apply for the distances from Johannesburg to the farm. The four different categories of distances from Johannesburg are (1) 0 to 300km; (2) 301 to 600km; (3) 601 to 900km; (4) further than 900km. Different transformer sizes also have different fixed costs – see Table A.5.

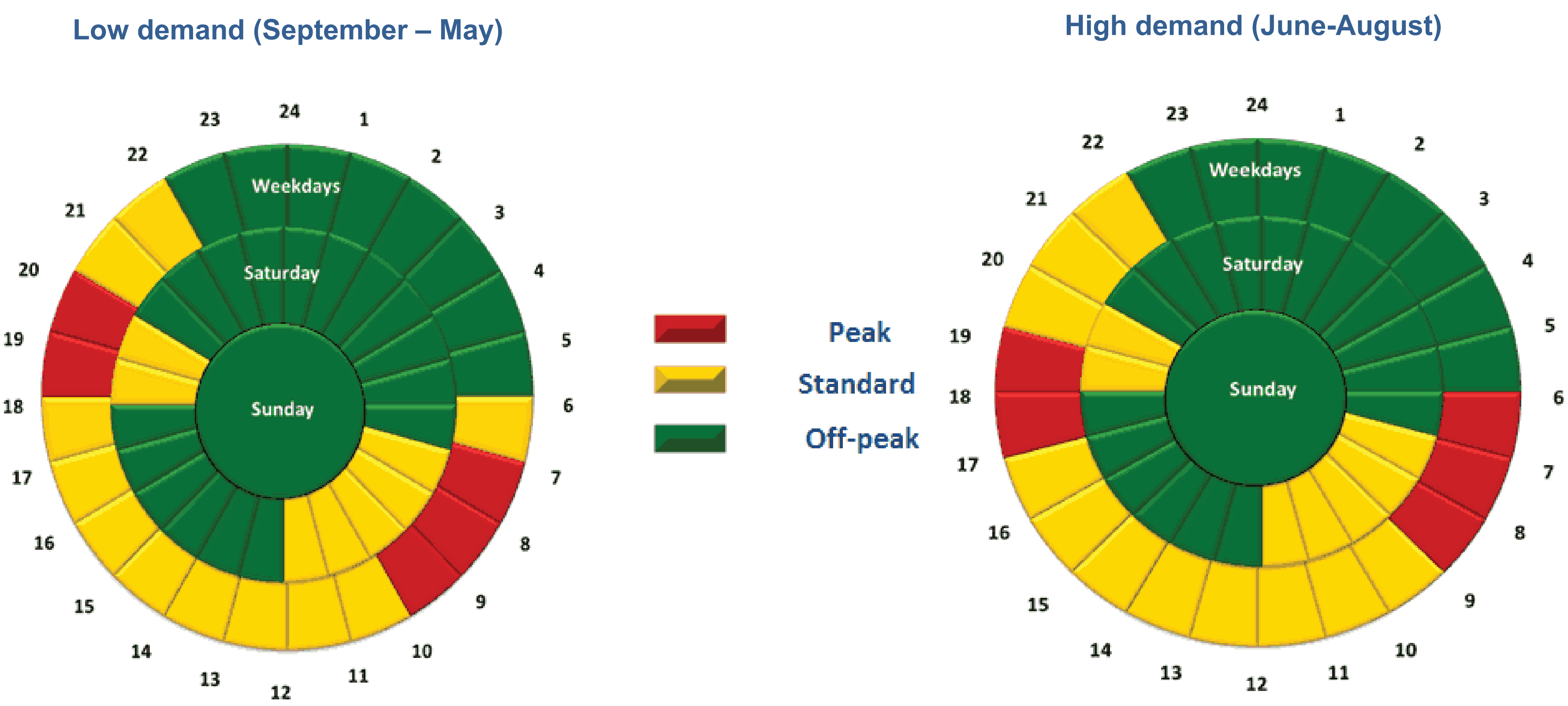


Figure A. 6: Ruraflex's time of use periods

Source: Eskom (2015/16)

Table A. 5: Ruraflex costs (2015/2016)

Ruraflex tariff

Non-local authority

Transmission zone	Voltage	Active energy charge [c/kWh]												Network capacity charges [R/kVA/m]	
		High demand season [Jun - Aug]						Low demand season [Sep - May]							
		Peak		Standard		Off Peak		Peak		Standard		Off Peak			
			VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl
≤ 300km	< 500V	**257.77**	*293.86*	**78.09**	*89.02*	**42.41**	*48.35*	**84.09**	*95.86*	**57.87**	*65.97*	**36.71**	*41.85*	**R 14.88**	*R 16.96*
	≥ 500V & ≤ 22kV	**255.22**	*290.95*	**77.32**	*88.14*	**41.98**	*47.86*	**83.26**	*94.92*	**57.29**	*65.31*	**36.34**	*41.43*	**R 13.64**	*R 15.55*
> 300km and ≤ 600km	< 500V	**260.35**	*296.80*	**78.87**	*89.91*	**42.83**	*48.83*	**84.92**	*96.81*	**58.45**	*66.63*	**37.09**	*42.28*	**R 14.93**	*R 17.02*
	≥ 500V & ≤ 22kV	**257.76**	*293.85*	**78.08**	*89.01*	**42.41**	*48.35*	**84.09**	*95.86*	**57.86**	*65.96*	**36.71**	*41.85*	**R 13.73**	*R 15.65*
> 600km and ≤ 900km	< 500V	**262.95**	*299.76*	**79.66**	*90.81*	**43.25**	*49.31*	**85.78**	*97.79*	**59.03**	*67.29*	**37.46**	*42.70*	**R 15.01**	*R 17.11*
	≥ 500V & ≤ 22kV	**260.34**	*296.79*	**78.86**	*89.90*	**42.83**	*48.83*	**84.92**	*96.81*	**58.45**	*66.63*	**37.09**	*42.28*	**R 13.78**	*R 15.71*
> 900km	< 500V	**265.58**	*302.76*	**80.46**	*91.72*	**43.68**	*49.80*	**86.62**	*98.75*	**59.62**	*67.97*	**37.83**	*43.13*	**R 15.07**	*R 17.18*
	≥ 500V & ≤ 22kV	**262.94**	*299.75*	**79.66**	*90.81*	**43.25**	*49.31*	**85.78**	*97.79*	**59.03**	*67.29*	**37.46**	*42.70*	**R 13.79**	*R 15.72*

Customer categories	Service charge [R/account/day]		Administration charge [R/POD/day]	
		VAT incl		VAT incl
≤ 100 kVA	**R 14.64**	*R 16.69*	**R 4.16**	*R 4.74*
> 100 kVA & ≤ 500 kVA	**R 49.94**	*R 56.93*	**R 23.15**	*R 26.39*
> 500 kVA & ≤ 1 MVA	**R 153.63**	*R 175.14*	**R 35.53**	*R 40.50*
> 1 MVA	**R 153.63**	*R 175.14*	**R 65.93**	*R 75.16*
Key customers	**R 3,010.96**	*R 3,432.49*	**R 65.93**	*R 75.16*

Voltage	Ancillary service charge [c/kWh]		Network demand charge [c/kWh] [All time of use periods]	
		VAT incl		VAT incl
< 500V	**0.33**	*0.38*	**21.19**	*24.16*
≥ 500V & < 22kV	**0.33**	*0.38*	**18.57**	*21.17*

Reactive energy charge [c/kVArh]			
High season		Low season	
	VAT incl		VAT incl
7.16	*8.16*	**0.00**	*0.00*

Source: Eskom (2015/16)

Eskom started a Critical Peak Day Pricing pilot project in October 2013 and it is currently being tested at various locations. A critical peak day is a day that is predetermined by Eskom, during which the national power system is severely constrained. The number of critical peak days is limited to 17 days in a year. Twenty four hours before this critical peak days Eskom will sent notifications warning customers that tomorrow is a critical peak day. The energy charge that will be applied from 06h00 to 22h00 will be significantly higher than usual. The critical peak day tariffs can be seen in Table A.6. If the producer decides not to reduce the consumption during the critical peak day, he/she will pay a much higher rate on the day, but the average tariff over the period of one year will be the same as if he/she had been on the standard Ruraflex tariff. If he/she curtails or reduces the consumption on the critical peak day, the average annual tariff will be lower than being on the standard Ruraflex tariff.

Example:

Data was obtained from a large commercial farming enterprise in Limpopo province where the Ruraflex CPD tariff is being tested. The cost of electricity for different delivery points on the farms are shown below in Table A.6.

Table A. 6: Example: Comparison of Eskom tariff costs

Type of electricity supply point	Number of points	kWh Per month	R Per month	R Per kWh
Landrate	336	1 166 127	2 201 430	1.89
Ruraflex	105	2 256 485	3 043 209	1.35
Total	441	3 422 612	5 244 639	1.53 (average)
Ruraflex CPD	42	2 531 743	1 646 897	0.65

It can be seen that the electricity cost of the Ruraflex points are R1.35/kWh compared to R1.89/kWh at the Landrate points. Furthermore, the cost at the Ruraflex CPD points (R0.65/kWh) is less than 50% of the cost at the ordinary Ruraflex points.

The time of use electricity tariffs allow irrigators to manage their total variable electricity cost. The electricity tariff structure has a significant impact on the irrigation system design capacities in that most irrigation systems have water application rates which in access of daily crop water requirements to ensure that lower tariff rates could be utilised. It is recommended that water users apply for time of use electricity tariffs such as Ruraflex or Ruraflex CPD whenever possible.

Table A. 7: Ruraflex CPD costs (2015/2016)

Active energy charge [c/kWh] NON-CRITICAL PEAK DAY rates for 348 NORMAL days

Transmission zone	Voltage	High demand season [Jun - Aug] Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Low demand season [Sep - May] Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl
≤ 300km	< 500V	**209.90**	*239.29*	**63.59**	*72.49*	**42.41**	*48.35*	**68.47**	*78.06*	**47.13**	*53.73*	**36.71**	*41.85*
	≥ 500V & ≤ 22kV	**207.81**	*236.90*	**62.96**	*71.77*	**41.98**	*47.86*	**67.79**	*77.28*	**46.64**	*53.17*	**36.34**	*41.43*
> 300km and ≤ 600km	< 500V	**211.99**	*241.67*	**64.22**	*73.21*	**42.83**	*48.83*	**69.15**	*78.83*	**47.60**	*54.26*	**37.09**	*42.28*
	≥ 500V & ≤ 22kV	**209.89**	*239.27*	**63.58**	*72.48*	**42.41**	*48.35*	**68.47**	*78.06*	**47.12**	*53.72*	**36.71**	*41.85*
> 600km and ≤ 900km	< 500V	**214.11**	*244.09*	**64.86**	*73.94*	**43.25**	*49.31*	**69.85**	*79.63*	**48.06**	*54.79*	**37.46**	*42.70*
	≥ 500V & ≤ 22kV	**211.98**	*241.66*	**64.21**	*73.20*	**42.83**	*48.83*	**69.15**	*78.83*	**47.60**	*54.26*	**37.09**	*42.28*
> 900km	< 500V	**216.24**	*246.51*	**65.52**	*74.69*	**43.68**	*49.80*	**70.54**	*80.42*	**48.55**	*55.35*	**37.83**	*43.13*
	≥ 500V & ≤ 22kV	**214.10**	*244.07*	**64.86**	*73.94*	**43.25**	*49.31*	**69.85**	*79.63*	**48.06**	*54.79*	**37.46**	*42.70*

Active energy charge [c/kWh] CRITICAL PEAK DAY rates for 17 CRITICAL PEAK days

Transmission zone	Voltage	High demand season [Jun - Aug] Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Low demand season [Sep - May] Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Network capacity charges	VAT incl
≤ 300km	< 500V	**453.31**	*516.77*	**307.00**	*349.98*	**42.41**	*48.35*	**311.88**	*355.54*	**290.54**	*331.22*	**36.71**	*41.85*	**14.88**	*R 16.96*
	≥ 500V & ≤ 22kV	**451.22**	*514.39*	**306.37**	*349.26*	**41.98**	*47.86*	**311.20**	*354.77*	**290.05**	*330.66*	**36.34**	*41.43*	**13.64**	*R 15.55*
> 300km and ≤ 600km	< 500V	**455.40**	*519.16*	**307.63**	*350.70*	**42.83**	*48.83*	**312.56**	*356.32*	**291.01**	*331.75*	**37.09**	*42.28*	**14.93**	*R 17.02*
	≥ 500V & ≤ 22kV	**453.30**	*516.76*	**306.99**	*349.97*	**42.41**	*48.35*	**311.88**	*355.54*	**290.53**	*331.20*	**36.71**	*41.85*	**13.73**	*R 15.65*
> 600km and ≤ 900km	< 500V	**457.52**	*521.57*	**308.27**	*351.43*	**43.25**	*49.31*	**313.26**	*357.12*	**291.47**	*332.28*	**37.46**	*42.70*	**15.01**	*R 17.11*
	≥ 500V & ≤ 22kV	**455.39**	*519.14*	**307.62**	*350.69*	**42.83**	*48.83*	**312.56**	*356.32*	**291.01**	*331.75*	**37.09**	*42.28*	**13.78**	*R 15.71*
> 900km	< 500V	**459.65**	*524.00*	**308.93**	*352.18*	**43.68**	*49.80*	**313.95**	*357.90*	**291.96**	*332.83*	**37.83**	*43.13*	**15.07**	*R 17.18*
	≥ 500V & ≤ 22kV	**457.51**	*521.56*	**308.27**	*351.43*	**43.25**	*49.31*	**313.26**	*357.12*	**291.47**	*332.28*	**37.46**	*42.70*	**13.79**	*R 15.72*

Customer categories	Service charge [R/account/day]*	VAT incl	Administration charge [R/POD/day]*	VAT incl
≤ 100 kVA	**R 14.64**	*R 16.69*	**R 4.16**	*R 4.74*
> 100 kVA & ≤ 500 kVA	**R 49.94**	*R 56.93*	**R 23.15**	*R 26.39*
> 500 kVA & ≤ 1 MVA	**R 153.63**	*R 175.14*	**R 35.53**	*R 40.50*
> 1 MVA	**R 153.63**	*R 175.14*	**R 65.93**	*R 75.16*
Key customers	**R 3,010.96**	*R 3,432.49*	**R 65.93**	*R 75.16*

Voltage	Ancillary service charge [c/kWh]*	VAT incl	Network demand charge [c/kWh]* [All time of use periods]	VAT incl
< 500V	**0.33**	*0.38*	**21.19**	*24.16*
≥ 500V & < 22kV	**0.33**	*0.38*	**18.57**	*21.17*

Reactive energy charge [c/kVArh]* High season	VAT incl	Low season	VAT incl
7.16	*8.16*	**0.00**	*0.00*

A2.3.2 Maximum design irrigation hours per week

The irrigation system with the lowest energy cost will be one that is operated 100% within the off-peak hours of a time of use electricity tariff (Ruraflex), of which there are 81 hours available per week (see Table A.8). This is subject to the water user being able to irrigate during off-peak periods (mostly at night and over weekends).

Table A. 8: Ruraflex tariff periods

	Off-peak hours	Standard hours	Peak hours
Weekdays	8 x 5days	11 x 5 days	5 x 5 days
Saturday	17	7	0
Sunday	24	0	0
Total hours per week	**81**	**62**	**25**

If this is not possible, the following norms are recommended:

- Micro and permanent sprinkler systems ≤143 hours/week
- Centre pivots systems ≤143 hours/week
- Moveable sprinkler and other movable systems ≤108 hours/week
- Flood irrigation systems ≤60 hours/week

An important factor that determines VEC is the product of kW requirement and irrigation hours. Irrigation hours are reduced if flow rate is increased while kilowatt requirement increase with an increase in flow rate given pipe diameter remains the same. Decreasing irrigation hours ensure that a higher percentage of irrigation can take place during cheaper timeslots which will reduce the VEC. The aim is therefore to design a system with the lowest possible flow rate, which implies that the maximum number of irrigation hours (available at the lowest possible electricity rate) are utilised.

Example:

The influence of flow rate on the variable electricity cost (VEC) for a 30 ha centre pivot in the summer rainfall area producing maize and wheat, is presented in Figure A.7 for Landrate and Ruraflex.

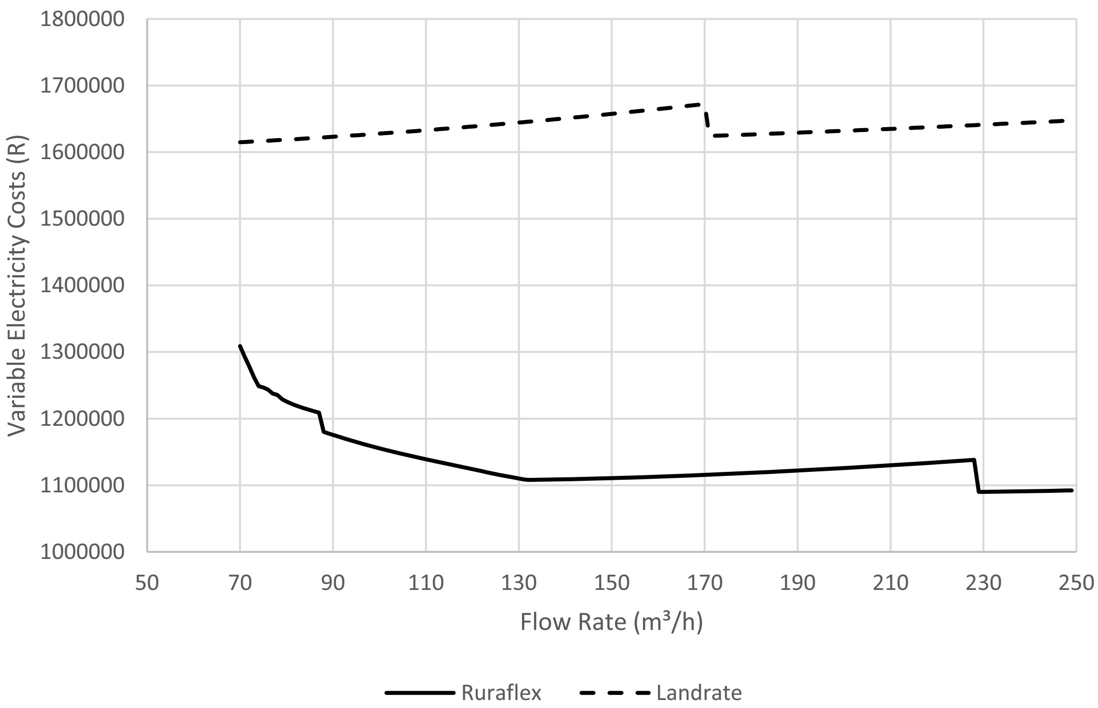


Figure A. 7: Change in variable electricity costs due to a change in flow rate for two electricity tariffs

The results for Landrate indicate that management has no impact on VEC because the only reason why VEC is increasing with increasing levels of Q is due the impact of Q on H_f. With Landrate, the charge per kWh is constant and the irrigator is allowed no leeway to manage irrigation costs through the timing of irrigation events. Variable electricity costs of Landrate are higher for the range of flow rates compared to Ruraflex.

In contrast to Landrate, Ruraflex is a time-of-use electricity tariff which allows the irrigator the opportunity to reduce VEC through managing the timing of irrigation events. The direction of change in VEC depends on the interaction between increasing kilowatt requirement and decreasing irrigation during times when electricity charges are high. Figure A.7 shows that the VEC for Ruraflex decreases as the flow rate increases to 132 m^3/h. During this stage the benefits of decreasing irrigation hours while irrigating less hours in peak electricity tariff timeslots is more significant than increasing kilowatt requirement. After the breakeven flow rate (132 m^3/h) the increase in VEC is due to the increase in kilowatt requirement and management becomes insignificant.

Figure A.8 illustrates the optimised Time Profiles for Ruraflex. Total irrigation hours decrease as flow rate increase. Higher flow rates can apply more water in one hour, thus, less irrigation hours are necessary to apply the same amount of water. For low flow rates irrigation takes place in peak timeslots, since the available hours in off-peak and standard is not enough to apply the required amount of irrigation. However, for higher flow rates the available irrigation hours in off-peak is enough and irrigation only takes place in off-peak resulting management to becomes insignificant.

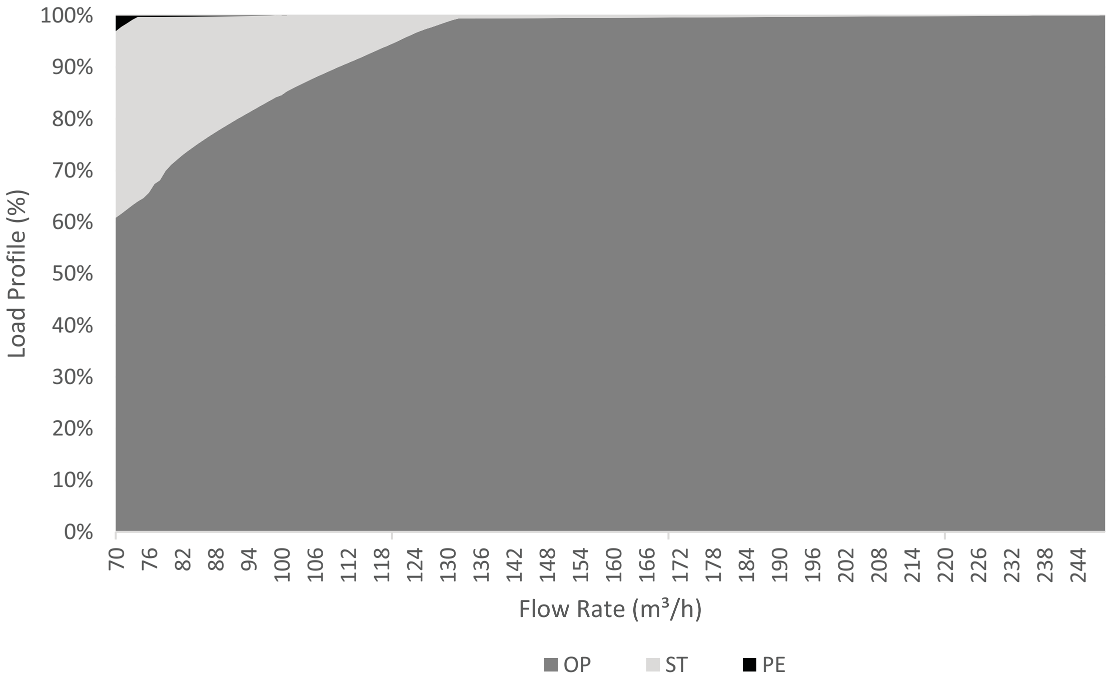


Figure A. 8: Change in the load profile of irrigation hours due to a change in flow rate for Ruraflex. (OP: Off-Peak; ST: Standard; PE: Peak)

A2.4 SYSTEM LAY-OUT

Both the horizontal and vertical displacement of water are considered.

Horizontally speaking, the most economical system lay-out will always be one where the water source is as central to the area to be irrigated as possible. However, the location of the water source relative to the irrigated area is often beyond the control of the designer.

When considering the vertical movement of water, there is no fixed limit to which water should be lifted with an irrigation system. In parts of the country, however, rules of thumb exist that suggest that it is uneconomical to irrigate areas located more than 50 m above the level of the water source. The origin of this rule of thumb is not known and it is usually applied in the context of surface water sources, as groundwater is often pumped from much greater depths than 50 m.

It is only in the case of moving irrigation systems where there are limitations on the topography that the system can handle. Centre pivots are subject so manufacturer specific limitations on the slopes and angles that can be handled. In the case of travelling irrigators, it is recommended that cross slopes over the strips be limited to less than 5% during system lay-out. A pressure regulator is recommended for travelling irrigators on steep slopes to ensure a constant flow rate. The effect of large topographic difference that must be overcome, is an increase in the pressure required from the pump and therefore an increase power demand.

Another consideration that is affected by topographic height differences, is the decision regarding which blocks or systems served by a single pump station should be irrigated simultaneously. Conventional design practice is to combine areas of similar sizes into different shifts as this will ensure an almost constant discharge at any given time during the irrigation cycle. The blocks or system irrigated simultaneously would also typically be scattered around the whole farm as to reduce the discharge in the mainline and therefore make it possible to use smaller pipe sizes. The result is a fairly constant power demand on the pump station. However, with the implementation of Variable Speed Drives, designers have to consider whether it isn't more beneficial to divide the total irrigated area into pressure zones and vary the speed of the motor to adjust the pressure and discharge of the pump. A decision regarding which strategy to follow should be taken at the outset of the design.

A2.5 MINIMUM GROSS APPLICATION RATE

Overhead type of irrigation systems usually have to apply water a minimum gross application rate in order to prevent excessive losses (especially evaporative losses) from occurring during every irrigation event. While systems can be designed to apply water at lower rates to save energy, it is not advisable as the application efficiency of the system will be very low and additional irrigation amounts or events will be required to make up for the losses.

The following minimum gross application rates are recommended for <u>impact sprinkler</u> systems:

- Moveable systems $\geq$ 5 mm/h
- Permanent systems $\geq$ 4 mm/h

The application rate of <u>micro sprinklers</u> should be equal to or greater than 3 mm/h on the wetted area (Lategan, 1995). Distribution tests can be done with the selected micro sprinkler on soils with poor water distribution ability, to ensure that dry patches will not occur in the wetting area of the sprayer.

A2.6 EMITTER SELECTION

When selecting an emitter for an irrigation system, the main consideration of the designer (apart from the fact that the emitter should supply water a suitable discharge, litre per hour), is the application uniformity that can be achieved by a newly manufactured emitter under ideal conditions. The performance is defined by various indicators, depending on the type of irrigation system. An emitter that performs well from an uniformity perspective, will benefit energy management as the irrigator will be assured that the largest part of his/her crop is getting near the optimum amount of water, minimizing the need for over-irrigation to compensate for poor uniformity.

A2.6.1 Sprinkler systems

The operating pressure, sprinkler application, wetted diameter and spacing of the sprinklers all influence the performance of the specific sprinkler and nozzle combination. The Christiansen's uniformity coefficient (CU) is used to determine the water application in a laboratory. The sprinkler with the best CU value must be selected. The following norms for the selection of sprinklers based on the laboratory-tested CU values are recommended:

- Minimum allowable CU = 84%
- Recommended CU ≥ 88%

A2.6.2 Micro irrigation

In the case of micro sprinklers and drippers, the manufacturer's coefficient of variation (CV) provides an indication of the variability in the flow rate of a random sample of a given emitter model before it has been subjected to any field operation. The CV is defined as the standard deviation over the average discharge of a sample of emitters.

For point source emitters (non-overlapping wetting patterns), CVs are classified as follows (Sne, 2006):

CV < 5%	Excellent
5% < CV < 7%	Good
7% < CV < 11%	Average
11% < CV < 15%	Poor
CV> 15%	Unacceptable

With recent improvements in technology, most point source emitters have CVs better than 10%, and selecting an emitter with a CV of better than 5% is recommended. Pressure compensating emitters have a slightly higher CV than pressure sensitive emitters because of the variability of the compensating mechanism.

For non-point source emitters (overlapping wetting patterns, especially drip tapes), the CV classification is:

CV < 10%	Good
10% < CV < 10%	Average
CV > 20%	Marginal to unacceptable

A2.6.3 Centre pivots

It is recommended that the CU as calculated by the supplier for the selected nozzle package should be ≥ 95%. In the field, an 85% CU value can then be expected.

A2.7 AVERAGE EMITTER PRESSURE AND ALLOWABLE PRESSURE VARIATION

When an emitter is selected, the emitter discharge, q_e, is defined at a specific pressure, p_{ave}, especially in the case of pressure sensitive emitters. The designer will design the irrigation system so that all the pressures occurring in the infield part of the irrigation system varies below and above this average value, within certain system type specific limits, Δp_{ave}, which will result in the discharge variation in the system being limited to allowable values, Δq_e, leading to uniform application of water. The average emitter pressure therefore has a direct effect on the power as it determines the starting point of the hydraulic pressure gradient, while the allowable pressure variation will set the maximum value of the pressure at the inlet to the infield part of the irrigation system. The aim should always be to select an emitter at the lowest possible average pressure without compromising the performance of the emitter, and to set the minimum allowable pressure variation without resulting in impractical and expensive system lay-outs (large allowable pressure variations make it possible to design systems with longer laterals and smaller diameter laterals and manifolds, which results in lower capital costs).

A2.7.1 Sprinkler pressure

The classification of sprinklers is shown in Table A.9. Most agricultural systems fall in the medium pressure category. Manufacturers often specify preferred pressure ranges and spacings for their products; care should be taken not to use sprinklers at low pressures as it will have negative effect on the distribution patterns and thereby on the CU.

Table A. 9: Sprinkler classification according to pressure

Sprinklers	Pressure [m]	Flow rate [m³/h]	Typical application
Low pressure	< 20	< 0,7	orchards
Medium pressure	25 - 40	< 3	cash crops
High pressure	> 40	< 50	pastures and sugarcane
High volume	> 45	20 - 100	pastures and maize

High pressure means high energy costs and application rates, while larger spacings mean low capital outlay and low application rates. Thus a combination must be chosen that gives the required gross application at a low total cost, while meeting the required minimum gross application rate.

As far as the allowable pressure variation for sprinkler systems are concerned, the system should be designed so that the pressure variation between different sprinklers irrigating simultaneously is not more than 20% of the design pressure (Jensen, 1983).

A2.7.2 Micro irrigation

Although not a norm, the nominal operating pressure of pressure sensitive drip emitters is usually 10 m and of micro sprinklers it is 15 m. However, the manufacturer's recommendations should be used.

As far as the allowable pressure variation is concerned, two different approaches are discussed here.

a) Conservative approach
The percentage emitter discharge variation of micro irrigation systems should not exceed 10% of the design emitter discharge. In the case of emitters with a discharge exponent of 0.5, this will result in a maximum allowable pressure variation of 20% of the design pressure.

b) Emitter uniformity (EU) approach
EU is a statistic parameter by means of which the expected uniformity of the emitter discharge within an irrigation block can be established, and where only the lowest and average emitter discharges are taken into account.

The following minimum emitter uniformity (EU) values are recommended for micro sprinklers:

- Level terrain where slope < 2%: EU = 95%
- Undulating terrain or slopes > 2%: EU = 90%

Table A.10 represent the recommended emitter uniformity (EU) values for pressure sensitive drip emitters:

Table A. 10: Recommended EU Values of pressure sensitive drip irrigation systems

Emitter Type	Number of emitters per plant	Topography or slope	EU (%)	
			Min	Recommended
Point application	≥3	≤2%	90	95
Point application	<3	≤2%	85	90
Point application	≥3	Undulating terrain or slope >2%	85	90
Point application	<3	Undulating terrain or slope >2%	80	90
Line source	All	≤2%	80	90
Line source	All	Undulating terrain or slope >2%	80	85

If the EU value of 90% cannot be obtained with pressure sensitive emitters, it is strongly recommended that pressure compensating emitters should be used. It is recommended that maximum allowable pressure variation of PC emitters will be within the following limits:

- Minimum pressure = the minimum pressure at which compensation takes place as per the manufacturer + 3m
- Maximum pressure = the maximum pressure at which compensation takes place as per the manufacturer – 5m

A2.7.3 Centre pivots

Sprinkler packages of different pivot manufacturers vary, but the following general guidelines are followed by the classification shown in Table A.11.

Table A. 11: Classification of pivot sprinkler packages according to pressure

Package	Pressure [m]	Typical wetted diameter [m]	Typical CU values [%]	Comments
Ultra low pressure	4 - 10	7 - 12	90	
Low pressure	10 - 14	11 - 18	88 - 93	Low energy requirements
Medium – low pressure	21	25 - 32	90	
Medium pressure	28	27 - 34	>90	
High pressure	35	33 - 40	85 - 90	Not used often

The diameter of the centre pivot lateral should be designed so that the total friction loss along the machine is ≤ 2.5% (m/100m) of the total centre pivot length.

A2.7.4 Traveling irrigators:

The type of sprinkler and pressure may be selected from the manufacturer's catalogue. Big gun sprinklers with a high jet angle (> 23 degrees) are only recommended for low wind areas. The following minimum working pressures are recommended to limit droplet size:

- 300 kPa for 12 mm nozzles
- 400 kPa for 14 mm and 16 mm nozzles
- 500 kPa for 18 mm and 20 mm nozzles

The moving direction of a travelling irrigator must be such that the pressure difference between the upper and lower ends of a strip does not exceed 20% of the working pressure.

A2.8 PIPE FRICTION IN MAIN- AND SUB MAIN LINES

The design of the main line of an irrigation system presents a problem to the designer. If a smaller pipe diameter is used, the capital costs of installing the system will be lower than when a larger diameter is used. On the other hand, the pump costs will be higher if a smaller pipe diameter is preferred to a larger pipe diameter. The optimum pipe size, or most economical diameter, can be determined through economic analysis that will result in graphs showing capital vs running costs for a range of possible pipe sizes that can be used (Figure A.9). The most economical diameter will be the one that occurs at the lowest point of the total cost graph.

This principle is valid for not only the pipe diameter but also all the ancillary fittings and accessories – smaller sizes means lower capital cost but higher friction loss and therefore higher power demand.

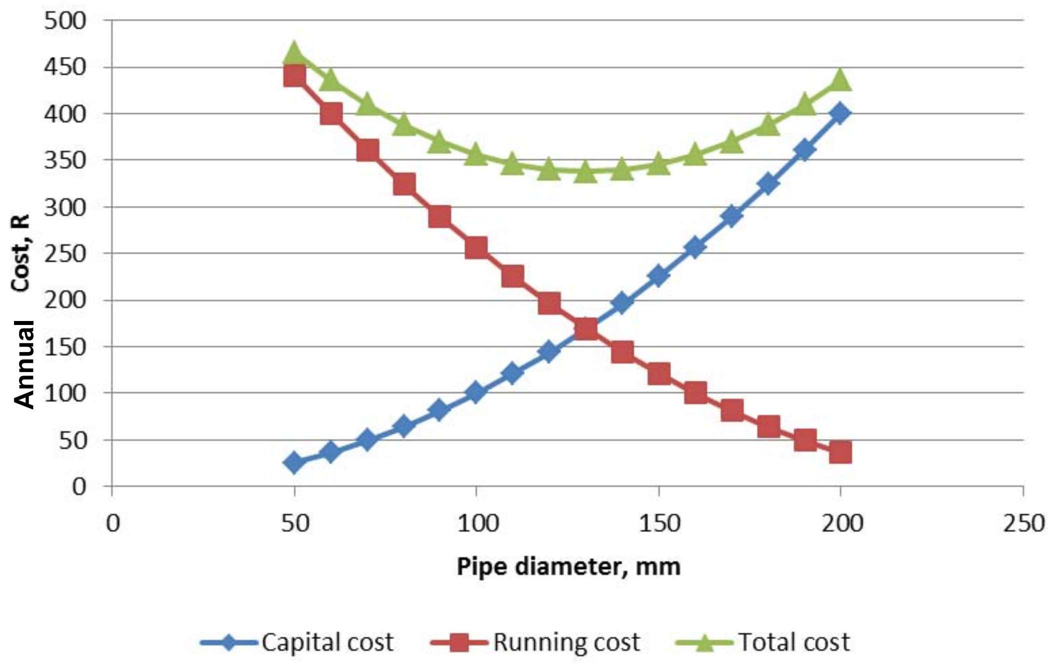


Figure A. 9: Economic design approach based on life cycle costing

The designer must take into account the possible effect of water quality on pipes as well as the deterioration of pipes with age during the pipe's life time. The following values for allowable pipe friction in mainlines are accepted as norms:

- Rising pipeline: Maximum friction loss = 1% (m/100m pipe length)
  Recommended friction loss = 0.6% (m/100m pipe length)
  Maximum velocity = 1.3 m/s
  Recommended velocity = 1 m/s
- Gravity pipeline: Maximum allowable flow velocity of 3.0 m/s

If the above figures are exceeded, then the designer must show that the chosen pipe diameter's total cost (capital and annual running cost) have been optimized and is the best of the available options.

Furthermore, a full life cycle cost analysis (capital and annual running cost) is recommended to find the most economical pipe sizes.

For all pipes, and especially in the case of diameters larger than 200 mm, the effect of water hammer is critical and must be investigated and optimized. An adequate number of air valves must be included in the design.

The continuous economic pipe diameter equation as published in the ARC's Irrigation Design Manual was also reviewed. The formula to calculate economic pipe diameter with the ARC method is presented by Equation 51.

$$d = kQ^a \quad (51)$$

Where:

d	Economic pipe diameter (mm)
Q	System discharge (m^3/h)
k	Constant
a	Exponential constant

The results are shown in Figure A.10, based on pumping systems using electricity (Ruraflex) as source are calculated.

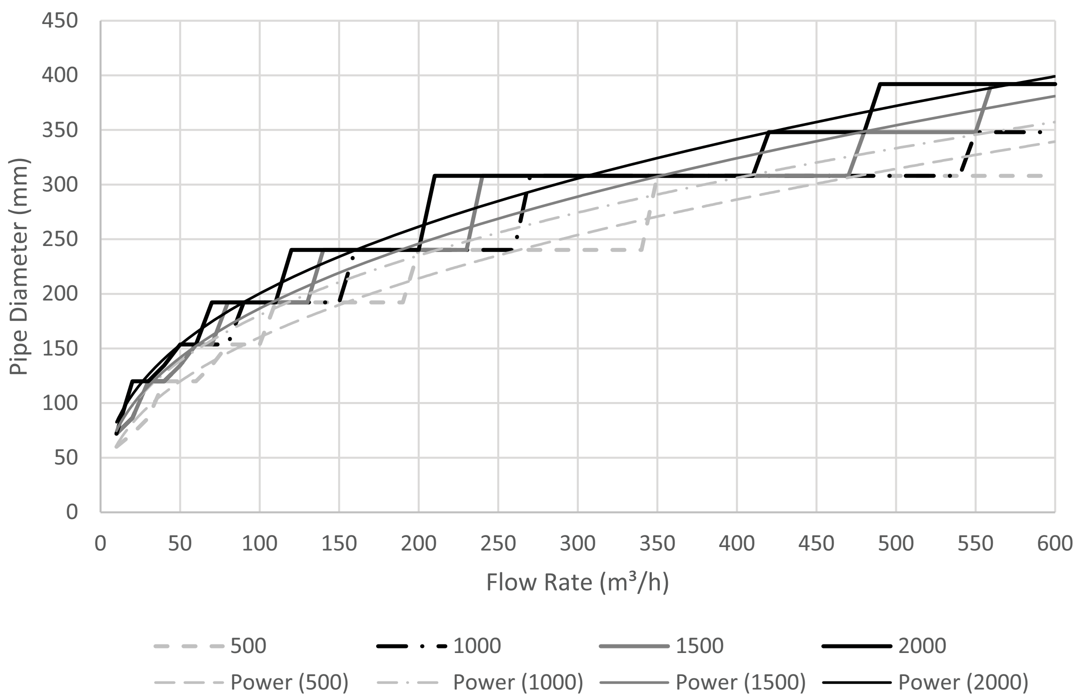


Figure A. 10: Economic pipe diameter calculation

The new equation for economic pipe diameter calculation is therefore:

$$d = kQ^{0.396} \quad (52)$$

Where k can be determined from:

Pumping hours per year	500	1000	1500	2000	2500	3000	3500	4000
k (electric pumping systems on Ruraflex)	26	28	30	32	34	36	38	40

A2.9 VALVES

The size of the valves at the inlet of the irrigation system must be chosen according to the manufacturer's recommendations for the specific application. In the absence of any recommendations, the valve must be chosen so that the pressure loss through the valve under normal operating conditions is less than 20 kPa, and that the velocity must be less than 5 m/s.

A2.10 FILTERS

The specification of filters is subject to any requirements stated by the manufacturer, for example the minimum pressure or flow rate required for the backwash of filters.

A2.10.1Disc and mesh filters

Disc / mesh filter openings must be ≤ 1/5 that of the emitter orifice diameter. The appropriate micro emitter manufacturer’s recommendations must be used for flow path openings of ≤ 1mm. The following norms are accepted (ASAE EP405.1, 1997):

Table A. 12: Allowable pressure difference over a filter bank

Type	**Allowable pressure difference over clean filter/-bank (kPa)**		**Allowable pressure build-up (kPa)**	**Allowable pressure difference before backwashing (kPa)**	
	Single filter	**Filter bank**		**Single filter**	**Filter bank**
Disc-/Mesh filter	10	30	40	50	70

A2.10.2 Sand Filters

When using a sand filter, a 200 μm control mesh or disc filter must be placed on the downstream side of the sand filter to catch the impurities in case of damage to the sand filter. The drip manufacturer's recommendations must be followed when using a disc- / mesh filter. The following norms are accepted.

a) Flow rate

The maximum allowable flow rate through a clean sand filter: Flow rate ≤ 50 m^3/h per m^2 of sand surface area with an allowable pressure difference over the clean sand filter of ≤ 10 kPa. A minimum of 50% of the maximum filtration rate (50 m^3/h per m^2 sand surface area) is required to backwash the filters (Burt and Styles, 1994). The maximum backwash rate must not exceed 1.2 times the filtration rate.

b) Pressure difference

The allowable pressure difference over a sand filter with disc-/ mesh filters. Allowable pressure difference over a clean filter bank (including sand and disc filter) ≤ 40 kPa and over the filter bank before backwashing should be ≤ 60 kPa. When using a disc-/ mesh filter, the allowable pressure difference norms as described above must be complied with.

Table A. 13: Allowable pressure differences over sand filters

Type	Allowable pressure difference over clean filter/-bank (kPa)		Allowable pressure build-up (kPa)	Allowable pressure difference before backwashing (kPa)	
	Filter	Filter bank		Filter	Filter bank
Sand filter	10	40	20	30	60

c) Outlet pressure during backwash

Minimum pressure during backwash of a sand filter: ≥200 kPa (Smith, 2010)

d) Sand specifications used in sand filters

Silica sand with a particle size that varies from 0.6 to 1.4 mm, with an acceptable sand grading, is recommended for sand filters. The recommended particle size grading must be 80 micron. A filtration performance of ≥90% must be achieved under laboratory conditions.

A2.11 DESIGN PUMP CAPACITY (SAFETY FACTOR FOR WEAR AND TEAR)

These values are added to the calculated system capacity and are used to determine the duty point (pressure and flow) when selecting a pump. The present norms are accepted:

- Discharge 10%
- Pressure head 5%

If fertilizers are pumped through the irrigation system then an additional 20% flow capacity can be designed for in the system.

When a hydraulically driven travelling irrigator is used, the design flow rate must be increased by ± 2.5 m^3/h to allow for driving power. Confirmation of this value is required by the specific supplier.

Care should be taken to not include too many safety or overdesign factors in various points of the system as this will lead to an oversized and energy inefficient system.

A2.12 PUMP EFFICIENCY

Although a fixed minimum value for efficiency of a pump cannot be given, the designer must always strive to choose a pump for the system where the duty point(s) fall as close to the Best Efficiency Point on the pump curve as possible.

The performance of a single pump can be regulated in several ways. The most common approaches for centrifugal pumps are throttling, bypass control, modifying impeller diameter and change of speed. Not all these approaches are necessarily advisable. A summary of these methods are shown in Table A.14.

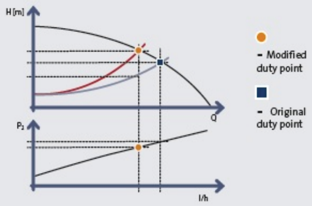
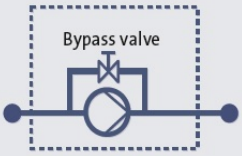
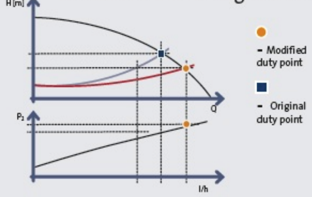
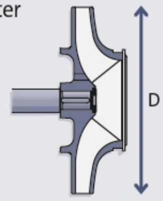
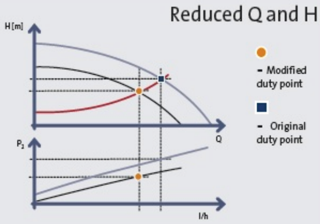
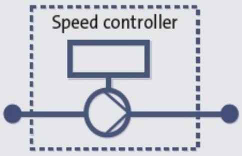
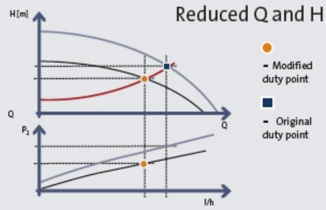
Furthermore, the supply of water from a pump station can be adjusted by using more than one pump for the system, operated either in parallel or in series, as discussed below.

Pumps connected in parallel are mostly used when the required flow rate is more than what a single centrifugal pump can supply, or when the system has variable flow requirements. The regulation is done by turning one or two pumps on or off. This is a good approach for an irrigation system, where the layout has several zones that are not always used at the same time.

Normally, pumps connected in parallel are of similar type and size. However, the pumps can vary if one or more of the pumps are fitted with a VSD. To avoid bypass circulation in pumps connected in parallel, a non-return valve must be installed after each pump.

Pumps connected in series are used in systems where a high pressure is required (more than what can be delivered by a single centrifugal pump). An alternative to pumps in series are multistage pumps which are bused on the same principle (1 stage = 1 pump).

Table A. 14: Summary of single pump control methods

Method	Continuous adjustment possible?	The resulting performance curve will have	Overall efficiency of the pump system	Relative power consumption by 20% reduction in flow
Throttle control 	Yes	Reduced Q 	Considerably reduced	94%
Bypass control 	Yes	Reduced H and changed curve 	Considerably reduced	110%
Modifying impeller diameter 	No	Reduced Q and H 	Slightly reduced	67%
Speed control 	Yes	Reduced Q and H 	Slightly reduced	65%

Source: Grundfos, 2009

Pumps of different sizes and pumps with VSDs can be used in series. The combination of a fixed speed pump and pump with a VSD in series is often used in systems where a high and constant pressure is required.

A2.13 MAXIMUM MOTOR POWER OUTPUT

The correct selection of an electric motor will ensure that the motor is never overloaded. It is therefore necessary to either select a motor with a power rating that is large enough for the selected pump and impellor, or to make provision against overload by means of protection devices. Table A.15 indicates norms for minimum power rating of an electric motor for specific output power if the motor is selected according to the normal duty point (output power required).

Table A. 15: Minimum power rating of electric motors for certain output powers

Output Power [kW]	< 7.5 kW	7.5 kW to 37kW	>37 kW
Minimum power rating of motor	Output power +20%	Output power + 15%	Output power + 10 %

An alternative approach is to consult the pump's power curve to determine the maximum possible power requirement. If this approach is followed, then the values in Table A.14 must not be added as this would result in over designing of the motor.

The reduction in the power rating of the motor for high altitudes and ambient temperatures must also be applied where necessary.

A2.14 MOTOR EFFICIENCY

It is recommended that electric motors with a rating of at least "IE2" (or "EFF1") are used to drive the pump.

Assessments have shown that the savings incurred from changing to more efficient motors are small relative to the savings that can be achieved from other interventions such as using the correct pump, proper scheduling and Variable Speed Drives.

Table A. 16: Efficiency classes of electrical motors

Efficiency	EFF system	IE systems
Premium		IE3
High	EFF1	IE2
Standard	EFF2	IE1
Lower than standard	EFF3	

A2.15 VARIABLE SPEED DRIVES (VSDS)

The VSD's main function is the ability to vary the speed of the motor it is connected to. In the case of a centrifugal pump it is therefore possible with the VSD to use the same pump and impeller combination to supply water at various flow rates and pressure heads (duty points) without changing the impeller of the pump.

A2.15.1General

- The basic principles of correct pump and motor design and selection apply at all times.
- The integration of the VSD with the control system and automation of the irrigation system should be investigated in order to find the most appropriate and cost effective solution.
- Alternative options should be considered first, such as cutting the impeller to the correct size and using soft starters, especially in the case of single duty point applications, as they can offer more cost effective solutions than the installation of a VSD.
- The motor should be capable of delivering the required power of the pump at all the different duty points without overloading but should not be oversized.
- If no other information is available, it is recommended that the supply frequency to the motor should not be less than 25 Hz and not be more than 60 Hz.
- At very low frequencies, it may be necessary to install an auxiliary fan to the motor to ensure adequate cooling takes place.
- The motor with which the VSD is to be used, should be rated VSD compatible according to the manufacturer.
- The enclosure of the VSD to be used should have a suitable IP rating for the environment in which it is to be used (dust, moisture, etc.)
- When more than one VSD is used in parallel, or if more than one pump is used per VSD, the designer should make sure that the pumps will operate in all cases without influencing one another negatively from a hydraulic perspective.
- The integration of the VSD with the rest of the electrical system at the pump station must be assessed and if the situation requires it, the necessary electrical filters should be installed to protect all components of the system.
- Before a VSD is supplied, the designer should ensure that support or maintenance services for the VSD are readily available in the area.

A2.15.2 Totally Enclosed Fan Cooled Motors (TEFC) Motors

- Where running speeds are expected to exceed the normal 50Hz frequency levels, contact the pump and motor manufacturers to find out if the proposed maximum running frequency of the motor is acceptable. Generally ≤ 60 Hz is accepted as the maximum but the manufacturer should confirm this.
- The motor maximum kW (power rating) must not be exceeded when pumping at any given time but in particular when running at higher than normal speed (> 50 Hz).
- It is generally advisable not to run the motor at a lower frequency than 25Hz for prolonged periods of time. If this is required, it is suggested that the motor manufacturer should be contacted to establish if the minimum running frequency of the motor can be decrease to below 25 Hz.

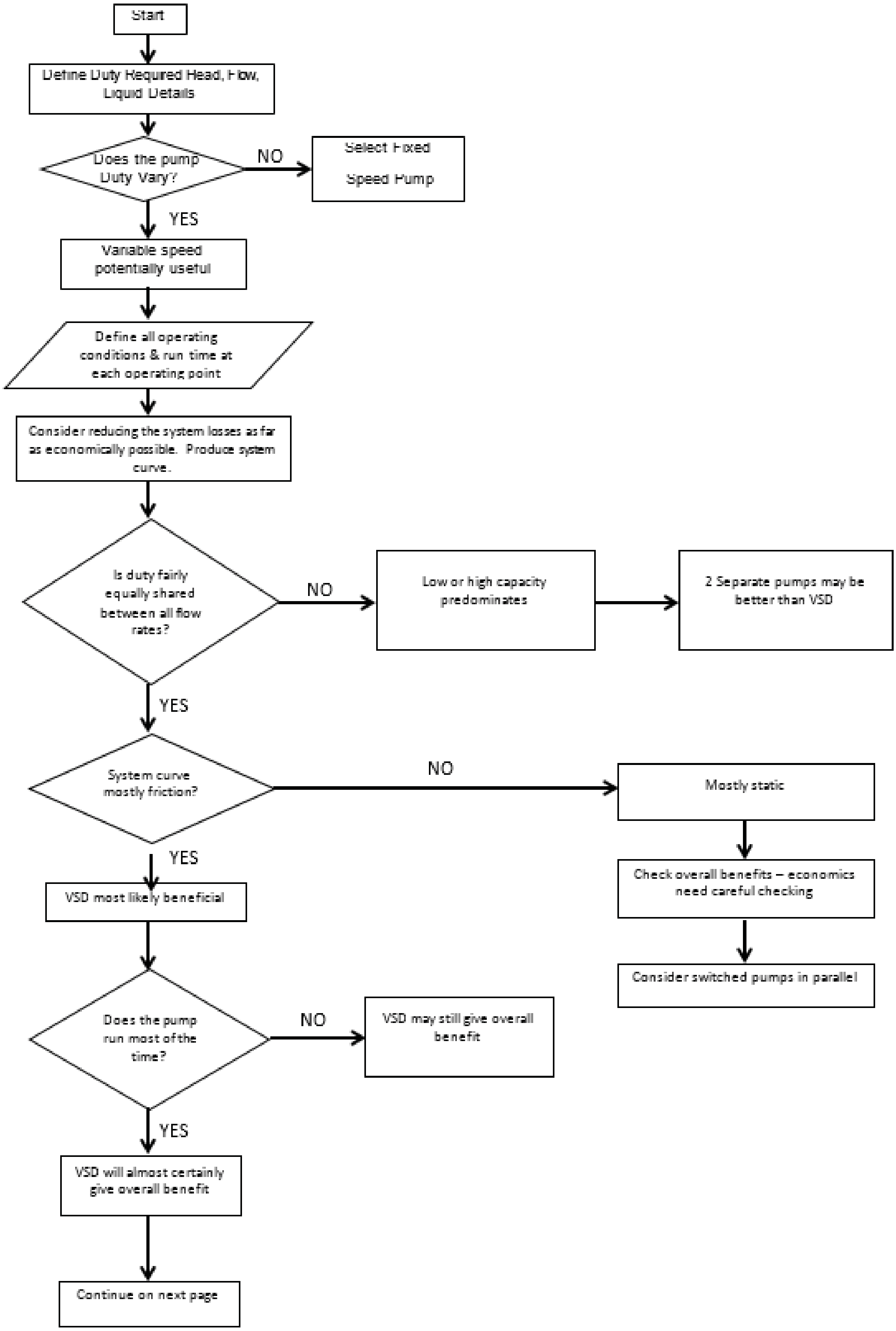
A2.15.3 Submersible motors

- See first two points under TEFC.
- The minimum running frequency of a submersible motor will be determined by the minimum flow velocity across the motor, as stipulated by the motor manufacturer, as the flow also contributes to cooling of the motor.
- The necessary precautions need to be taken to prevent prolonged periods of no flow through the pump as it may lead to the damage of the motor.
- The maximum number of motor starts per day is as stated by the motor manufacturer.
- The maximum current demand of a submersible motor is usually greater than the current demand of a TEFC motor of similar power rating. The VSD must be able to meet both the current and the power requirements of the motor.

A2.15.4 Electrical supply and connection

- The maximum allowable cable length between the motor and the VSD as recommended by the VSD manufacturer should be adhered to. This is of particular importance in the case of submersible motors. In general, it is recommended that all situations where the distance between the VSD and the motor is greater than 15 m, is investigated from a cable sizing perspective.
- The earthling of the VSD and motor must be in accordance to the requirements of the VSD manufacturer.
- If a VSD is used in conjunction with a generator, approval should be sought from both devices' manufacturers that the generator and the VSD can be used together.

A recommended procedure for determining the viability of using a VSD is shown below.


Start
Define Duty Required Head, Flow, Liquid Details
Does the pump Duty Vary?
NO
Select Fixed Speed Pump
YES
Variable speed potentially useful
Define all operating conditions & run time at each operating point
Consider reducing the system losses as far as economically possible. Produce system curve.
Is duty fairly equally shared between all flow rates?
NO
Low or high capacity predominates
2 Separate pumps may be better than VSD
YES
System curve mostly friction?
NO
Mostly static
Check overall benefits – economics need careful checking
Consider switched pumps in parallel
YES
VSD most likely beneficial
Does the pump run most of the time?
NO
VSD may still give overall benefit
YES
VSD will almost certainly give overall benefit
Continue on next page

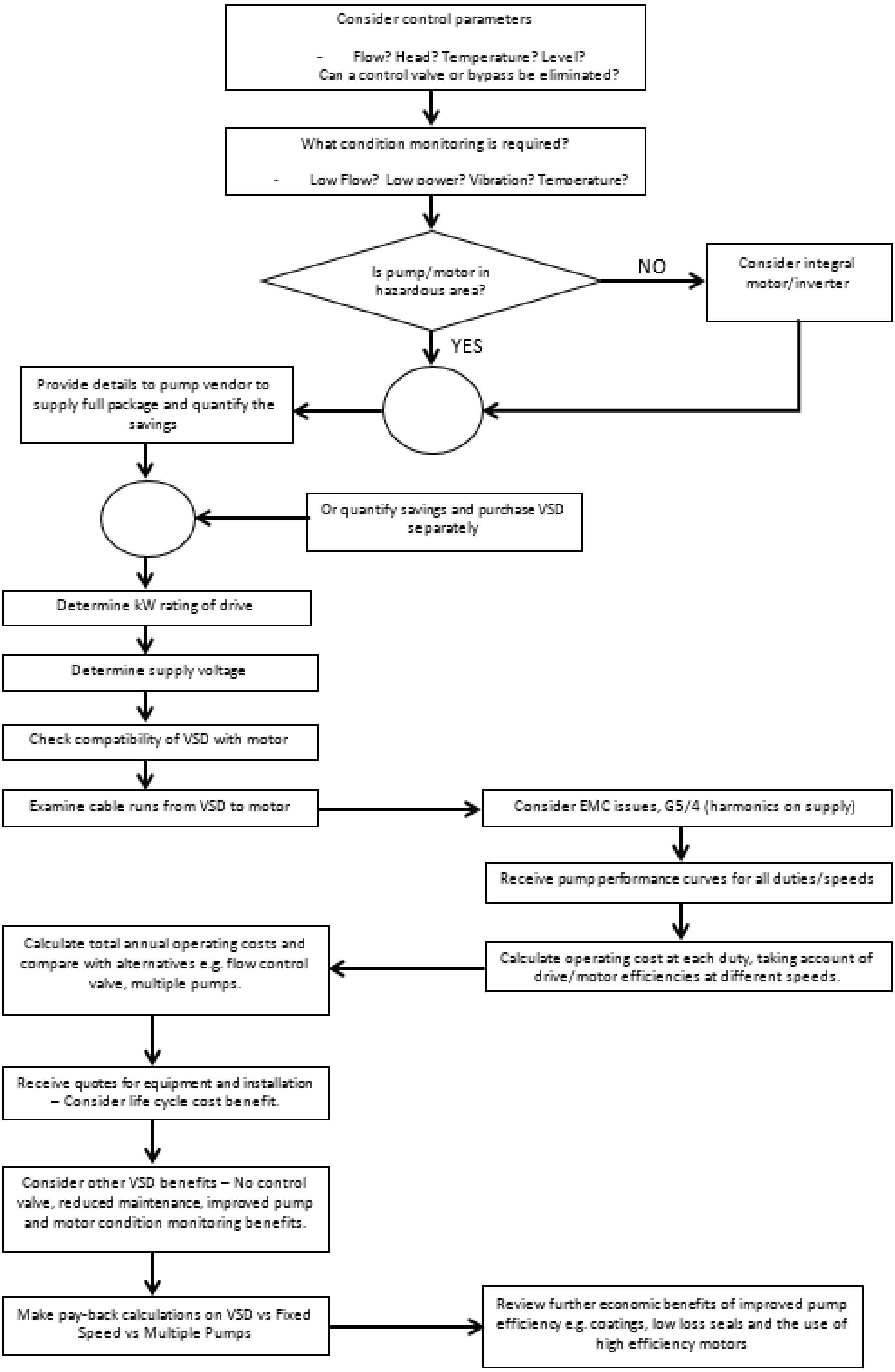


Figure A. 11: Determining the suitability of a VSD for a pump system

Source: BPMA (2013)

A2.15.4Estimating energy savings with VSD

Irrigation farmers depend on a pumping system to pump water for irrigation. Electrical energy is required for such a pumping system. The electrical energy required is determined by the head and flow rate requirement of an irrigation system, often refer to as the operating point or duty point. In practice the flow rate and head requirement can change, especially when more than one irrigation system share the same mainline. Throttling valves; by-pass valves and variable speed drives are commonly used to control the flow rate and pressure (head) in the system. Within a South African context throttle valves are most common. Currently there is a drive towards the use of variable speed drives to control flow and pressure head. Some manufactures claims up to 50% savings in electricity costs when installing a VSD. However, literature has shown that systems that are characterised by a significant static head may not be suitable for VSD applications (Schofield, undated).

The purpose of this section is firstly to illustrate the potential energy saving through the use of a VSD when compared to a throttle valve. Secondly, the effect of static head on the efficiency of a VSD is illustrated.

(a) Throttle valve vs VSD

Figure A.12 shows the relative energy use for a system where control is executed via a throttle valve and speed control using a VSD.

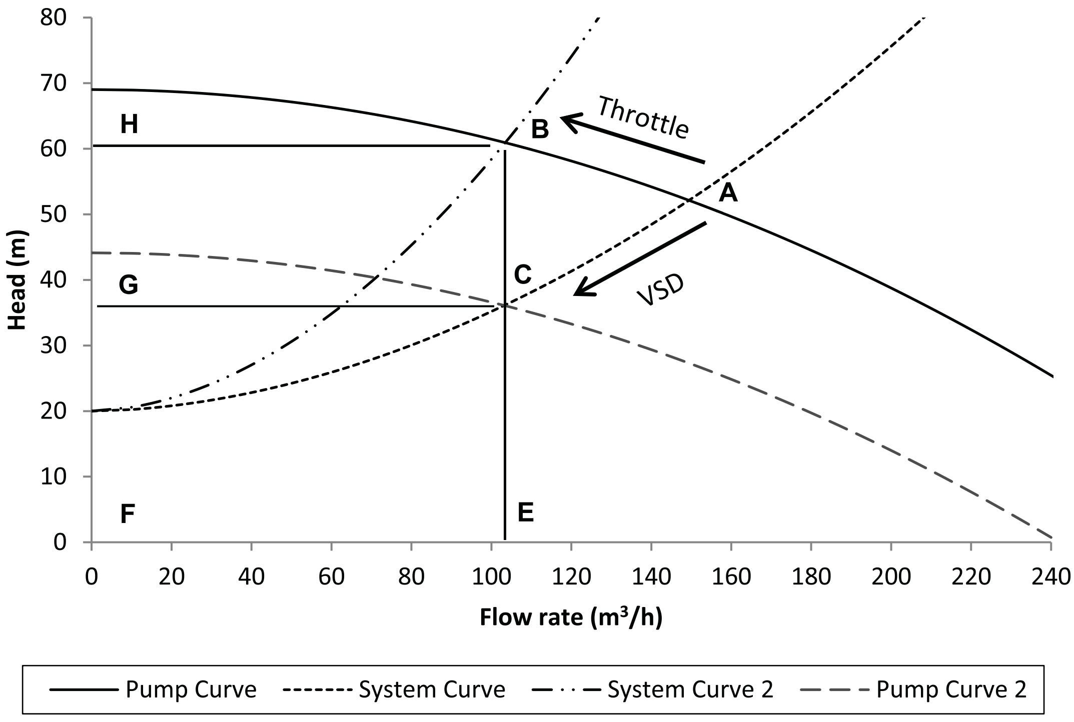


Figure A. 12: Throttle control vs variable speed drive (VSD) control

The operating point of the pump at its best efficiency point is shown as A. The operating point shifts from A to B when flow is rate is controlled by a throttle valve. At operating point B the desired flow rate is obtained but at a higher pressure and lower efficiency.

Rectangle FEBH is an indication of the energy usage when the pump is operating at point B. The same flow rate could be achieved through the use of a VSD. The VSD changes the speed of the motor to control the flow rate of the pump. A reduction in the speed of the motor results in the pump curve to shift down. The new pump curve is calculated through the use of the affinity laws. Rectangle FECG is indicative of the energy usage when using a VSD to achieve the desired flow rate.

From the example it is clear that a VSD is able to achieve the same flow rate but at a lower pressure resulting in energy savings. The energy usage through the use of a throttle valve (area FEBH) is larger than the energy usage through the use of a VSD (FECG). Efficiencies changes due to a reduction in the speed of the motor are claimed to be negligible small and mostly constant efficiencies are assumed. Constant efficiencies are more typical of systems where static head is zero or very little.

Next the effect of static head on the efficiency is shown.

(b) Effect of static head on efficiency

For systems with a zero static head, reducing pump speed moves the operating point along with the system curve, parallel with the efficiency curves, keeping the efficiencies more or less constant. The operating point is reduced proportionally; this allows the pump to keep operating at the best efficiency point at a lower flow rate and pressure. The operating point is determined through the use of affinity laws. Figure A.13 illustrate the change in the operating point at a zero static head.

Figure A.14 shows the effect of static head on changes in efficiency when speed control is applied to systems with significant static head. In systems with a static head the system curve does not start at the origin but at the static head value. Hence the system curve is not parallel with the efficiency curve but intersects the efficiency curves. A small reduction in flow rate has a significant effect on the pump efficiency. The affinity laws can no longer be used to obtain the operating point and energy savings (US Department of Energy, undated).

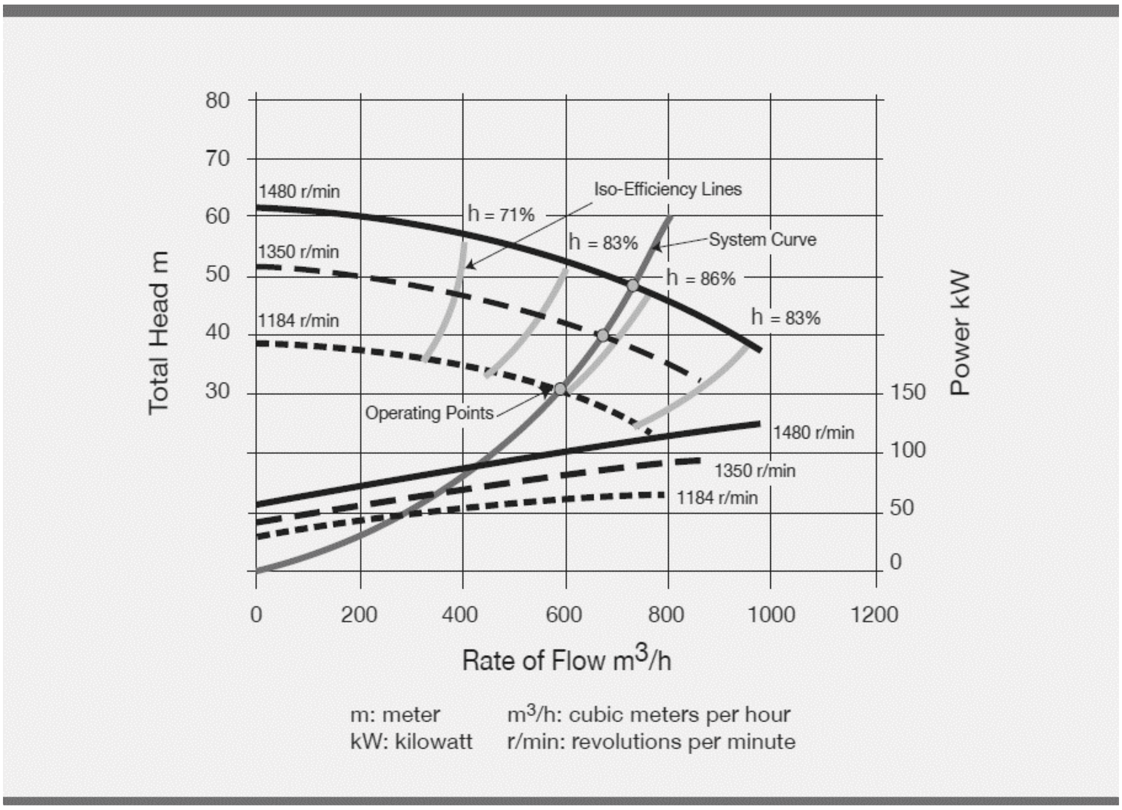


Figure A. 13: Change in operating point with a zero static head using a VSD

Source: US Department of Energy (Undated)

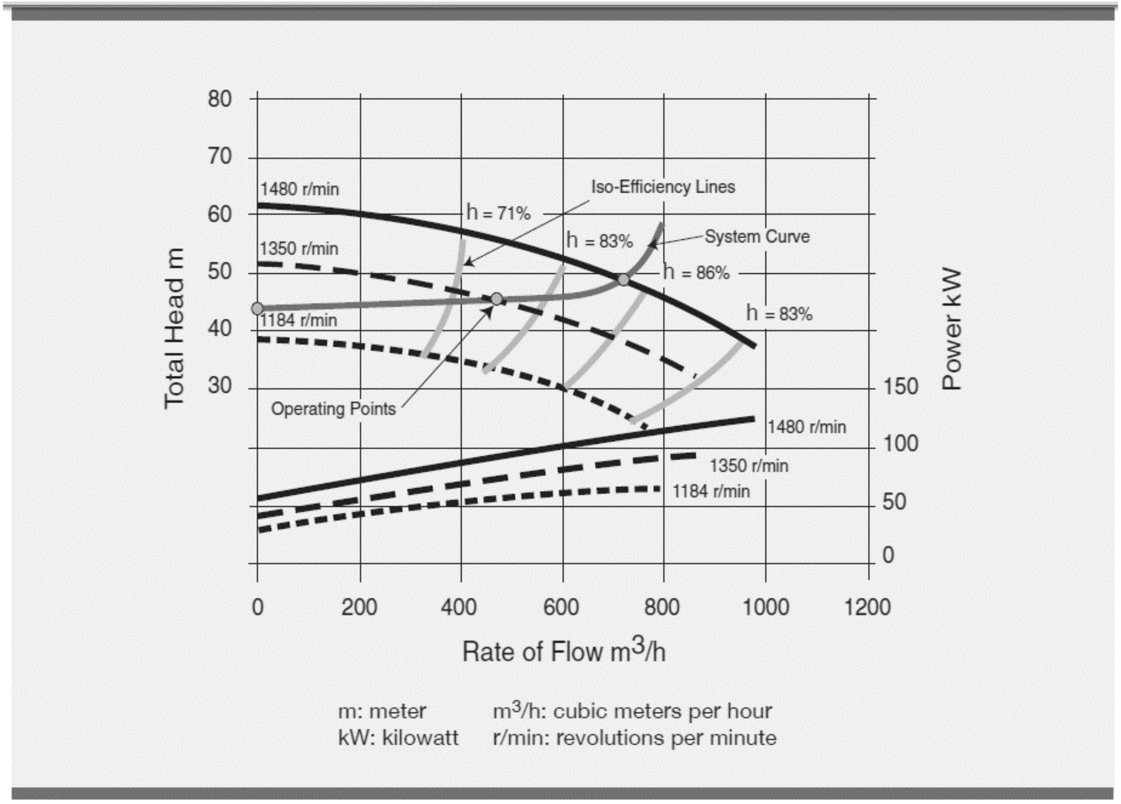


Figure A. 14: Change in operating point with a static head using a VSD

Source: US Department of Energy

The examples above clearly show that care should be taken when evaluating the energy savings that can occur through the use of new technologies such as variable speed drives. As a result the evaluation of the feasibility of a VSD should be case specific. Methods are available to estimate the changes in the pump efficiency in situations with zero static head. However, procedures to estimate efficiency changes for systems that are characterised by static head are not readily available. The Gator Pump Tuner software from Irri-Gator ignores changes in efficiency arguing that the irrespective what the reduction in inefficiency will be, the reduction in kW required due to changes in H will always be more (Chalmers,2013).

The advantages and disadvantages of using VSDs can be summarised as follows (Cloete, 2016):

- Advantages:
  - Better motor protection
  - Lower current peaks
  - Improved power factor and less reactive energy charges
  - Fewer control valves required
  - Less stress on irrigation systems due to varying pressures
  - Reduced pipe bursts and down time
  - Automatic restart of motor after electricity outages
- Disadvantages:
  - Compatibility with old motors / motors with poor insulation
  - Proper motor selection is essential (overload point)
  - Limitation on cable length between VSD and motor (40m)
  - Electricity cannot be left disconnected for long periods (capacitors discharge)
  - Proper earthling and cabling required
  - Knowledgeable support services required to limit down time after breakdowns
  - Cost and sensitivity to installation environment
  - Harmonics must be checked – filters may be required

APPENDIX B

KNOWLEDGE DISSEMATION

PAPERS PUBLISHED

Venter, M. and Grové, B. (2016). Modelling energy-pipeline investment economic trade-offs for improved energy management in irrigation agriculture. *Water SA,* 42(2):542-550.

Abstract:

Higher electricity tariffs have accentuated the importance of the trade-off between lowering investment cost by buying pipes with smaller diameters and the higher operating costs that result from the increased power requirement to overcome the higher friction losses of the thinner pipes. The Soil Water Irrigation Planning and Energy Management (SWIP-E) mathematical programming model was developed and applied in this paper to provide decision support regarding the optimal mainline pipe diameter, irrigation system delivery capacity and size of the irrigation system. SWIP-E unifies the interrelated linkages between mainline pipe diameter choice and the timing of irrigation events in conjunction with time-of-use electricity tariffs. The results showed that the large centre pivot resulted in higher net present values than the smaller centre pivot and the lower delivery capacities were more profitable than higher delivery capacities. More intense management is, however, necessary for delivery capacities lower than 12 $mm \cdot d^{-1}$ to minimise irrigation during peak timeslots. Variable electricity costs are highly dependent on the interaction between kilowatt requirement and irrigation hours. For the large centre pivot the interaction is dominated by changes in kilowatt whereas the effect of irrigation hours in relation to kilowatts is more important for smaller pivots. Optimised friction loss expressed as a percentage of the length of the pipeline was below 0.6%, which is much lower than the design norm of 1.5% that is endorsed by the South African Irrigation Institute. The main conclusion is that care should be taken when applying the friction loss norm when sizing irrigation mainlines because the norm will result in pipe diameters that are too small, consequently resulting in increased lifecycle operating costs. A clear need for the revision of the friction loss design norm was identified by this research.

WORKING PAPERS

Venter M and Grové B. *Determining the economic benefit of variable speed drives for centre pivots operating at a slope.* In preparation for Water SA.

Abstract:
Higher electricity tariffs create serious problems for irrigation farmers, since irrigation depend mainly on electricity to pump water. Significant opportunities exist for irrigation farmers to reduce electricity cost through irrigation system design, renewably energy resources and adopting new technology. However, cognizance need to be taken of the trade-off between investment and operating costs if new technology are adopted. An important strategy to minimise variable electricity costs is the adoption of Variable Speed Drives (VSD) so that the minimum amount of kilowatts is required to drive water through the system. Variable Speed Drive's (VSD) main function is the ability to vary the speed of the motor it is connected to. Changing the speed of the pump can result in less electricity consumption which lead to lower electricity costs. However, pump speed adjustment is not appropriate for all irrigation systems. Therefore, a proper economic review needs to be done to determine the economic trade-off between operating and investment costs for installing a VSD. The main objective of this paper is to design a model to calculate the economic trade-off between decreasing operating costs and increasing investment costs for adopting new technology. From the results the variable electricity cost of using a VSD and a fix speed pump intersect between 3% and 6% and 6% and 9% for a small and large center pivot, respectively. Thus, a VSD will become more beneficial at lower gradients for larger center pivots compared to smaller center pivots. However, from the results a VSD will not be beneficial for a center pivot ranging between 1% and 15% gradient, since the savings in variable electricity cost through the use of a VSD is less than the discounted investment cost of a VSD. The conclusion is that careful consideration of the economics is necessary to calculate the energy savings through the use of a VSD.

POPULAR PRESS

Grové, B. (2015). Snoei koste van besproeiingselektrisiteit deur ontwerp, bestuur en elektrisiteitstarief keuse. *Graan SA*. http://www.grainsa.co.za/snoei-koste-van-besproeiingselektrisiteit-deur-ontwerp,-bestuur-en-elektrisiteitstarief-keuse

Venter, M. (2016). Rek jou rande met veranderlike spoed-aandrywingstelsel vir spilpunte. *Graan SA*. http://www.grainsa.co.za/rek-jou-rande-met-veranderlike-spoed-aandrywingstelsel-vir-spilpunte

CONFERENCE PAPER

Venter, M. and Grové, B. (2013). An economic evaluation of the trade-off between capital investment and operating costs for irrigation farmers. AEASA 2013, Bela Bela.

Abstract:
The main objective of this research is to develop a non-linear optimisation model that integrates irrigation system design aspects (pipe diameter selection), electricity tariffs and agricultural water use planning to facilitate water and energy management in agriculture. The integrated model is applied to demonstrate the impact of irrigation system delivery capacity and static head on optimal pipe selection, energy and water use under two different electricity tariffs. Results showed that the irrigation tariff structure has a significant impact on mainline design and resulting electricity costs. Therefore the general practise of comparing the impact of alternative electricity structures on electricity costs for predefined irrigation systems will lead to biased conclusions. Results further showed that Landrate should not be used in situations where static head is significant.

PRESENTATIONS

Grové, B. (2014). Energy and water conservation in irrigated agriculture. GRUNDFOS farmers' forum 2014, Cape Town.

Grové, B. (2014). Optimising irrigation planning with non-uniform water applications. "Water, Food and Energy in the 21st Century" SANCID 2014 symposium.

Venter, M. and Grové, B. (2014). Modelling energy-pipeline investment economic trade-offs for improved energy management in irrigation agriculture. "Water, Food and Energy in the 21st Century" SANCID 2014 symposium.

Van der Stoep, I. (2015). Optimering van watertoediening met spilpunte. Sandveld werkgroep boeredag, 10 November 2015, Velddrif.

APPENDIX C

CAPACITY BUILDING AND ARCHIVING OF DATA

C1. CAPACITY BUILDING

Name: Marcill Venter
Degree: M.Sc. Agric (Agricultural Economics)
Status of study: Graduated in 2015
Title: An economic analysis of alternative capital investments for managing electricity costs in irrigation agriculture.

Abstract:
The main objective of this research is to develop an integrated non-linear programming model that unifies the interrelated linkages between mainline pipe diameter choice and the timing of irrigation events in conjunction with electricity tariff choice to facilitate better evaluation of the economic trade-offs of irrigation pipe investments for improved energy management.

The Soil Water Irrigation Planning and Energy Management (SWIP-E) programming model was developed to address the main objective of the research. The model includes an irrigation mainline design component, soil water budget calculations and an energy accounting component to model the interaction between irrigation system design, irrigation management and time-of-use electricity tariff structures. The SWIP-E model was applied in Douglas to evaluate the impact of different electricity tariff structures and irrigation system designs on the optimal pipe diameter of an irrigation mainline, electricity costs and profitability.

The results showed that Ruraflex is more profitable than Landrate which is a direct result of higher electricity costs associated with Landrate. The large center pivot resulted in higher net present values than the smaller center pivot and the lower delivery capacities were more profitable than higher delivery capacities. More intense management is necessary for delivery capacities lower than 12 mm/day to minimise irrigation during peak timeslots. Variable electricity costs are highly dependent on the interaction between kilowatt requirement and irrigation hours. For the large center pivot the interaction is dominated by changes in kilowatt whereas the effect of irrigation hours in relation to kilowatts is more important for smaller pivots. Landrate with relatively higher electricity tariff charges resulted in a change in the optimal pipe diameter at lower delivery capacities compared to Ruraflex. Optimal pipe diameters will increase for a breakeven percentage of between

0.6% and 0.66% for Ruraflex and between 0.4% and 0.6% for Landrate which is much lower than the design norm of 1.5%.

The overall conclusion is that the SWIP-E model was successful in modelling the complex interrelated relationships between irrigation system design, management and electricity tariff choice that influence the trade-off between main pipeline investment decisions and the resulting operating costs. Electricity tariff choice has a significant impact on the results which suggest that economic principles are important and that it should be included in the design process. A shortcoming of the model is that the risk of lower irrigation system delivery capacities was not included in the model. The conclusion that lower delivery capacities are more profitable should therefore be interpreted with care. The low breakeven friction percentages optimised in this research suggest that the norm of 1.5% friction is too high and a lower norm should be considered.

Future research should focus on extending the model to include a combination of irrigation systems and the inclusion of risk to evaluate the risk associated with low irrigation delivery capacities in combination with load shedding.

Name: Primrose Madende
Degree: M.Sc. Agric (Agricultural Economics)
Status of study: Final submission 2017
Title: Risk efficiency of optimal water allocation within a single and multistage decision-making framework.

Name: Berhane Okubay Haile
Degree: PhD (Agricultural Economics)
Status of study: Graduate 2017
Title: An economic analysis of salinity management with evolutionary algorithms in Vaalharts.

Abstract:
The main objective of this research was to develop a bio-economic salinity-management model to evaluate the stochastic efficiency, water-use efficiencies and environmental impact of optimal irrigation-scheduling practices while taking cognisance of irrigation-water quality, soil conditions, irrigation-technology constraints, crops and stochastic weather.

A bio-economic salinity-management simulation model was developed in MATLAB through the integration of the **S**oil **WA**ter **M**anagement **P**rogram (SWAMP), by combining electricity-cost calculations with enterprise budgets to evaluate the impact of current irrigation schedules used by irrigators. The resulting SWAMP-ECON model was linked to an evolutionary algorithm to determine the benefits of following an optimised irrigation-scheduling strategy for each field crop. The model was also extended to model inter-seasonal allocation of water between two consecutive crops

grown on the same field, to evaluate changes in the irrigation schedule of the first crop to manage the impact of soil salinity on the second crop. Risk was included in the analyses through the use of a state-general characterisation, where decisions are made without any knowledge of which state will occur. The models were applied to a case study farm in Vaalharts Irrigation Scheme with a 30.1 ha centre-pivot irrigation system. The farm is characterised by Bainsvlei soil type and a shallow water table close to or below the root zone. The scenarios considered to run the model were two water qualities (low and high), two irrigation-system delivery capacities (10 mm day^{-1} and 12 mm day^{-1}), and three field crops (maize, wheat, and peas) with different salinity-tolerance levels. The field crops constitute the crops grown for intra-seasonal and one-year inter-seasonal applications. Stochastic efficiency, low water-use efficiencies and environmental-impact indicators were calculated to interpret results of irrigation-management options for achieving economic and environmental sustainability.

The results show that the farmer's existing irrigation schedules for the field crops in the study were over-irrigation strategies characterised by low water-use efficiencies, which are the direct result of farmers ignoring the contribution of the shallow water table to crop water use. Over-irrigation resulted in large amounts of drainage water releasing between 11 000 and 26 600 kg ha^{-1} of salt into the environment. Decreasing water quality increases the risk of failing to reach potential production levels of the more salt-sensitive crops (maize and peas), however, the impact on expected margin above specified costs was low. Peas is the most profitable enterprise, followed by maize, and then wheat. On average, the expected margin above specified costs for peas, maize, and wheat, respectively, is ZAR 448 370, ZAR 321 909 and ZAR 245 885. The conclusion is that the current irrigation strategy is inefficient, has a large impact on the environment and presents the opportunity to improve profitability through better irrigation-scheduling practices that acknowledge the contribution of the shallow water table.

Results of the optimised irrigation schedules show significant increases in expected margin above specified costs, associated risk exposure, water-use efficiencies and water productivity, as well as decreases in environmental impact due to a reduction in the amount of salt leached (SL). The main contributing factor to the results is the fact that the amount of irrigation water could be reduced because the shallow water table contributed 40% to 62% to crop water use evapotranspiration, depending on crop type, water quality, and irrigation system delivery capacity scenario selected. The largest benefits were observed for the highly salt-tolerant crop (wheat), because no leaching was necessary to manage salt levels. Consequently, a large salt build-up in the soil was observed. Decreasing water quality, compared to good quality water, impacted more negatively on MAS, risk exposure and the extent of drainage losses by the more salt-sensitive crops. Irrigation system delivery capacity did not affect water-application rates significantly, but the results show that it is easier to manage electricity costs with the larger capacity by using a time-of-use electricity tariff. The conclusion is that the benefit of an optimised irrigation strategy is considerable, though careful consideration should be given to the trade-off between decreasing water applications and increasing salinity levels in the soil. Results of the inter-seasonal optimised irrigation scheduling strategy water use show that the leaching needs to increase during the production of the first crop to reduce the starting soil-salinity level when the follow-up crop is planted, especially when the second crop is sensitive to high salinity levels. Low WUE, WP and profitability are the consequences, taking the follow-up crop into account. In conclusion, a risk-neutral farmer should only consider increasing the water applied to the first crop (e.g. maize) if the plan is to plant a salt-sensitive crop (e.g. peas) in the second season. In both the intra-seasonal and the inter-seasonal applications, a risk-averse decision-maker will use more irrigation water to reduce the variability of outcome.

The main recommendation from this research is that alternative institutional arrangements should be considered to ensure that irrigators do not lose their water use entitlements if the water that is not used is deemed a non-productive use. A scheme-level hydrology analysis is necessary to determine the impact of on the water table if all water users start mining the water table. Future research should focus on extending the model to include the long-term problem of salinity and enhancing the model to deal with state-specific applications of water to crops as new information becomes available to farmers about a state of nature.

C2. ARCHIVING OF DATA

The models and data will be archived within the Department of Agricultural Economics. The models and data will also automatically be backed up on the University backup system.

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9781431208869