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Selection and Appraisal Framework for Power Source of Pumping System for Small Holders

إطار لاختيار وتقويم مصدر القدرة لنظام المضخات لصغار الملاك

Dissertation Submitted in Partial Fulfillment of the Requirements of M.Sc. in Agricultural Engineering

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DEDICATIONS

To

The Candles that burnt to light the road for me… my Husband …my Uncle Bader Aldeen…My Sister.

To my Kids

To the Spirit My Mother and My Grandmother (Set aboha)

TO

All my family and friends

ACKNOWLEDGEMENTS

I thank God so much for taking the Master degree and thank my teacher, and exemplary **Prof. Dr. Hassan Ibrahim Mohamed** and especially thank Dr. Omran Musa for helping me in the difficult.

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ABBREVIATIONS

CO2	Carbon dioxide
PV	Photovoltaic array
WP	Peak watts
Khw	Kilowatt hour
KW	Kilowatt
W	Watt
m	Meter
m^2	Meter square
m^3	Cubic meter
m/s	Meter per second
r.p.m	Radius per minute
Vr	Rated wind speed
Vd	Design wind speed
Vout	Cut-out wind speed
Cpη	The overall power coefficient
Cp	Power coefficient
CE	Efficiency coefficient
Cp max	Maximum value of overall power coefficient
ERI	Energy Research Institute
FMIS	Farmers managed irrigation system
SAB	Sudanese Agricultural Bank
CWD	Crop Wat
FMIS…………………………….	
MCA	Multi-criteria analysis
MJ	Mega joule
MJ / m^2 / day	Mega joule per meter square per day
W/m^2	Watt per meter square
C°	Cent grate

WB	World Bank
P	Power
Q	Pumping rate
H	Head
kg/m^3	Kilogram per cubic meter
kg/m	Kilogram per meter
ρ	Density of air
V	Wind speed
λd	Design tip speed ratio
PDF	Peak demand factor
AAC	Average annual cost
AACC	Average annual capital cost
ARC	Annual recurrent costs
ANN	Annuity factor
I	Investment
r	Interest rate
n	Lifetime
a	Measurement of criteria
ai	Criteria measurement of plan i
vi	Normalized value of ai
I/V	Voltage curve
galls/ hr	Gallon per hours
gall/min	Gallon per minute
cm	Centimeter
mm	Millimeter
m^3 / day	Cubic meter per day
lit/sec	Liter per second
Hp	Horse power
HP-Hrs	Horse power per hours
$	Dollar

SDG	Sudanese pound
SDG/Hr	Sudanese pound per hours
SDG/100hrs	Sudanese pound per 100 hours
HDBE	High density poly ethylene
X obs	Observed value
X 2	Mean of a set of observed values
X	Predicted value
P hydr	Hydraulic Power Requirements
ALS	Average linear sensitivity index
I1, I2	values of input parameter with a chosen range plus and minus a percentage of a base value I
O 2 1, O 2 and O	their respective output values

ABSTRACT

Renewable energy, particularly solar and wind power, offers important opportunities for remote communities to provide power supply, improve local energy security and living conditions. The rising price of fossil fuels in recent years and concerns about the environmental consequences of Carbon dioxide emissions have resulted in emerging interest in the development of renewable energy applications especially for prime mover for smallholder pumping system. The objective of this study is to develop a pump prime mover selection produce in computer format.

The selection procedure implies determination of irrigation requirement based on combining climate inputs, hydrology, crop type and developing stage, soil type, moisture and irrigation method etc. at each time stage of irrigation. The procedure for selection of the suitable pump power type includes: power efficiency water application efficiency, average annual capital cost, max system capacity, cost hp/hrs, output hp/hrs, annual cost / feddans, and unit water costs. The study confirms to use the developed pump type selection model on basis of its statistical validation by test of the data reported by World Bank.

Using input data of Alosaylat Farm application of the multi-criteria analysis of the selection model resulted in ranking the different types of pumps in descending order of: electric, wind, diesel and solar.

Sensitivity analysis is undertaken for three different outputs (hydraulic power requirement, total annual cost and power efficiency) by changing four inputs (head, speed, pipe diameter, and discharge) at positive and negative increments of ±10%, 20% and ±30% for each one of the studied pumps.

The thesis ended with conclusions drawn from the inferences of analysis of collected data and recommendations for both policy making and future studies.

Keywords: Water Pumping, Small holder pumping system, Power source selection, pump selection.

الخلاصة

توفر الطاقة المتجددة ، وخاصة الطاقة الشمسية وطاقة الرياح ، فرصًا هامة للمجتمعات النائية لتوفير إمدادات الطاقة ، وتحسين أمن الطاقة المحلي وظروف المعيشة. أدى ارتفاع أسعار الوقود في السنوات الأخيرة والمخاوف بشأن العواقب البيئية لانبعاثات ثاني أكسيد الكربون إلى ظهور اهتمام متزايد بتطوير تطبيقات الطاقة المتجددة خاصة بالنسبة للمحرك الرئيسي لنظام ضخ المياه للحيازات الصغيرة. الهدف من هذه الدراسة هو تطوير طريقة لاختيار أنسب محرك مضخة في شكل نموذج رياضي على الكمبيوتر.

يعني إجراء الاختيار والتصميم على تحديد متطلبات الري القائمة على الجمع بين المدخلات المناخية، والهيدرولوجيا ، ونوع المحصول ، ومرحلة النمو ، ونوع التربة ، والرطوبة، وطرق الري، في كل مرحلة زمنية من فترة الري. تتضمن طريقة اختيار نوع قدرة المضخة المناسبة: كفاءة استخدام المياه كفاءة استخدام الطاقة ، متوسط تكلفة رأس المال السنوية ، قدرة النظام القصوى ، التكلفة ، التكلفة السنوية / الأفدنة ، وتكاليف وحدة المياه. تؤكد الدراسة على استخدام نموذج اختيار نوع المضخة الذي تم تطويره على أساس التحقق الإحصائي من خلال اختبار البيانات المقدمة من البنك الدولي و تحديد بيانات المدخلات الأكثر حساسية لتطبيق وتثبيت مضخة الكهرباء في مزرعة العسيلات.

باستخدام بيانات المدخلات لمزرعة العيلفون، أدى تطبيق التحليل المتعدد المعايير الخاص بنموذج الاختبار إلى ترتيب أنواع المضخات تنازليا: الكهرباء، الرياح، الديزل والطاقة الشمسية.

تم إجراء تحليل الحساسية لثلاث مخرجات مختلفة (متطلبات الطاقة الهيدروليكية والتكلفة السنوية الإجمالية وكفاءة الطاقة) عن طريق تغيير أربعة مدخلات (ارتفاع الطلمبه والسرعة وقطر الأنبوب والتصرف) بزيادات موجبة وسالبة تبلغ ± 10٪، ±20% و ± 30٪ بالنسبة لكل مضخة من المضخات المدروسة.

انتهت الرسالة بخلاصات مأخوذة من تحليل البيانات التي تم جمعها وبتوصيات خاصة بصنع السياسات والدراسات المستقبلية.

كلمات البحث المفتاحية: ضخ المياه، نظام ضخ المياه للحيازات الصغيرة، واختيار مصدر الطاقة، نموذج اختيار قدرة المضخة.

CHAPTER ONE

INTRODUCTION

1.1 Overview

The rapid increase in energy prices occurred during the last decades has created the need for increased emphasis on efficient energy use. In many water distribution systems, due to large amounts of energy required to pump, transport and apply water, improved management of pumps leading to a reduction in energy usage and operational cost must therefore be regarded as a priority for more efficient system operation. In solving this problem, account should be taken of the efficiencies of the pumps, the structure of the electricity tariff, the consumer-demand pattern, the interaction between the pump controls, the resulting pump power consumptions, and the energy head and flow regime.

1.2 Background and Justification:

Sudan occupies the northeastern part of the continent of Africa. Between 4 and 22 norths of the Equator and longitudes 22 and 38. The length of the maritime border along the Red Sea coast is about 670 km, bordered by two Arab states (Egypt and Libya) and 7 African countries. Sudan has an area of 700,000 square miles.

Sudan is located in East Africa and occupies an area of 1,865,813 square kilometers, which is the second largest country in Africa after Algeria, the third in the Arab world after Algeria and Saudi Arabia, and the sixteenth worldwide (the largest area in the Arab world and Africa before The secession of the south in 2011, the tenth in the world, an area of 2.5 million square kilometers)

Agricultural production in the Sudan depends mainly on large scale public irrigated projects mainly for arable crops. Vegetable production is confined to the valley of the River Nile near the main cities. However, the demand for food increased in recent years due to people migration to cities due to drought. Consequently, number of pumping farms increased to cope with such increase in demand. The majority of these pumps are operated by diesel energy. However, other alternative energy such as wind or solar energy is used in the past for domestic water supply only in the old Gezira Scheme. The energy prices are rising at alarming rate. It is therefore rational to decide on the most optimum alternative energy source. To arrive to such decision technical and economic parameters need to be considered.

1.3 Problem Definition:

Water is a general need in rural areas of developing countries, and therefore means of water lifting are required, grid electricity is generally not available in most rural areas. Diesel fuel is expensive, and the supply to remote areas is uncertain, due to the weak infrastructure and use of dirty roads, especially in the rainy season.

For these reasons it is important to consider the potential of alternative renewable energy sources to provide the power source to operate the pumps.

The alternative prime mover for commercial small holder vegetable farms is to employ either wind pump or electric pumps or diesel pumps.

In general, either the individual or groups of farmers do not have a good device for selecting the best alternative mean for economic irrigation of their farms. Farmers now a day’s follow norms and customs. In some cases, they make decisions on basis of current value of the good rather than the future change in money value due to inflation and technological variations.

1.4 Study Objectives:

The objectives of this study are:

1- To develop hydraulic design scheme using Excel spread sheet for
sizing and setting the specification of smallholder pump operated by either wind, diesel, electricity or solar power.

2- To test verification of the model.

3- To test sensitivity of model output to changes in inputs.

4- To compare and select the most suitable energy source for operating a pump for a smallholder irrigation and domestic use on techno-economic grounds

1.5 Study Scope:

The scope of this study is to analyze the economic and technical feasibility of different energy sources for smallholder pumps used for plantation and domestic supply. This thesis is presented in six chapters.

Chapter one explore the background information regarding the problem faced when the user is confronted with the dilemma of selecting the most preferred watering pump prime mover with constraint of rising prices of energy and lack of electricity in remote areas. Even if the type of energy source to drive the water supply pump the question a rise what is the suitable design under the prevailing environment to employ. On the basis of these problems the objectives of the study were formulated.

Chapter two: provides an overview of history of irrigation of smallholders: its status, issues and future plans and development in Sudan. The review covers theories of design of pumping system of various types with different sources of energy (renewable and non- renewable).

Chapter three: provides development of selection and design model and description of the model.

Chapter four: provides input data collected data analysis, and model development. The chapter gives programming techniques and style, limitation, iterative logic and calculation procedures. Derivation of steps of the selection procedure and the rationale of the proposed and design approach are detailed aided by conceptual flow chart.

Chapter five: focuses on the explanation of the results and discussions. The chapter covers: validation and verification of the design schemes by comparing model outputs with those given by World Bank reports for renewable energy sources (wind and solar).

Sensitivity analysis was run to aid in checking the effects of changing of inputs on models outputs. Finally, the design scheme was applied for the case study of Alosaylat Farm.

Chapter six: gives the conclusions drawn from the inferences of previous chapters and recommendations for future studies.

CHAPTER TWO

LITERATURE REVIEW

2.1 Pumping System

2.1.1 Classification of Water Lifting Devices

According to power sources water lifts can be classified as manual, animal and power operated devices. The power operated devices either be: wind, solar, diesel and electric as described below:

2.1.2 Wind Pumps

According to Meel and Smulders (1989) wind pumping installation incudes the windmill, the transmission, the pump, the storage tank, and the distribution system. The type of windmill referred to in this study is the classical horizontal axis windmill with a mechanical transmission driving a piston pump. This type of windmill in widespread use for which a reasonable amount of validated experience is available. It is important to consider the wind pump installation as a whole, because the total cost of the installation gives the truest picture of what it costs to use wind power to assure a given supply of water. A key consideration is the rotor area of the windmill. The investment cost for a wind pump system is roughly proportional to the rotor area. The total energy production of a wind pump (or amount of water pumped over a certain height) is directly proportional to the rotor area. This means that the design of a windmill installation requires more accurate information on total water consumption than is normally needed for an installation using an engine-driven pump. The amount of water one needs influences the size of rotor one must select, which influences the cost of the windmill. Another important consideration is storage. While storage is not always needed when engine-driven pumps are used (an engine-driven pump can be started up whenever water is needed), a windmill would be practically useless without a storage tank. A windmill only pumps when wind is available. So, a storage tank must be built large enough to store surplus water during periods of strong wind for later use when there is less wind or no wind at all. The matching of windmill and pump is of the utmost importance for a satisfactory performance. Choosing a large pump leads to a high pumping rate when the windmill is running, but on the other hand the windmill will often be standing still if the wind is not sufficient to start the large pump. Choosing a small pump means starting will be easier and the windmill will run more hours, but the pumping rate during those hours will be lower. The optimal choice of the size of the pump depends on the wind regime: for strong winds one may use a larger pump than for weak winds (Meel and Smulders,1989).

The wind rotor is coupled mechanically (directly, or through a gear box) to the piston pump. This is by far the most common type and will be discussed in more detail in the following section Meel (1984)

1) Windmills with rotating transmission: The wind rotor transmits its energy through a (mechanical) rotating transmission to a rotating pump, (centrifugal pump or a screw pump). Both are used especially for low head/high volume applications.
2) Windmills with pneumatic transmission. A few manufacturers fabricate windmills driving air compressors. The compressed air is used for pumping water by means of an air lift pump (basically two concentric pipes), or a positive displacement pump (basically a cylinder with a few valves). This type of transmission allows the windmill to be installed at some distance from the well. Another advantage is the absence of pump rods, and - in case of an air lift pump - of any moving part inside the well.
3) Wind electric pumping systems. Wind electric generators are sometimes used to drive electric pumps directly (without being coupled to an electric grid). Again, this transmission provides the freedom to install the wind machine at a windy site at some distance from the well. Electric

submersible pumps may be used to pump water from narrow boreholes, with flow rates far in excess of those attainable with piston pumps.

4) Windmills with hydraulic transmission: for pumping by means of a hydraulic transmission water is used as the operating fluid.

The types of windmills described above are all horizontal axis windmills. Vertical axis machines will not be mentioned further (Meel, 1984)

2.1.3 Solar Pump

As reported by World Bank (2001) solar pump technology is now commercially mature and technically suitable for most water pumping options. There are more than 40experienced solar pump manufacturers and distributors who have supplied at least 2000 photovoltaic pumping systems. Many are known to be working to the satisfaction of their users. Photovoltaic (PV) pump consists of a series PV module (termed a PV array), which converts sunlight to electricity. This powers an electric motor-pump unit. For deep boreholes (>10m) the motor-pump unit is either a submerged motor with a multi-stag centrifugal pump or a surface motor with a submerged rotary pump or piston pump. For low lift applications surface motor-pumps may be used. Photovoltaic pumps are rated in peak Watts (symbol WP). This is the power output under peak sunlight conditions. The required rating for a particular application depends on the amount of solar radiation available at the proposed installation site. As with wind pumps, a solar pump must be sized to provide sufficient water in the critical month. The critical month is the month in which the ratio of the energy required to the solar energy available is a maximum (Kenna and Gillett1984). The approximate array size for a solar pump can be calculated

Using:

Array size in Wp = 8.2 * Volume head product in m^4/day ÷ Average daily solar irradiation in khw/m^2……………………………………………2.1

Where the volume-head product and the average daily solar irradiation are for the critical month.

2.1.4 Diesel Pumps

The internal combustion engine is the world's most common prime mover and it has had more than a century of intensive development. It is a mature technology; however, it is sometimes incorrectly applied resulting in uneconomic operation. Diesel engines are often over-sized for small, remote power applications of less than one hp) KW. This results in poor part-load performance (Lancashire, *et al* 1987).

The main characteristics of a diesel pump that should be noted if a diesel engine is being considered are listed below:

1. Power rating:

The power rating required is calculated using:

Power rating = 2.7 * Volume head product in m^4/day ÷ Daily pumping time in hours ÷ pump efficiency ……………….2.2

For some applications the required power rating will be less than the smallest commercially available diesel engine. In this case an over-sized engine will have to be used and the engine will have to be either derated or used with a larger pump so that more water is pumped in a shorter time. De-rating usually increases the fuel Consumption. The de-rating factor is the ratio of the required power to the power of the engine being used. It is calculated using:

De-rating factor = Power rating of engine * Power rating required……2.3

The de-rating factor must be known in order to estimate the fuel consumption (Figure 2.1).

2. Life:

Small, lightweight (low cost) diesel engines tend to have short useful lives because they run at high speeds. Wear in machinery is greater at higher speeds. For example, a small 3 kw diesel engine may have a useful life of about 5000 hours between overhauls, whereas a large 50 kw engine will typically achieve over 10,000 hours before sufficient wear has taken place to require a major overhaul.

3. Fuel consumption:

Unfortunately, it is easy to run an inefficient engine system without realizing it, because any shortfall in performance is compensated by running the engine for a longer period. Fuel consumption is dependent on the de-rating factor (figure 2.2).

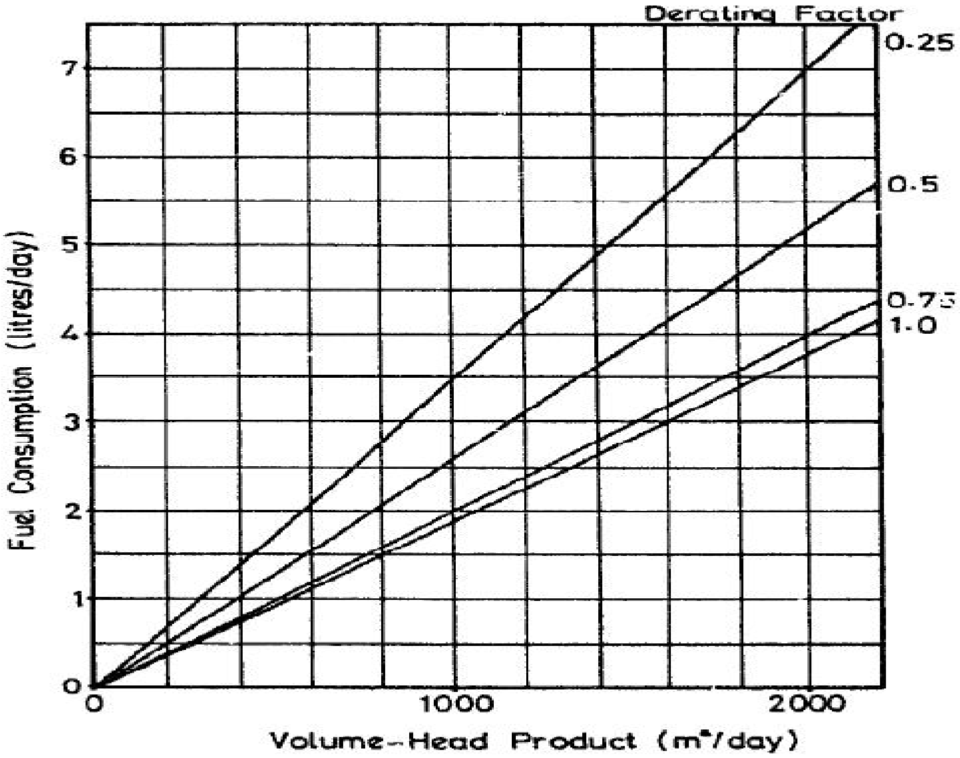


Figure 2.1 Typical fuel consumptions for small diesel engines

Source: (Lancashire, *et al* 1987).

1.2.5 Electrical Drive Pumps

Electric motor is used in many irrigation systems if properly installed and protected, electric motors will provide many years of service. Advantages of electric power include relatively long motor life, low maintenance costs, dependability, and ease of control and operation. An electric motor will deliver full power throughout its life and can be operated from no load to full load without damage. Disadvantages of electric motor include constant speed, an electric power supply required at each pumping location, and normally an annual minimum power cost. (Darnell, 1990).

Motor types:

Most large electric motors are used for irrigation are squirrel cage in duct ion type, three phases, 460 volt motors. Pumps may be connected to the motors by direct of couplings, right angle drives or belts. Most common, if practical, is direct coupling. Right angle drives and belt drives are less than 100 percent efficient and require more energy.

Most electric motors used in centrifugal pumps will be horizontal shaft (figure 2.2)

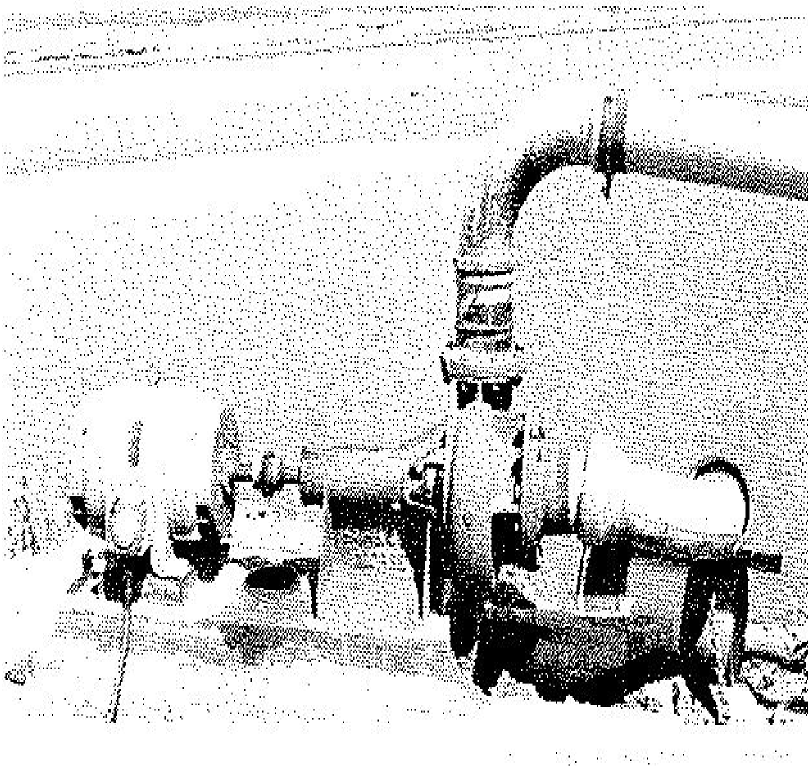


Figure 2.2 Pump with horizontal shaft

Source: (Darnell, 1990)

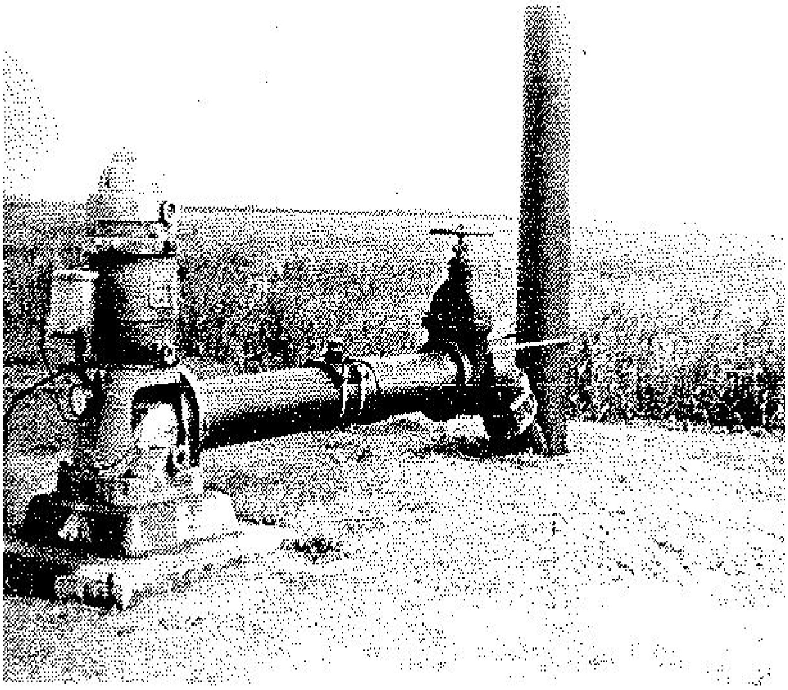


Figure 2.3 Pump with vertical shaft

Source: (Darnell, 1990)

On deep well turbine pumps either a vertical hollow – shaft electric motors (figure 2.3) or Horizontal shaft electric motor together with a hollow-shaft right angle drives must be used (figure 2.2). The hollow-shaft right is necessary so pump impellers can be adjusted

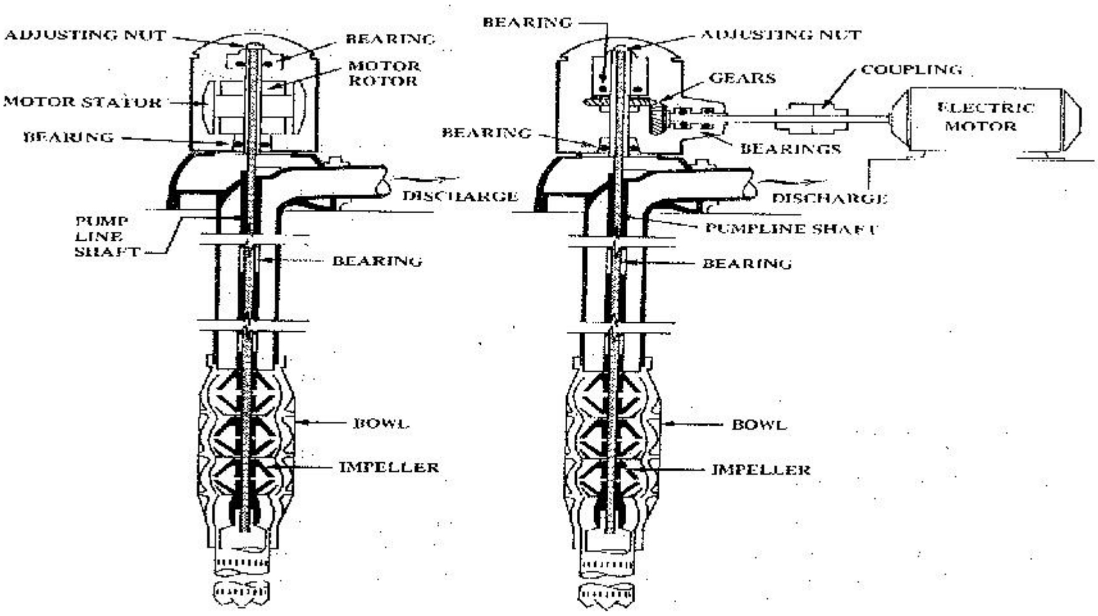


Figure 2.4 Deep well turbine pumps

Source: (Darnell, 1990)

2.2 Pump Irrigation System in Sudan:

Along the centuries primitive methods for lifting irrigation water like Sagia and shaduf were known in northern Sudan, then irrigation by pumps from rivers was introduce on small scale. It has since steadily developed and now takes a very important place in the economic life of the country, now the pump irrigation system, covers an area of about 1.5 million feddans and represent about 35% of the total irrigated area (World Bank's Report,2001).

According to Elaraki (1995), and the world bank's report on Sudan Agrico, sector review, pump schemes in Sudan are classified into public pump irrigation schemes and private pump irrigation schemes. The public pump schemes are mentioned lies behind river bank as White Nile Project. The private pump schemes include the entire private irrigated agricultural in Sudan, and this are classified into:

i) Large scale private pump schemes managed by non-governmental agencies like Abu-Naama scheme on the Blue Nile and Kenana sugar scheme on the White Nile.

ii) Medium-scale pump scheme which were recently privatized.

iii) Small scale private pump manages by farmers which are distributed along the banks of the river Nile tributaries making up an area of about 7000,000 feddans. On the Blue Nile, they extend from Abu-Naama to Khartoum. On the main Nile, they extend from Khartoum Okasha in north of Sudan.

The small private pump schemes that use the ground water are scattered all over the country. Sudan has great potentialities for agricultural production.

According to the Annual Report of Khartoum Ministry of Agriculture (1985), the cultivable area is equal to about 223,629 feddans out of which 88,701 are cultivated. The above mentioned report stated that the irrigation method practiced in the state is the surface irrigation and water is lifted by pump from the Niles and ground aquifers. The area cultivated represents and 40% of the total cultivable area crops grown include vegetables, forages and fruits. The report also stated that all schemes are private and classified to:

1- Large-scale irrigation systems covering an area of 27,649 faddans these are managed by non-Governmental agencies. They include: ElSeleit, El Waha, El Eilafoon, Omdurman schemes and Ummdom project.
2- Medium- scale system managed by cooperatives covering an area of 9,835 feddans.
3- Small- scale irrigation system covering an area of 51,217 feddans

Comprising 57, 75% of the total cultivated area. These schemes are farmer-managed, 2996 of them, extending along the banks of the Blue Nile, White Nile and the Main Nile, (irrigated from the Niles Water) and 2100 of them, irrigated by ground water, are scattered all over the state. FMIS are irrigated by 4908 modern pumps using electric motors and diesel engines.

Farm irrigation system must supply water at rates, quantities and times needed to meet farm irrigation requirements and schedules. They divert water from a water source, convey it to cropped areas of the farm and distribute it over the area being irrigated; in addition, it is essential that the farm irrigation system facilitates management by providing means of measuring and controlling flow (Horst, 2001).

In the pump irrigation system water is raised by pumps from natural sources, whether surface or underground, to the elevation of higher parts of the land so that it will flow over the land by gravity for irrigation purposes. This practice, known as irrigation pumping, is widely followed in arid regions of the world Operation and maintenance for rural water supplies (World Bank's Report 2001).

In a study conducted in Nigeria to estimate the economic returns of small-scale shaduf and pump irrigation system, Kenna and Gillett (1985), concluded that the difference in the returns of irrigation with shaduf and pump irrigation technology is quite high, and recommended that the benefit from promoting these small-scale lifting devices should be considered by policy makers to increase agricultural output.

The focus on irrigation development in most sub-Saharan African countries appears to be shifted toward small-scale irrigation based on motorized pumps. A study was conducted to compare the potential of the new system with traditional methods of irrigation. Data were collected from farmers producing vegetables under traditional shaduf and pump irrigation system in Bauchi state, Nigeria in dry seasons. Irrigation with a pump was superior to irrigation with shaduf in terms of resource use, crop yield and financial returns. Pump users cultivated large plots than shaduf users the use of pumps reduces human energy requirements and drudgery and leads to a higher water discharge rate (Dijk, 1986).

Karunaratne *et,al,*. (1986), analyzing the pump irrigation system in Philippines, concluded that the sizes of potential crop area can be increased by increasing the number of pumps and time of operation, and that there is a potential for major saving in operating costs by reducing the allowable period of pump operation during the wet season, without significant reduction in yields.

Primitive pumps such as Persian wheels- water wheels (sagia) - and shaduf have been used for lifting irrigation water for centuries in Egypt, India and other countries. Now modern pumps of high efficiency that resulted from laboratory research together with carful study of field pumping conditions by competent engineers are used on many irrigated farms Meel (1984). Irrigation pumps are of different types Krutzsch (1976), classified them broadly, He also mentioned that pumps are produced in an endless vanity of sizes and types. A basic system of classification of pumps first defines the principle by which energy is added to the fluid, and then defines the means by which this principle is implemented and finally defines specific geometries commonly employed. Under this system all pumps may be divided into two major categories:

1- Dynamic pumps, in which energy is continually added to increase the fluid velocities within the machine to values in excess of those occurring at the discharge such that subsequent velocity reduction within or beyond the pump produces a pressure increase.

2- Displacement pumps, in which energy is periodically added by application of force to one or more movable boundaries of any desired number of enclosed, fluid-containing volumes resulting in direct increase in pressure up to the values required to move the fluid through valves or ports into the discharge line.

2.3 Irrigation Problems in Sudan:

According to National Council for Research (1982), and Maha, (1997) some of the problems that cause low irrigation efficiency system in Sudan are:

1-Problems at the storage and conveyance system summarized as follow:

a-Losses due to evaporation and evapotranspiration, seepage breakage and weeds at the reservoirs and canals.

b- Silting problems at the reservoirs and canals

c-The calibration of gates and hydraulic structures at both dams and conveying canals has accuracy below the anticipated required.

d- Lack of an efficient system of annual or, even daily recording of actually irrigated area and the amount of water delivered to that area.

2- Problems at the field: lake of work that concentrates in improving the application efficiency such work may require cooperation between research institutes. irrigation engineers, agriculturists and farmers.

Wind driven water pumping systems, windmills, are some of the oldest machines. Predating Christ, windmills have been developed by many cultures to lift water for livestock, land drainage, irrigation, salt production, and domestic supplies. The evolution of these various windmill designs reflects their sources, economic development, skills, geography, and water needs of the different cultures and regions. These designs encompass a broad spectrum of technological sophistication. At one end of this spectrum are the centuries old indigenous windmills such as are still used today in the Mediterranean region and in Southeast Asia. These designs use many wood components including bearings, sail cloth and bamboo mat ' blades ', and are fabricated and maintained locally. On the other end of this spectrum are the motor-type windmills developed at the end of the 1800's and available on today's international export market. These windmills played a major role in opening the western frontiers of North America and Australia, and are used extensively today in these areas primarily for watering live stock. These designs are highly evolved and they "have proven histories of reliability and effectiveness.

Generation of electrical energy from wind can be economically achieved only where a significant wind resource exists. Because of the cubic relationship between wind velocity and output energy, sites with small percentage differences in average wind speeds can have substantial differences in available energy. Therefore, accurate and thorough monitoring of wind resource at potential sites is a critical factor in the sitting of wind turbines. An accurately measured wind-speed frequency spectrum at a site is another important factor. For assessment of the wind-power potential of a site, most investigators have used simple wind-speed distributions that are parameterized solely by the arithmetic mean of the wind speed. Assessment of power output of a wind turbine will be accurate if the wind speeds measured at the hub height (30–50 m) of a wind turbine-generator are known. However, the existing wind data available at most of the meteorological stations worldwide is measured at a height of 10 or 20 m above the ground. Therefore, wind speeds measured at anemometer heights are extrapolated to the hub height of the wind turbine. Many investigators have proposed simple expressions for height extrapolation of wind speeds. This paper reviews wind-speed prediction and forecasting, and development of techniques for accurate assessment of wind-power potential. Also, the need of wind-resource assessment and the techniques and methods used for it are highlighted.

2.4 MCA Evaluation Methods:

Multi-criteria analysis (MCA) is a valuable and increasingly widely-used tool to aid decision making where there is a choice to be made between competing options. MCA can be applied at all levels of decision-making, from the consideration of project alternatives to broad-reaching policy decisions guiding a transition towards sustainability and the green economy.

In particular, multi-criteria methods - aim to identify the best possible alternative or the most plausible ranking of alternatives out of a set of distinct choice possibilities (Janssen, 1992). A variety of MCA methods have been developed during the last decade, rendering the choice of an MCA method for a specific evaluation problem a very tricky task. These are differentiating as to: the nature of the data handled (quantitative, qualitative or mixed data); the formal relationship between policy objectives and choice attributes; the nature of weights attached to the evaluation criteria (quantitative or qualitative); the treatment of outcomes of alternatives in an impact matrix (e.g. pair wise comparison); the specification of decision rules; the type of standardization used for the criteria outcomes; etc.

Use of different methods can sometimes lead to divergent results, in particular when a complete ranking of alternatives is needed (Finco and Nijkamp, 1997). This implies the need for a careful selection of the MCA method to be used in each single evaluation problem, based on the specific characteristics of the method and the problem at hand. To deal with the method uncertainty, many authors suggest the use of two or more MCA methods in a certain evaluation problem in order to validate results obtained. Such a multi-method approach can enrich policy making by reviewing preferences and judgments derived from more than one MCA method (Voogd, 1983; Mysiak, 2006).

CHAPTER THREE

DEVELOPMENT OF SELECTION AND DESIGN MODEL

3.1 Development of Selection Procedure and Design Model

3.2 Description of the Model

The selection model is designed on spread sheet of Excel as program base and runs under the shell of Visual Basic. The program consists of four initial modules each is allocated for one type of pump (wind, solar, diesel and electrical), and one final module for making the selection process. Once the user selected the type of pump he will be prompt to enter input data and run the program to arrive to output data. If the user intended to select the most suitable pump type for certain location, he will be asked to select other types of pumping system sequentially and do the same steps done for the first pump. On completing outputs for the proposed four pumps the user will be asked to run Multi-Criteria Analysis (MCA) module for selecting the most suitable pump. If the user already decided the type of pumping plant, then he just takes the output generated for the said pump as design element.

3.2.1 Pumping System Selection and Appraisal Framework:

Sizing of alternative pumping systems can be done following the steps:

1- Assess the water requirements

2- Determine the monthly hydraulic power requirements.

3- Determine the available power resources.

4- Identify the design month.

5- Size the power source and pump and selection of a suitable system configuration

6- specifying pump performance and evaluate the economic and financial status

7- State specifications and outputs

8- Run Multi-Criteria Analysis (MCA).

1. **Assessment of the water requirements:** This step, is identical for all pumping technologies, it will not be repeated for each pump it will be explained when design procedure is delineated for wind pump.

2. **Determining monthly hydraulic power requirements:** There are identical for all pumping systems and it will be extensively described in the design procedure is delineated for wind pump. In short, the average monthly pumping rates must be determined as well as the total pumping head.

3. **Determination of the available power resources:** For solar power, data are required in a format similar to that used in selecting wind pump. In tropical regions, the solar irradiation reaching the earth's surface is of the order of 10 to 20 MJ / m^2 / day (or 100 to 200W/m^2). (Details are given in solar pump selection procedure). Other power sources (engine fuel, animal, human power) are assumed to be available on demand and details shall be depicted in their respective selection procedure. In reality the availability of fuel sometimes poses problems.

4. **Determination of the design month:** The procedure for identification of the design month for each type of pump is outlined in their respective selection procedure given below.

For the wind pump system, the design month is the month in which the water demand is highest in relation to the wind power resources.

For Solar pumps the design month is the month having the highest ratio of daily average water requirements to daily average solar irradiation.

For Diesel Engine, animal and hand pumps: the design month is the month with the highest water demand. It should be noted, however, that the real costs of pumping may increase in harvesting and sowing periods when both human and animal labor are in short supply.

5. **Sizing of the power source and pump:** Wind pumps: The necessary steps for assessment are summarized in wind pump detailed procedure. For the example system, the design month power requirement is 41 W. The

average wind speed in the design month is 3.3 m/s. The performance of the wind pump being a classical wind pump with high pumping head, will lie somewhere between "low" and "medium". In this way one finds from the monograms in Figure 3.1 a rotor diameter between 3.8 and 5.4 m. With the detailed method of Section 3.4, we found 4.5 m, resulting in the choice of a 4.3 m wind pump. A tank size of 30 m is chosen somewhat more than two days of storage.

For Solar pumps: The outlined detailed procedure for sizing solar pumps given in coming section provides a guide on sizing of both the power source and pump. A photovoltaic array (PV array) is rated at a temperature of 25C° under full sunshine (specifically 1000 W/m^2 irradiance) by its electrical output, i.e. its peak power performance in Watts. The efficiency of solar cells at peak power lies between 10 and 13%. At higher temperatures the efficiency is lower.

For Engine driven pumps aspects taken into account in sizing of the power source and pump and explained in the detailed procedure.

Number of hours of operation: This is related to irrigation practices, presence of a storage tank, etc. For example, for direct field application pump may be operated by its owner for four hours per day. For a large irrigation scheme of several farms, a diesel pump may operate twelve hours per day.

1- De-rating factor: Usually the engine is oversized in relation to the pump. For small pumps the de-rating is around 0.5, for large motor pump sets, matched to the application, and is around 0.7.
2- Minimum motor size: The smallest size of diesel motor readily available is approximately 2.5 kW, and the smallest size of kerosene motor used in pump sets is of the order of 0.5 kW. For very small pumping requirements these sizes may be too large. In such cases the number of hours of operation will be reduced. Sometimes the de-rating factor is further reduced. Storage tanks are normally not used for irrigation with engine

pumps. Rural water supply schemes usually incorporate storage tanks with a capacity of half a day to two days.

6. **Evaluate the economic and financial status**

An economic or financial analysis is intended to determine whether the investment in a wind pump is justified. Such an analysis can also help to determine if it makes sense to start a dissemination program. Clearly its success depends on whether or not prospective users benefit from investing in the technology, it is customary to discern two levels of analysis:

1- Economic analysis (also referred to as national or macroeconomic analysis): Is the investment profitable from a national resource allocation perspective?

2- Financial analysis (also referred to as business or microeconomic analysis): Is the investment profitable from the user's perspective?

Financial analysis for the direct user can be split up into two parts (Figure3.2):

i) Cost-benefit analysis: is the investment profitable, i.e. do the total benefits exceed the costs over a certain period?

ii) Cash flow analysis: can the user finance his investment? In a cash flow analysis all expenditures and receipts are calculated year by year. All loans, subsidies, profits, the user's own capital, etc. should be included in the analysis. If the farmer is to survive, all expenditures within one single year must be covered by receipts in

Costs are basically divided into investment costs (or capital costs) and recurrent costs. The investment is a cost incurred once in the lifetime of an installation (although payment of terms and interest may be spread over a longer period). Recurrent costs occur every year in more or less the same way. They include operation, maintenance and repair costs. In order to make investment and recurrent costs comparable one may adopt two approaches:

1) Annuity method: Convert the investment into an equivalent yearly cost called the annuity. This is the amount of money that would have to be paid every year during the (economic) lifetime of the installation, if the

investment were financed through a loan. The annuity is constant throughout the years, exactly covering repayment of the investment and interest on the debt. The total yearly costs are then obtained by adding the annuity and the recurrent costs together.

2) Present worth method: Convert the recurrent costs into an equivalent capital, the present worth. The present worth of future costs is the amount of capital that should be reserved at the moment of investment in order to cover all future costs. It is calculated taking the interest on the capital (or what is left of it) into account. The total "life cycle cost" is then obtained by adding the investment cost and the present worth of the recurrent costs together. In this work we will use the annuity method. It is somewhat simpler than the life cycle cost method and the results are more directly understandable for a broad audience. The conclusions that can be drawn from both methods are practically identical, although the annuity method is somewhat more limited with respect to future cost escalations of isolated cost components, such as fuel.

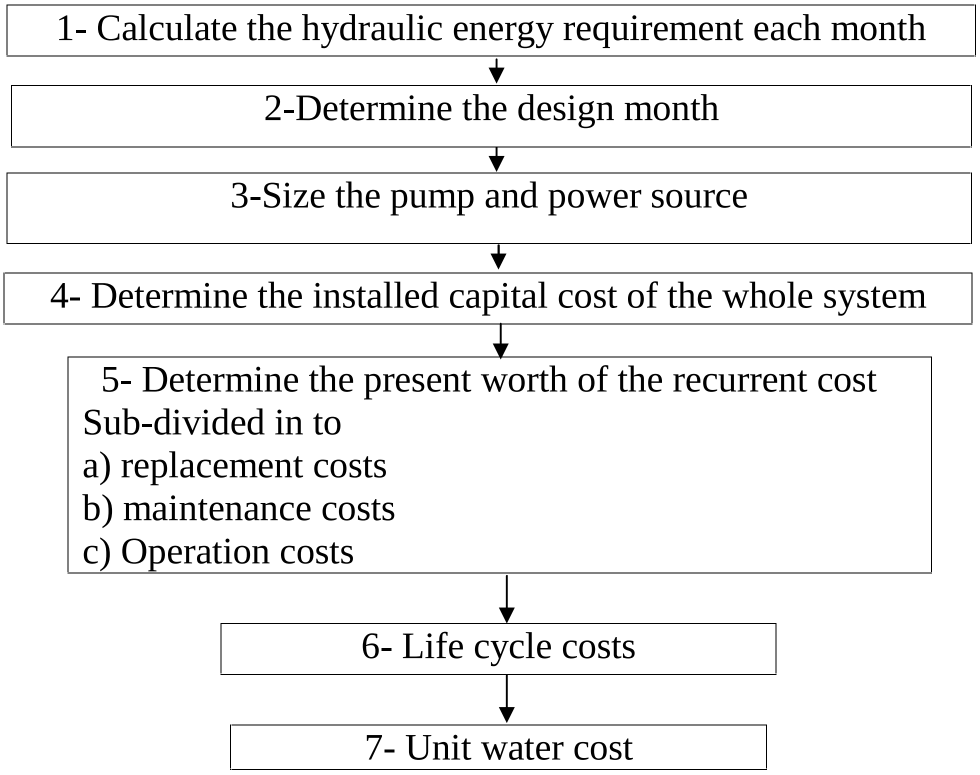


Figure 3.1 :Step by step procedure to determine pumping costs

Source: (Meel and Smulders1989)

7. Determination of specifications and outputs:
8. Determination of MCA and ranking and selection of alternative pumping system.

3.2.2 Wind Pump Selection and Sizing Module

The steps to be followed in selecting the optimum size of wind pump for a site are: Assess water requirements, determine hydraulic power requirements, determine the available wind power resources, identify the design month, and Size the main components of the pump.

If one were to choose to operate the wind pump as a fuel saver, sizing of the pump would be an iterative process, going from sizing to economic analysis, and back to sizing again. Choosing a very large windmill which fulfils all needs would save a large amount of fuel, but is not necessarily the most economical solution: there will be periods of high wind speeds with excess of water which cannot be used, and this does not correspond to any fuel saving.

For a very small windmill all output can be put to use, but the fuel saving is less than the real potential. One must find the optimal size through the iterative process.

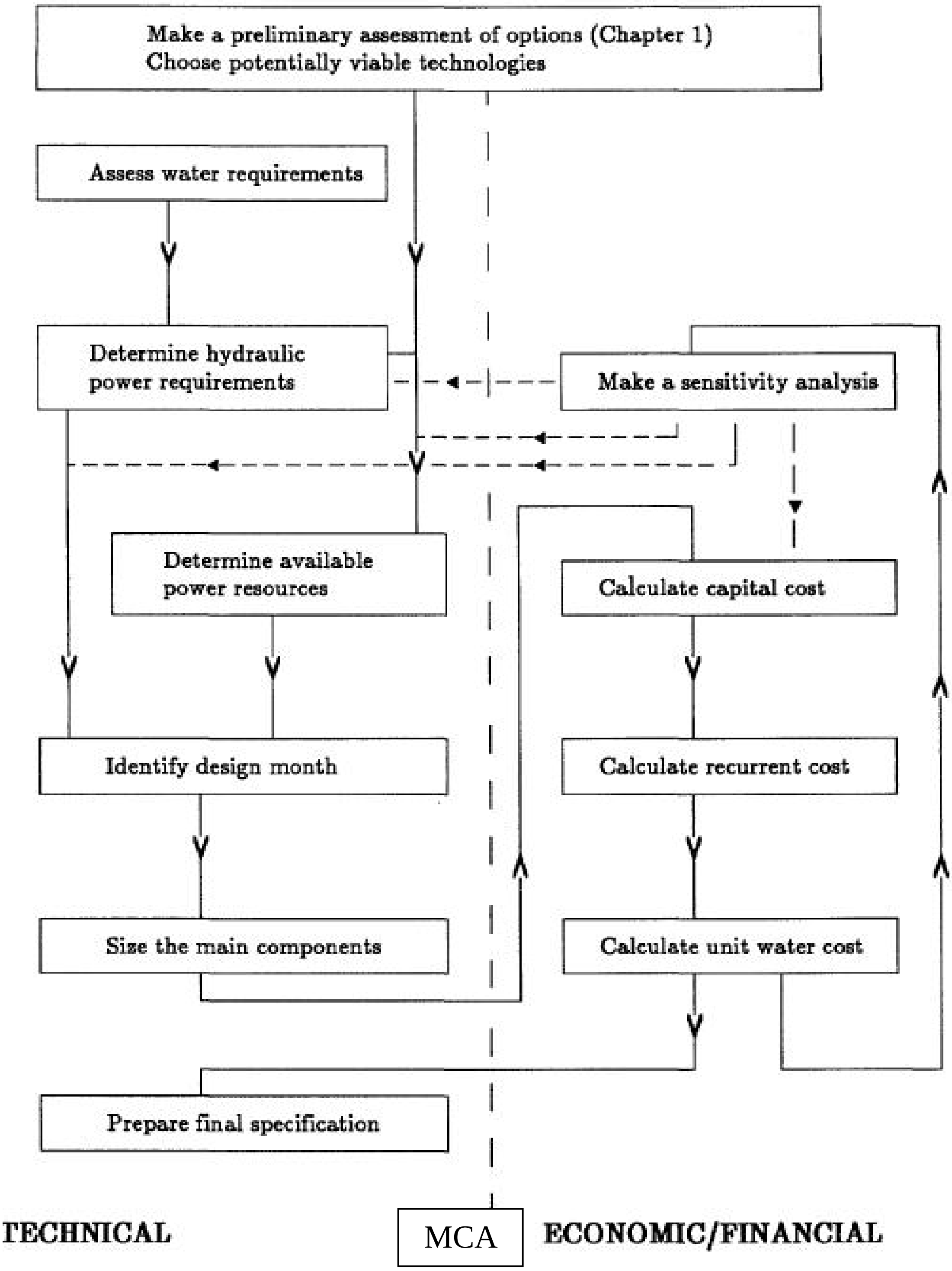


Figure 3.2: Steps to be taken for evaluation and design of wind pumping installations

Source: (Meel and Smulders,1989)

The data required for sizing optimum wind pump as described and used by World Bank (WB) is given in (Table 3.1).

Step1: Assess water requirements: this includes: water needed for irrigation and domestic uses.

- The amount of water needed to irrigate a given area depends on a number of factors. The most important of these are: - Nature of crop, crop growth cycle, - Climatic conditions - Type and condition of soil, - Topography of the terrain, - Conveyance efficiency, - Field application efficiency, and - Water quality.

An estimate of the quantity of water required for irrigation can usually be obtained from local experts, preferably agronomists. However, crop wat program of FAO may be used to estimate water needs. It involves three major stages:

a. Crop water requirements are estimated, using prediction methods, because of the difficulty of obtaining accurate field measurements.
b. The effective rainfall and groundwater contributions to the crop are subtracted from the crop water requirements to give the net irrigation requirements.
c. Field application and water conveyance efficiency are taken into account to give the gross pumped water requirements.

- Water requirements for Domestic uses (rural water supply): The estimate of water demand for villages and livestock is considerably easier than that for irrigation, because the volume required can be obtained by multiplying the number of people or animals by their estimated per capita consumption. Domestic water requirements per capita vary markedly in response to the actual availability of water. If there is a home supply, consumption may be five or more times greater than if water has to be collected at a public water point.

A World Health Organization survey in 1970 showed that the average water consumption in developing countries ranges from 35 to 90 liters per capita per day. The long-term aim of water development is to provide all people with ready access to safe water. For the near future a reasonable goal to aim for would be a water consumption of about 40 liters per capita per day. Thus for typical village populations of 500, water supplies will have to be sized to provide about 20 m per day. In order to limit the time spent on collecting and carrying water, a single pump or water point should usually supply no more than about 500 people. The typical daily water requirements for a range of livestock are given in (Table 3.2).

Table 3.1: Typical daily water requirements for a range of livestock

Species	Liters of water/head
Camels	40 - 90
Horses	30 - 40
Cattle	20 - 40
Milk cow in production	70 - 100
Sheep and goats	1 - 5
Swine	3 - 6
Lactating sow	25
Poultry	0.2 - 0.3
Human	40

Source: (Meel and Smulders1989).

Step 2: -

Based on estimate of the water requirements, the hydraulic power requirements can be determined, using the equation 3.l.

$P = 0.113 \times q \times H$ ……………………….3.1

Where: P = average power (W), q = pumping rate (m^3/day), H= total head (m)

The total head includes: - Pumping height: (Static water level of the water source below ground level and Drawdown of the water source), Static lifting height above ground level, and Head losses in the piping (due to friction). For wind pumps the pressure loss is mostly kept very small, about 5% to 10% of the total head.

Step 3: - Determine the available wind power resources:

For the study location data needed to include: Height above sea level (m), Hub height (m), Terrain roughness, Combined correction factor for hub height and roughness, monthly data for: Average potential wind speed at 10 m (m/s), Average wind speed at hub height (m/s), and Density of Air (kg/m^3).

The necessary steps for assessment are summarized here:

- Interpretation of data of meteorological service.
- Correction and conversion of data to so-called potential wind speed, which would be observed at that location if the terrain were completely flat and open.
- Correction for the terrain characteristics of the site and the hub height of the projected wind machine to obtain the real monthly average values of the potential wind speed, at hub height.
- Assessment of the site's wind power resources.
- Once the average wind speed and the air density are known, one may calculate the specific wind power:

The Specific wind power (power input to a wind pump) then shall be estimated using the relation:

$P_{wind} = 0.5 * \rho * V^3$ ………….3.2

Where:

ρ = density of air (kg/m^3), V= average wind speed (m/s)

Step 4: - Identify the design month:

The sizing methodology for stand-alone systems is based on the concept of the critical month or design month. This is the month in which the water demand is highest in relation to the wind power resources, i.e. the month when the system will be most heavily loaded. The design month is found by calculating the ratio of the hydraulic power requirement to the wind power resource for each month. The month in which this ratio is a maximum is the design month. This ratio has the dimension of an area and will be referred to as the reference area. It is related to the rotor area needed to capture sufficient power. In sizing the wind pump, this reference area will be converted into a real rotor area by incorporating specific wind turbine parameters.

Step 5: - Size the main components of the pump:

Considerations in choosing the type of wind pump: Choosing the type of system that would fulfill the requirements of a customer is not easy. (Table 3.3) and gives a rough indication of which type of wind pump suits a certain requirement.

Table 3.2: Types of pumps suitable for application in combination with wind machine

Type	Typical pumping head	Maximum efficiency pump +pump transmission	
Piston pump	›20 m	›90%	80 - 90%
	10 m	70 -80	60 -70%
	3 m	50 -60%	40 -50%
	‹3 m	decreasing to zero	
Centrifugal pump			
Single stage, direct drive	1- 10 m	40 - 60 %	30 -50%
Multistage, electric, deep well	10 - 200 m	50 - 60 %	20 – 30%
Screw pump	0 - 3 m	60 - 70 %	40-60%
Air lift	10 -50 m	20 -30 % *	10 %*
Air-driven displacement	02-50 m	40 -70 %	10-30 %

(Source: Meel and Smulders1989).

Values with 200 an asterisk are tentative as field data are scanty.

In some cases, more options are feasible and these will have to be checked. One important consideration is whether or not a design is available on the market.

If a mechanical wind pump driving a piston pump is the only solution; one still has to decide whether to go for a classical multi-bladed wind pump or one of a more modern design. It is more important that, one must decide whether to import the wind pumps or to start local production.

In general - and especially for deep well pumping - the classical multi-bladed wind pumps are more reliable than the modern pumps of innovative designs. Field experience with classical wind pumps runs over decades, while none of the modern designs has been field tested for more than 10 years. However, maintenance of the classical windmill can be difficult if specialized spare parts have to be imported. In general, the modern designs make more use of standard materials that can be obtained on the local market. In all cases a minimum requirement for proper maintenance is the availability of spare parts.

The sizing of a wind pump system must be based on the establishment of a compromise between two conflicting demands: - High output (i.e. a lot of water must be pumped) - High output availability (i.e. the water must become available in a regular, continuous fashion).

A wind pump with a large pump will lift a large amount of water, but needs more wind to get it started, and therefore often stands still. It provides high output but low output availability. A wind pump with a small pump will start easily, but pump less water. It provides a low output but has high output availability.

To perform the sizing procedure, the following information is needed: Tower height, Rotor diameter, Pump size, Storage tank, and Piping.

1. Tower height: The tower height should be chosen so as to raise the rotor blades well above any obstacles in the surroundings of the windmill. In the presence of trees, the rotor tips should have a clearance of at least one rotor diameter over the tree tops. The choice of the tower height is limited, as manufacturers normally supply a standard range of towers, from 10 to 15 m high (standard height of 12 m). For small windmills one finds towers down to 6 m and for large windmills up to 24 m.

2. Rotor diameter: The rotor diameter is the most important characteristic of a wind pump, determining both its output and its cost. The Monogram in Figure 3.4 may be used to determine the required rotor size as follows:

a- The starting point is the axis of the reference area, which is the ratio of average hydraulic power requirement and specific wind power. This ratio was determined in the format sheet for determining the design month.

b- The right hand part of the Monogram accounts for the energy production coefficient, which is related to the type of wind pump.

c- The left hand part of the Monogram accounts for the peak overall power coefficient, which depends mainly on the pumping height.

d- Finally, one finds the required rotor diameter. If a windmill of exactly this diameter is not available, choose the nearest standard size.

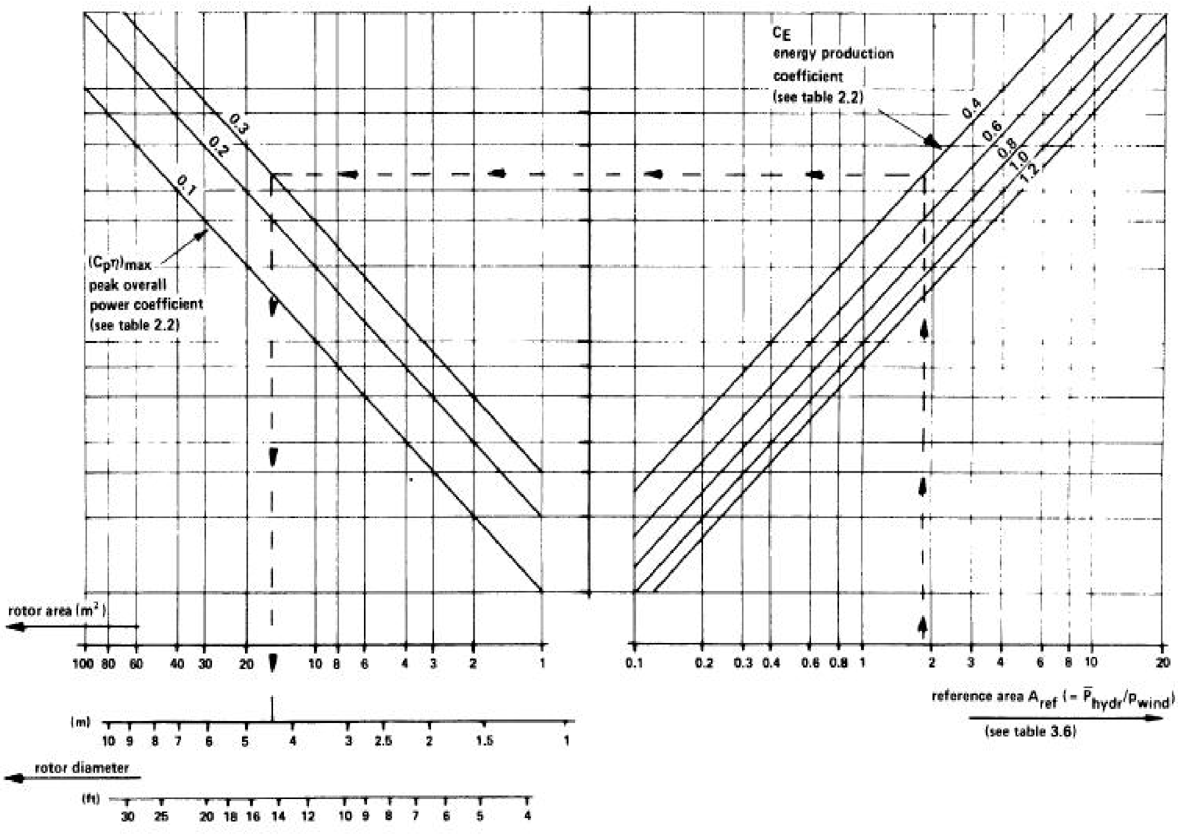


Figure 3.3 Monogram to determine wind pump rotor size

Source: (Meel and Smulders 1989).

3. Pump size: The Monogram in (Figure 3.5) may be used to determine the size of the pump, characterized by its stroke volume.

The Monogram can be used as follows:

- The starting point is the rotor diameter, the horizontal axis on the right.
- The design wind speed is taken into account in the upper right quadrant. (Value of the ratio of design wind speed to average wind speed. If the density of air differs significantly from 1.2 kg/m, apply a correction as indicated in the figure: instead of Vd one should take Vd times V (p/1.2).
- The speed of operation is represented in the upper left part of the Monogram. The design tip speed ratio(λd) is approximately 1.0 (unity) for most classical wind pumps, and 1.5 to 2.0 for recent designs. The transmission ratio is equal to unity for directly-driven wind pumps and around 1/3 for back-geared wind pumps. The Monogram has been drawn for a value of the peak overall power coefficient of 0.25. If it differs significantly apply a correction as indicated in the (figure3.5), multiplying (λd.i) by 0.25/ (Cpη) max. In the example system, comprising a classical back-geared wind pump, (λd.i) is equal to 0.3. As indicated earlier the peak overall power coefficient (Cpη) max = 0.3. Therefore, the corrected value 0.3 x 0.25 / 0.3 = 0.25 is applied.
- The lower left part of the Monogram takes into account the total head.
- Find on the lower vertical axis the effective stroke volume, the volume of water to be pumped in each stroke. The geometric stroke volume V stroke must be slightly larger (V-stroke is the volume displaced by the piston in each stroke). The relation between the two is expressed in the volumetric efficiency 71 vol. For the slow-running pumps of classical wind pumps it ranges from 0.9 to unity. For pumps in recent designs, especially pumps having a starting nozzle, 7vol may be lower, around 0.8.

- On the basis of the stroke volume thus obtained select the pump diameter and the stroke. The result will depend on the stroke settings available in the windmill's transmission, and on the pump diameters available. Sometimes an important limiting factor for the pump diameter is the tube-well in which the pump has to fit.

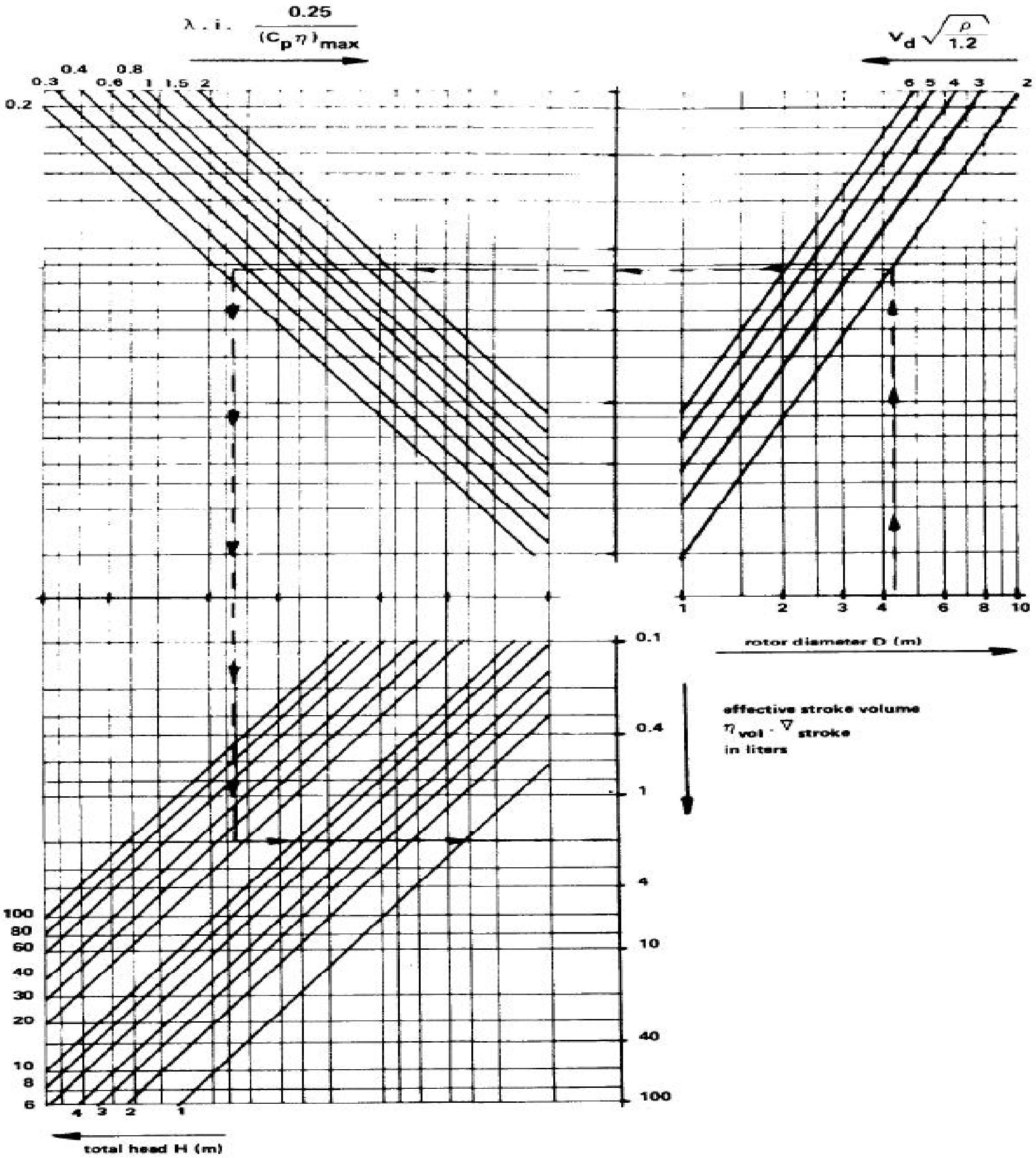


Figure 3.4 Monogram for sizing pump for wind pumping plant

Source: (Meel and Smulders1989).

(Figure 3.6) can be helpful in selecting a combination of diameter and stroke. Note that the figure gives the internal diameter of the pump cylinder, whereas the external diameter has to fit into the tube well.

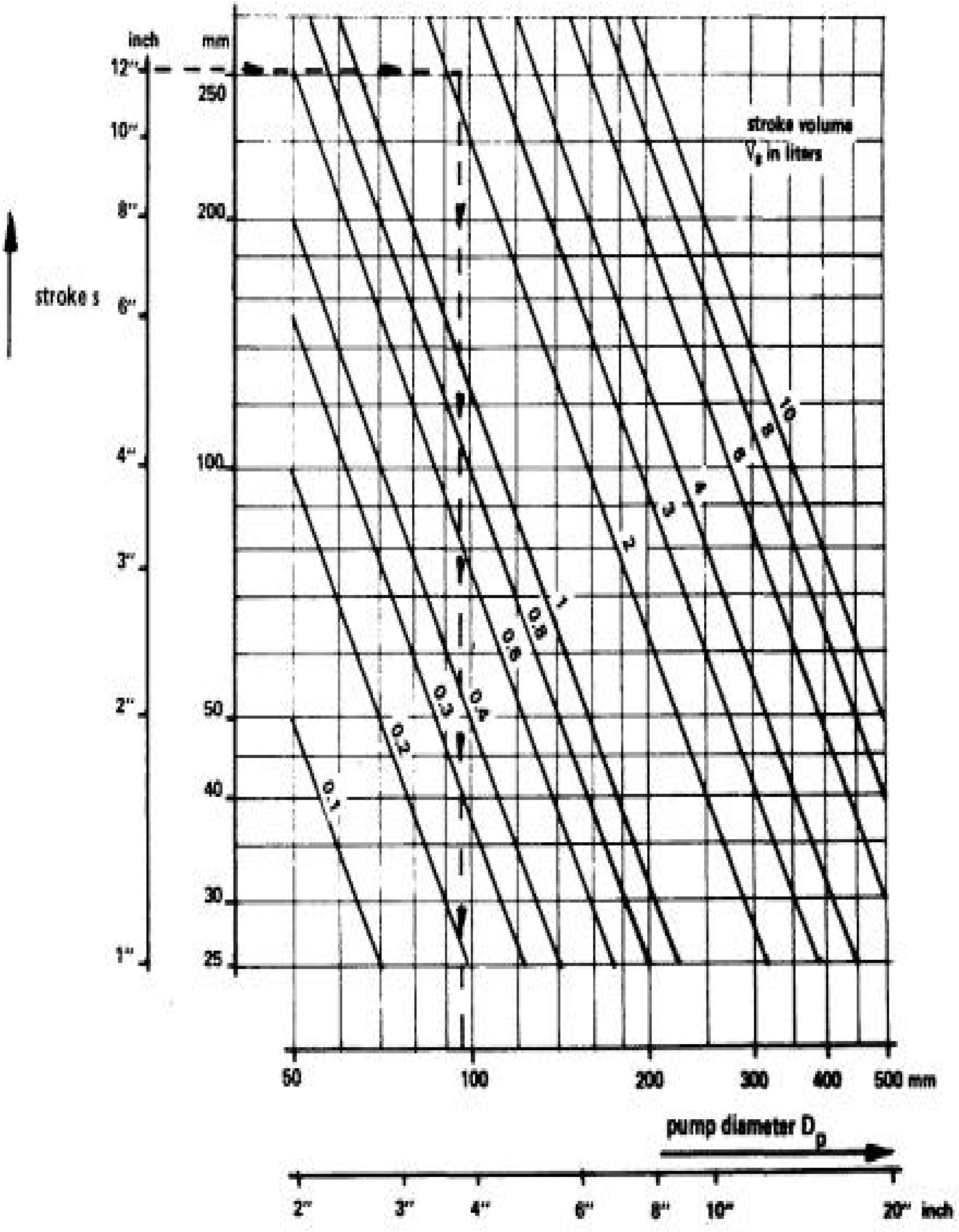


Figure 3.5 Monogram to choose stroke and diameter of piston pump

Source: (Meel and Smulders1989)

4. Storage tank: With engine-driven pumps, storage tanks are normally made large enough to adapt the pumping rate to the rate of consumption

(supply this peak demand). The tank should also be large enough to guarantee some emergency supply in case the pump breaks down. For Sizing the tank of a wind pump system the tank should be made large enough to store all water pumped during the hours that consumption is low or zero (especially at night). In calculating tank sized in this way should be large enough to store some water for days when the wind speed is below average. Tanks are usually designed to hold enough water for 1 to 3 days of consumption.

For irrigation, a storage tank should have a minimum capacity large enough to store about half-a-day's output in the month of highest demand.

For economic reasons the maximum size is normally 1 or 1.5 days of storage. The maximum cost (and hence the maximum size) of the storage tank also depends somewhat on the crops to be grown. For high-value crops, a somewhat higher cost for the storage tank may be acceptable. A very detailed way of sizing a tank is possible on the basis of sequential hourly wind data. One may calculate the output of a windmill on an hourly basis, and calculate excess and deficit of water. Analyzing these data one may choose an appropriate size for the storage tank.

5. Piping: The network of pipes that carries water to the storage tank is an integral part of the wind pump system. It can be designed using well-established engineering rules. In order to size the piping, the maximum flow rate of the water must first be estimated. The maximum pumping rate will be approximately 3 to 5 times the average pumping rate in the design month. If there are no air chambers, the flow of water pumped will not be continuous but pulsating. The peak flow will be approximately 3 times the maximum pumping rate. The flow rates suggested for sizing the pipe work are: - Wind pump without air chambers – 10 to 15 times the average pumping rate during design month. Wind pump with air chambers - 3 to 5 times the average pumping rate during design month. The piping of a wind pump must be designed for a relatively low head loss of around 10% of total pumping height.

6. Preparing the final specifications: The Format sheet for specification of wind pump performance is given in (figure 3.7).

WIND PUMP PERFORMANCE SPECIFICATION

Location ………………………………. Height above sea level ………..m

1. Water source

Type……………………

Distance (for surface pumping)……….m

Diameter (for wells) ……………………….mm

Water level (when pumping)……………..m

2. Delivery system

Type………………………………

Length…………………………..m

Pipe diameter……………………..mm

Efficiency ……………………..%

3. Storage system

Type…………………………..

Volume …………………………..m³

Height ………………………..m

4. Design month details

Month…………………………………

End use water requirement……….. m³/day

Pumped water requirement………….. m³/day

Hydraulic power requirement……….. W

Average wind speed at hub height ………m/s

5. Wind regime and water requirement

	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec
average wind speed at hub height(m/s)												
Pumped water requirement(m³/day)												

6.Windmill specification

Tower height………m

Machine type ……

Rotor diameter…………………m

Stork………….mm

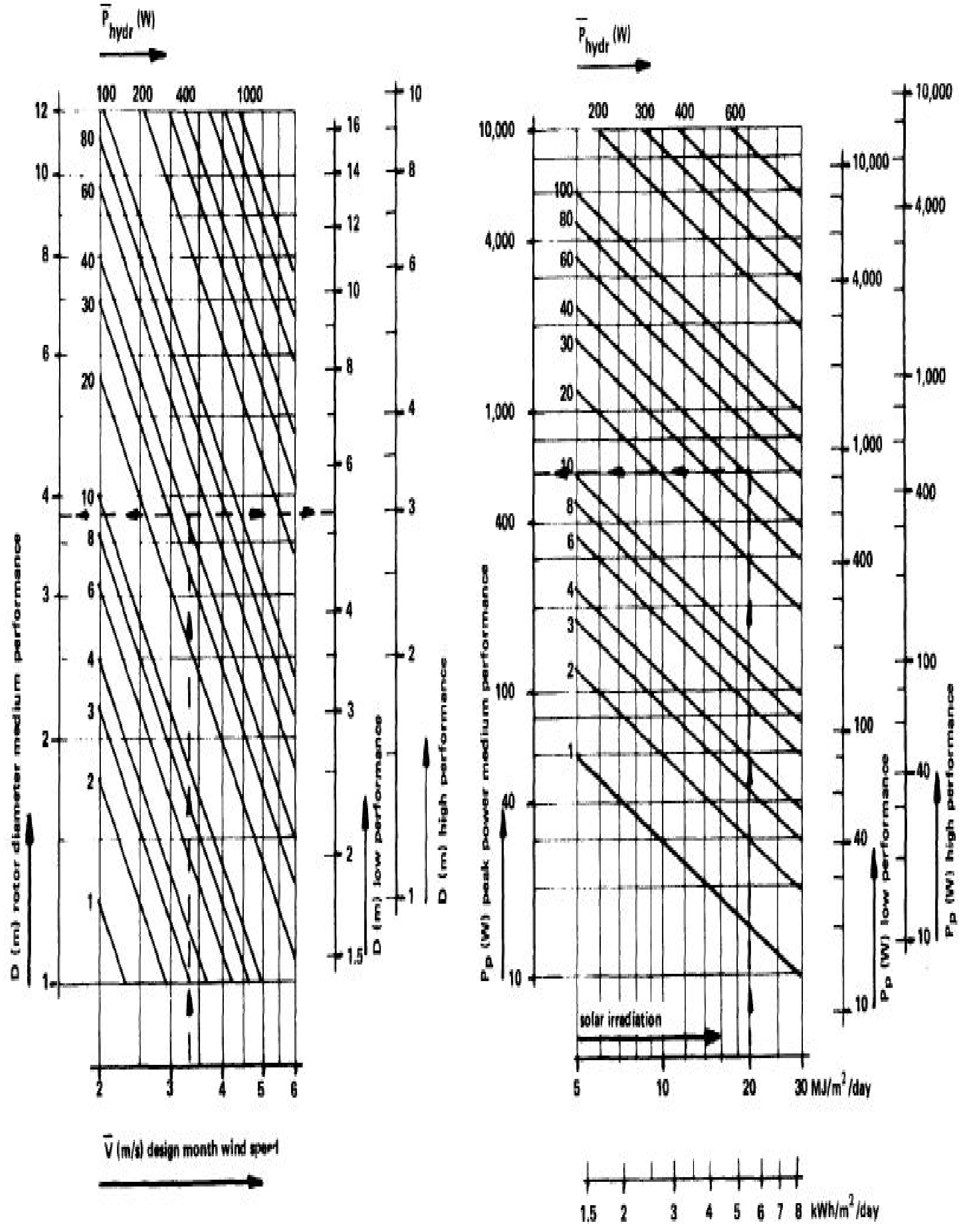
Pump type…………………

Cylinder diameter………………mm

Figure 3.6 Format sheet for specification of wind pump performance (Meel and Smulders1989).

3.2.3 Solar Pump Selection and Sizing Module

The pumping unit is designed to be well matched to the array under full sunshine conditions. At lower irradiation levels, however, the matching is poorer and the total efficiency of the system drops. It is customary (World’s reports 2001) to define daily subsystem efficiency, defined as the ratio of daily hydraulic energy output to the daily electrical energy input from the solar panel. (Table 3.4) (Taken from the "Solar Water Pumping Handbook, (world bank's report,2001). provides a guide on typical values for different types of system configuration. From Table 2.9 we have chosen three typical levels of performance: - low performance, 7s = 25% - medium performance, 77s = 35% - high performance, 77s = 45%. The overall (daily) average efficiency - the ratio of the daily water energy output to the solar irradiation input - is the product of the array efficiency times daily subsystem efficiency; e.g. if 71array = 10% and 71s = 35% then the overall (daily) efficiency is 3.5%. A value of 5% represents a system with a good efficiency. Also for solar pumps one needs to consider the sizing of the storage tank. For irrigation the storage tank may be somewhat smaller than in the case of a windmill, since some water is pumped during daylight hours each day. For rural water supply one may assume two days of storage.



a. Wind pumps

b. Solar pumps

Figure 3.7 Monogram for determining approximate size of wind and solar pumps

(Source: Meel and Smulders1989)

Table 3.3: Subsystem efficiency

Lift	Sub-system type	Typical Subsystem daily energy efficiency		Typical Subsystem peak power efficiency	
		Average	Good	Average	Good
2 meter	Surface Suction or floating units with submerged suction utilizing brush or brush-less permanent magnet d.c. motors and centrifugal pumps	25%	30%	30%	40%
7 meter	-floating d.c. units with submerged pump - submerged pump with Surface mounted motor, brush or brush-less permanent magnet d.c. motors single or multi stage centrifugal pumps	28%	40%	40%	60%
20 meter	- a.c or d.c submerged multi stage centrifugal pump set or - submerged positive displacement pump with d.c. Surface motor	32%	42%	35%	45%

(Source: Kenna and Gillett, 1985)

To help the reader make an initial appraisal of the feasibility of using a solar pump, the decision chart in (Figure 3.8) has been prepared. It refers only to the major mechanized options for water lifting, i.e. wind, solar and diesel, and is based on the unit water costs. Trace a path from the starting point of the chart for the particular values of energy equivalent (Vh), peak demand factor (PDF), solar irradiation (H) and wind speed (u). Figure 3.8 is used for irrigation pumps and (Figure 3.9) for rural water supplies. Choices are represented by diamond shaped boxes. The assessment is given when a rectangular box is reached.

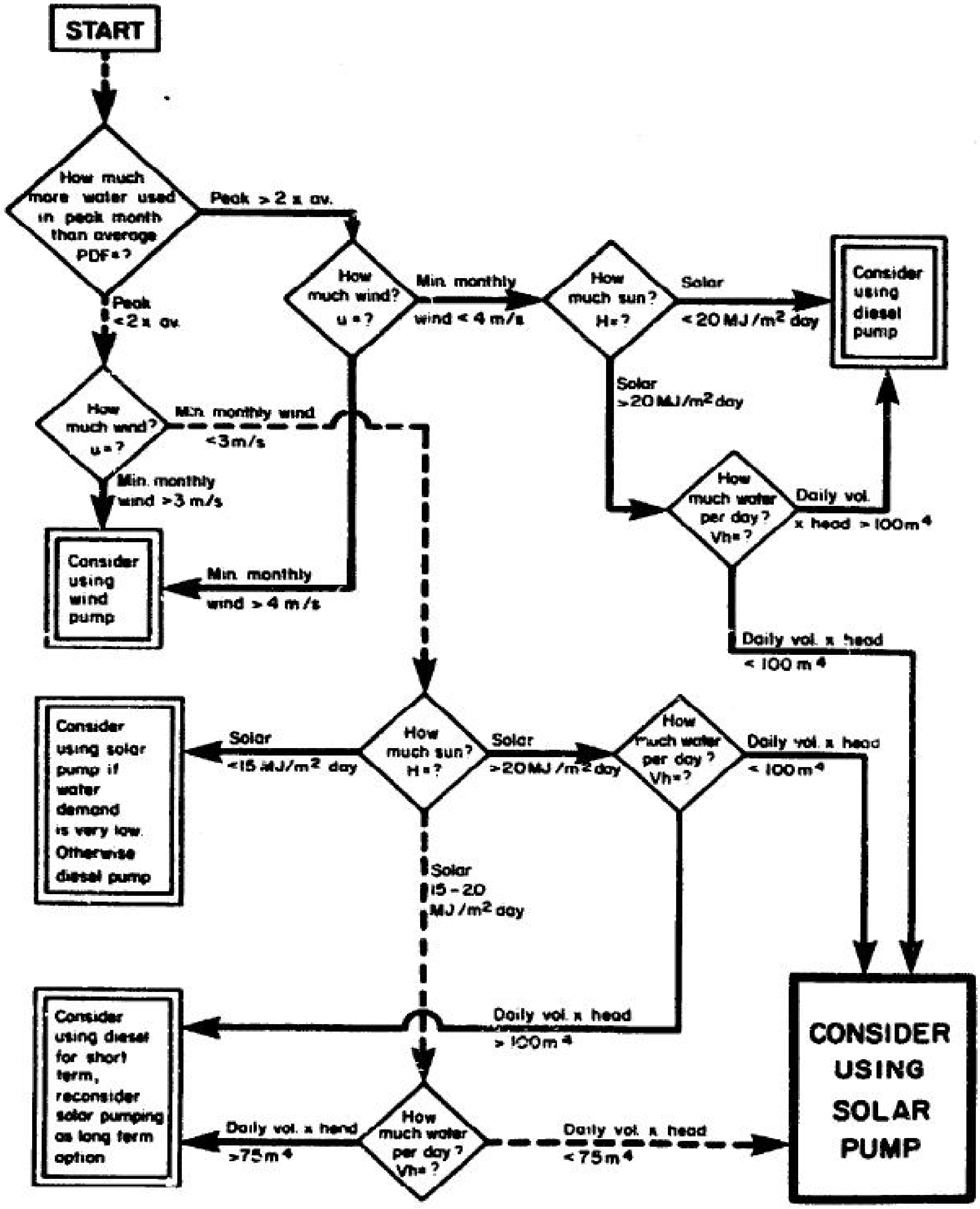


Figure 3.8 Decision chart for an appraisal of solar pumps for irrigation

(Source: Kenna and Gillett,1985)

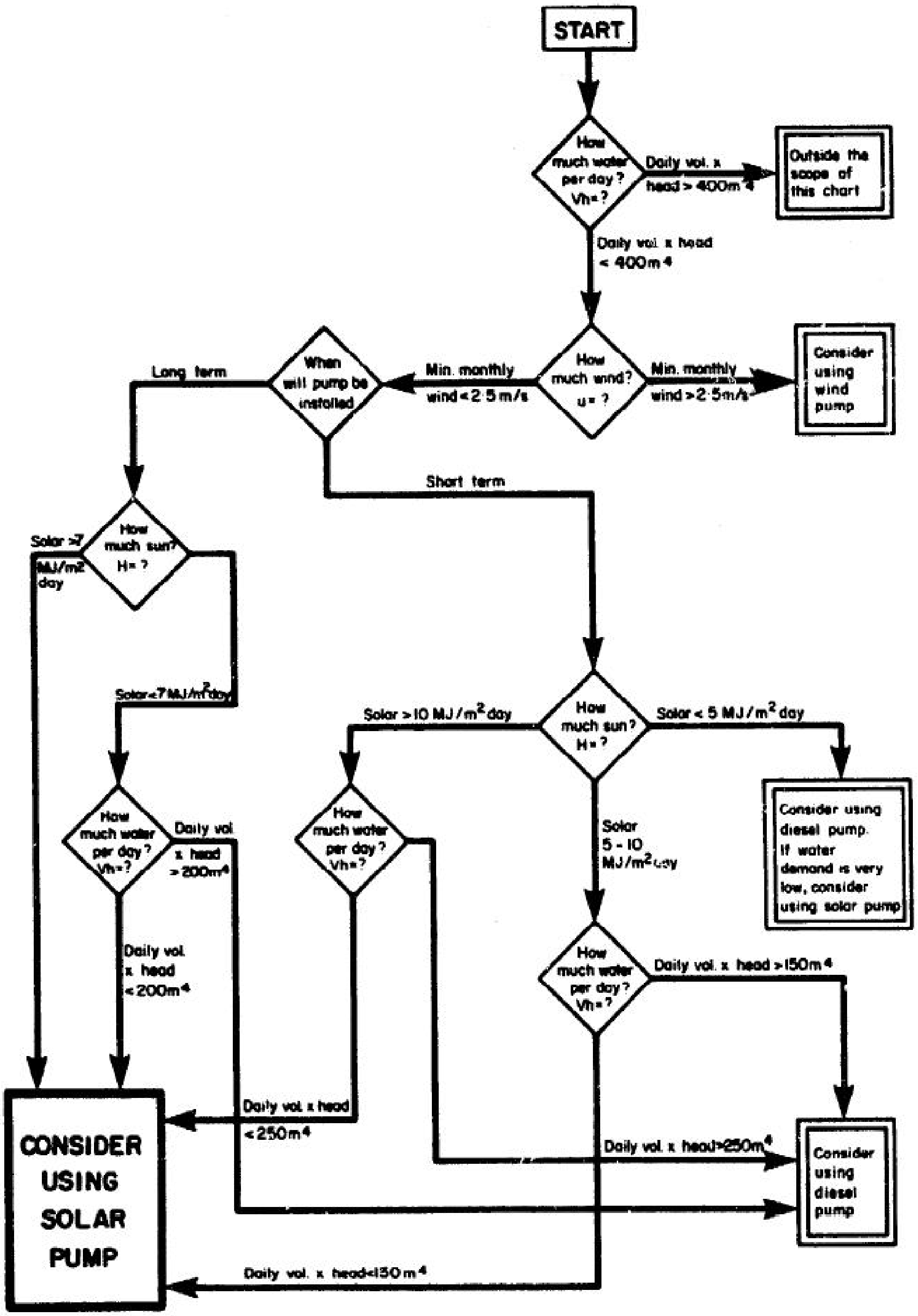


Figure 3.9 Decision chart for an appraisal of solar pumps for rural water supply

(Source: Kenna and Gillett,1985)

Stages used by solar appraisal and selection module are typical to main pump selection and appraisal framework given in section 3.1.2.

1- Assessing water requirements: Methodology used for the determination of water need for irrigation or domestic use or both is given in the model framework.

2-Calculation of hydraulic energy required: Once the gross water requirements are known, the hydraulic requirements can be determined, as outlined in model framework, using the equation:

Hydraulic energy = (9.81 x volume (m^3/day) x total head (m))/1000…. 3.3

3-Determination of available solar energy (m^3/day): Month by month solar radiation data are required, in order to assess adequately the suitability of a location for solar pumps. To estimate the solar irradiation for a particular location one simply multiplies the extra-terrestrial solar energy for the location (appendix1) (Kenna and Gillett,1985) by the clearness index for the location. Since the clearness index is only specified at intervals of 0.1, the accuracy of the resulting solar irradiation will be no better than ± 10%. Where no local solar radiation data are available, an estimate can be made from the maps given in Appendix1. These maps show the fraction of the extra-terrestrial solar energy that is transmitted to ground level for each month (this fraction is known as the clearness index) and have been prepared by the World Meteorological Organization(WMO), (1981).

The solar radiation available on a tilted or tracking surface differs from that on a horizontal surface, and it is the solar radiation that the PV array receives that is important for the sizing procedure. Conversion factors must therefore be used to determine the irradiation on the array from the horizontal irradiation data. The conversion calculations are also dependent on the fraction of diffuse irradiation. As a simplified procedure, (appendix2) given in (Kenna and Gillett,1985) have been prepared to estimate how the radiation on tilted surfaces is related to the horizontal irradiation, These Tables show the ratio of the solar irradiation on surfaces of different orientations to the solar irradiation on the horizontal plane as a function of latitude, month and clearness index.

The sizing methodology for depend on determination of the design month. This is the month in which the water demand is highest in relation to the solar energy available, i.e. the month when the system will be most heavily loaded to meet the demands. The design month is found by calculating the ratio of the hydraulic energy requirement to the solar energy available for each month. The month in which this ratio is a maximum is the design month.

The data for the design month are used to calculate the required component sizes in the step by step procedure given below.

Step 1: Size the PV array: The electrical energy required from the PV, array is equal to the required hydraulic energy divided by the average sub-system daily energy efficiency. The electrical output of the PV array depends on three factors (the latter two of which affect the array efficiency):

1. The solar irradiation incident on the array,
2. The average cell temperature which in turn depends on ambient air temperature and solar irradiance levels,
3. The electrical load because this determines the operating point on the PV array current/voltage (I/V) curve.

For a solar pump without impedance matching electronics, the electrical output of the array is reduced below its maximum value except when operating at the knee of the (I/V) curve. The objective of the procedure is to determine the required array rating in peak watts (Wp). The principle of the method can be illustrated by first considering an array that is operating both at the reference cell temperature (of 25 C°) and at the maximum power point on the current/voltage curve throughout the day. This means that when the solar irradiance is at a 1000 w/m^2 the PV array will produce its rated output. The daily solar irradiation can be considered in terms of peak irradiance conditions at 1000 W/m for an equivalent time period. For example, a daily irradiation of 18 MJ/m (5 kWh/m^2) could be considered as equivalent to 1000

W/m² for a period of 5 hours. By assuming, as a first approximation, that the array will work at its rated output for this time period, then a first estimate of the array size can be made. Under actual conditions the incident solar energy would be spread out over the daylight hours and the average power output from the PV array would be considerably less than the rated output. Also, in real conditions the array rating calculated above would be too small because of cell temperature effects and impedance matching losses. Therefore, it is necessary to increase the array rating by factors which account for the decrease in efficiency when not operating at reference conditions.

To guide the reader who does not wish to make the detailed calculations the monogram in (Figure 3.10) has been prepared and can be used to determine the required PV array size to meet the hydraulic energy load for the design month. The starting point is axis OB whets the hydraulic energy is given in MJ per day. Halving antic-clockwise and picking appropriate sub-system daily energy efficiency from (Table 3.5), the required electrical load in MJ per day is given on axis OC. The array rating in peak watts (Wp) is then selected from axis OA for the appropriate design month solar irradiation.

Table 3.4: Sub-system daily energy efficiency

Lift	Sub-system type	Typical Subsystem		Typical Subsystem	
		daily energy efficiency		peak power efficiency	
		Average	Good	Average	Good
	Surface Suction or floating units with submerged suction utilizing brush or brush-less permanent magnet d.c. otors and centrifugal pumps	25%	30%	30%	40%
7 meter	-floating d.c. units with submerged pump - submerged pump with Surface mounted motor, brush or brush-less permanent magnet d.c. motors single or multi stage centrifugal pumps	28%	40%	40%	60%
20 meter	- a.c or d.c submerged multi stage centrifugal pump set or - submerged positive displacement pump with d.c. Surface motor	32%	42%	35%	45%

(Source: Kenna and Gillett 1984,1985)

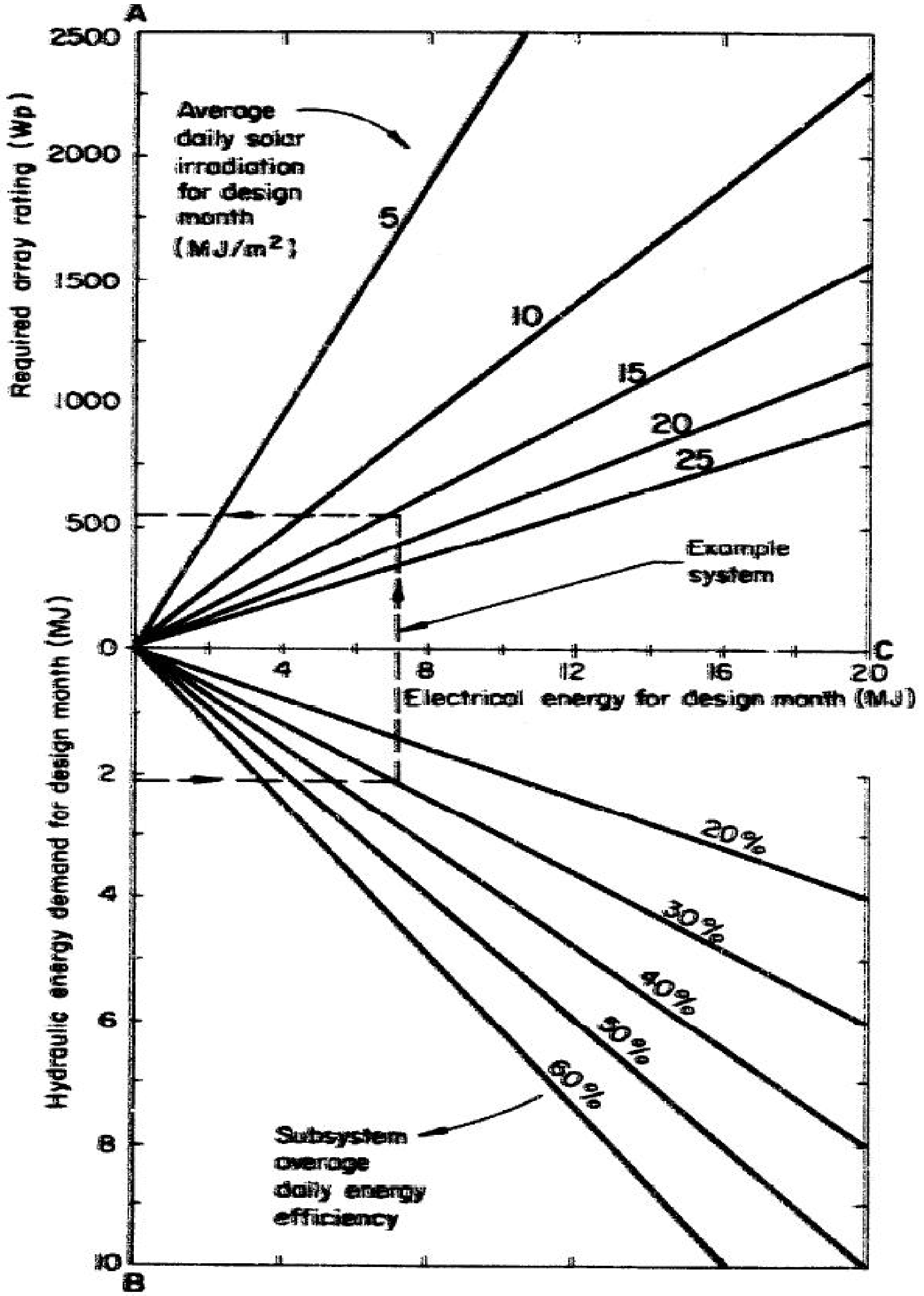


Figure 3.10 Nomogram to determine the PV array rating for a given hydraulic duty

(Source: Kenna and Gillett, 1985)

Step 2: Size the motor: The motor must be able to withstand the peak output of the array. Since electric motors are generally rated in terms of their electrical input power, the maximum rating of the motor must be at least as great as the array rating. Thus the example system requires a motor rated at 540 Watts. The configuration of the PV array can usually be arranged to match the current and voltage limitations of the motor, provided that the maximum power ratings are adequate.

Step 2: Determine the Design Month

A procedure for identifying the design month for solar pumps is outlined in the framework. A similar procedure can be adopted for wind pumps. (Figure 3.11) shows the water pumped per square meter of swept rotor area as a function of monthly average wind speed and total head. These curves have been derived by assuming an average wind pump performance; where available actual performance data should be used.

To determine the design month, the volume pumped per square meter of swept rotor area must be determined for each month. The month with the highest ratio of water requirement to pumped volume per m^2 of swept rotor area is the designated design month.

For electrical or diesel pumps the design month is simply the month with the highest water demand.

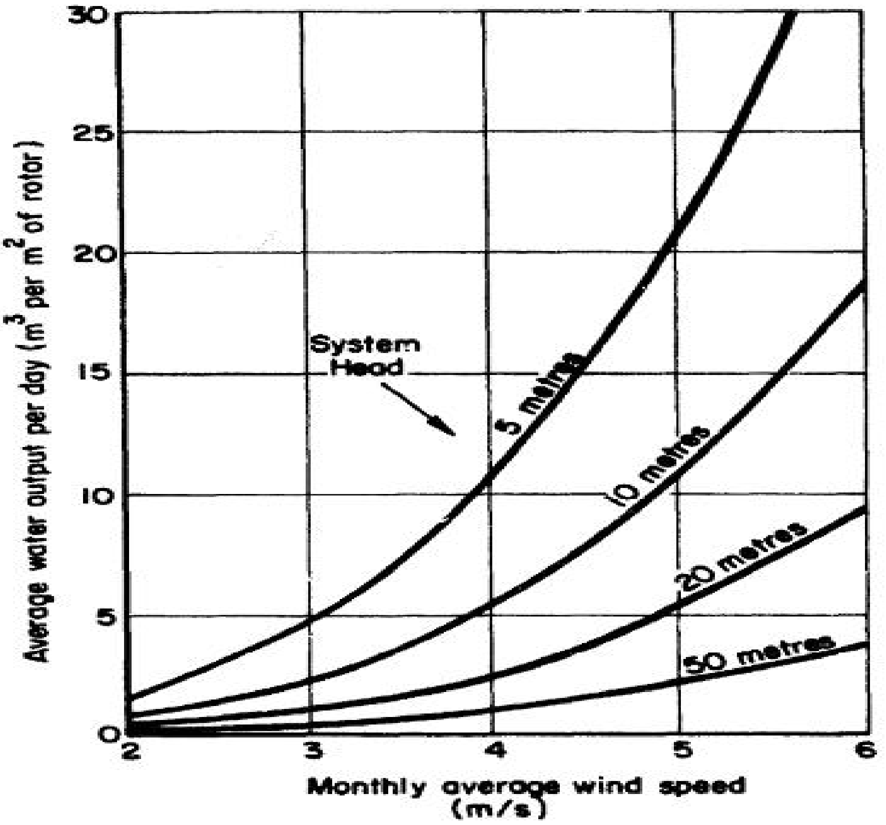


Figure 3.11 Average daily water output for wind pumps expressed in m^3 per m^2 of rotor area

(Source: Kenna and Gillett,1985)

Step 3: Size the pump: For a wind pump the required rotor size is determined by dividing the pumped water requirement, for the design month, by the pumped volume per m^2 of swept rotor area for the design month.

The peak hydraulic power output of the solar pump will be given by the product of peak array power output and peak subsystem power efficiency. The peak flow rate required from the pump can be obtained either by using the equation relating hydraulic power to flow rate and head or by using the monogram in (Figure 3.12). The array rating is given on axis OB and the peak hydraulic power is obtained for appropriate sub-system power efficiency. The peak flow rate can then be obtained from axis OA, for the required system head.

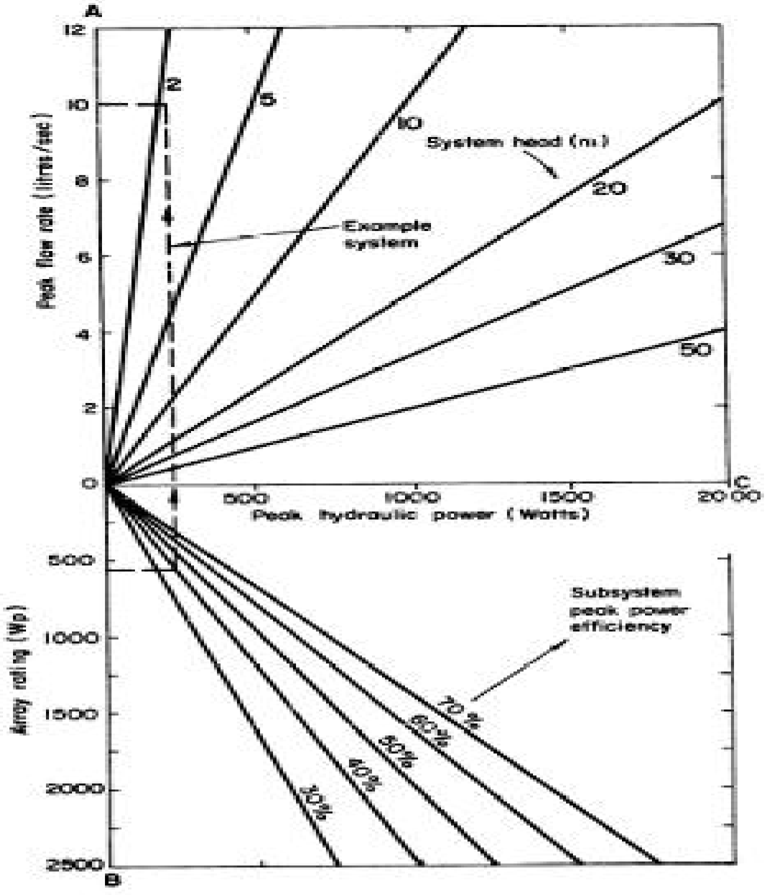


Figure 3.12 Monogram to determine pump rating for a given PV array rating

(Source: Kenna and Gillett,1985)

Step 4: Size the Pipe work (where included):

The required pipe diameter to meet the head loss specified when calculating the hydraulic energy may be determined by using Hazan-Willium or Darcy-Weisbakh equations.

Step 5: Economic Evaluation**:** An integrated approach is used for the cost appraisal suggested in the framework, considering the system as a whole from the water source to the point of use. The explained step by step procedure (section3.2.6) is based on a life cycle costing of the whole system. It takes into account each of the identifiable costs, but ignores the benefits gained by the users of the water. Consequently, the results do not indicate whether a water pumping system is economically viable per se (for example whether additional crops grown using water supplied for irrigation are worth more than the cost of the water provided).

Step 6: Specification of System Performance and Configuration: The purchaser should now be in a position to make his/her own preliminary assessment of solar pumping viability in accordance with the Decision Chart discussed in Section 3.2.3, and to supply full details of his/her requirements. Before a purchase is completed it will be important to ensure that the purchased system is technically able to meet the demand and that it will meet the economic constraints. A specification sheet, need to be included in a tender document.

3.2.4 Diesel Pump Selection and Sizing Module

Engine driven pumps: (Figure 3.13) may be used for an approximate sizing of engine-driven pumps.

The following aspects are to be taken into account:

Number of hours of operation: This is related to irrigation practices, presence of a storage tank, etc. For example, for direct field application a small kerosene pump may be operated by its owner for four hours per day. For a large irrigation scheme of several farms, a diesel pump may operate twelve hours per day.

De-rating factor: Usually the engine is oversized in relation to the pump. For small pumps the de-rating may be around 0.5, for large motor pump sets, matched to the application, it may be 0.7.

Minimum motor size. The smallest size of diesel motor readily available is approximately 2.5 kW, and the smallest size of kerosene motor used in pump sets is of the order of 0.5 kW. For very small pumping requirements these sizes may be too large. In such cases the number of hours of operation will be reduced. Sometimes the de-rating factor is further reduced. From the Monogram in (Figure3.13) three values may be found for the size of the motor for different

Levels of performance, characterized by the combined efficiency of the pump and lines:

- Low performance, η pump, lines = 30%
- Medium performance, η pump, lines = 40%
- High performance, η pump, lines = 50%

For very small pumps and low pumping heads, the performance can be expected to be relatively low. For large sizes and larger pumping heads, a relatively high performance can be expected. Storage tanks are normally not used for irrigation with engine pumps.

Rural water supply schemes usually incorporate storage tanks with a capacity of half a day to two days. The example case is also indicated in (Figure 3.13). Since the example is concerned with a deep tube well, the type of engine pump to be applied will be a deep-well turbine pump driven by a diesel motor. As indicated earlier, the average hydraulic power requirement is 41 W. For a diesel pump, this is a relatively low requirement, and one will apply the smallest available size of diesel motor: 2.5 kW. A medium level of performance can be expected (large pump head, but relatively small size). Since the pump is too large in comparison to the water requirement, it is used only 4 hours a day with a de-rating factor of 0.25 (this corresponds to a pump demanding 630 W power input.

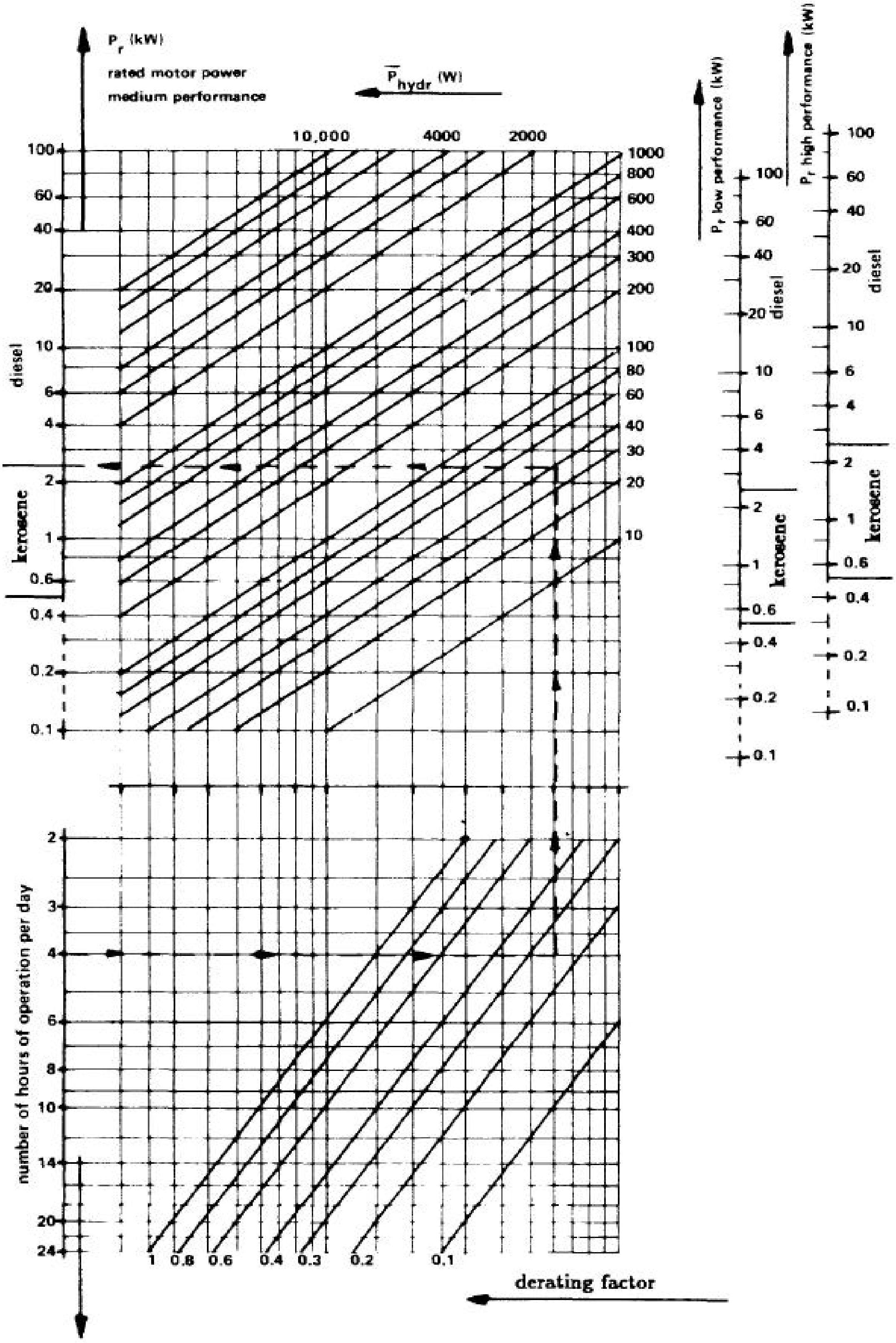


Figure 3.13 Monogram for determining approximate size of wind and solar pump

(Source: Kenna and Gillett,1985)

3.2.5 Electrical Pump Selection and Sizing Module

Aspects are to be taken into account for electrical Pump Selection and Sizing are typical to that explained for diesel pump except that price of fuel and its accessories is replaced by that for electricity.

3.2.6 Pumps Financial Appraisal Module:

Appraisal of pumps the bare costs of water can be used to compare the principal small-scale water-lifting systems:

Wind pumps, Solar pumps, Engine-driven pumps (diesel or electrical). In order to calculate the cost of water delivered to the user, the complete system should be considered, including the water source (well), power source, pump, piping, storage tank, distribution network, and in case of irrigation field application. When comparing different pumps, one may leave out some of the components. For example, if a certain amount of water is to be pumped from a well, using either a wind pump or an engine-driven pump, one may leave out the cost of the well, which is the same in both cases. One will then find the costs of pumping water (which may be used for a comparison), and not the total cost of the water. The same can be true for other cost components (e.g. field application). Anyhow, one must first make sure that calculations used for comparisons are truly comparable.

The cost comparison procedure as presented in this module is based on the following main assumptions:

1- Benefits are equal for different pumping technologies.

2- The rate of interest is constant.

3- The rate of inflation is constant and equal for all cost components.

The procedure for cost comparison corresponds to the economic/financial boxes in Figure 3.1, Chapter 3; and is of three folds:

1-Calculate the average annual capital cost (AACC).

2- Calculate the annual recurrent costs (ARC).

3– Calculate the unit water costs.

Once these costs have been calculated one can then determine sensitivity of the outcome to variation in the input data, such as change in interest rate, wind speed, and so on.

Analysis of module includes:

1- Investment it’s the initial cost of pump.
2- Life time which estimate time operation of pump.
3- Real interest rate.
4- Annuity.
5- Average Annual capital cost.
6- Average cost of maintenance &repair.
7- Total Cost.

The different steps will be described briefly:

Calculating average annual capital cost (AACC): The first is to determine the capital cost, or cost of investment. This cost is incurred once in the lifetime of a pumping installation. In order to make it comparable to recurrent costs, which occur every year, the cost of investment must be converted into an annual capital cost, using the following formula:

$AACC = ANN \times I$……………………3.4

With:

AACC = annual average capital cost; ANN= annuity factor; I = investment. The AACC, annual average capital cost, is a fixed annual amount, covering exactly repayment of capital and interest throughout the lifetime of the investment. The annuity factor ANN given in (Table 3.6), depends on both lifetime and interest rate in the following way:

$ANN= (r)/ (1 – ((1+r) ^n))$ ……………3.5

With: r = interest rate and n= lifetime (years).

Table 3.5: The annuity factor for various values of interest rate and lifetime

Years	r=2	3	4	5	6	7	8	10	12
1	1.0200	1.300	1.0400	1.0500	1.0600	1.0700	1.0800	1.1000	1.1200
2	0.5151	0.52261	0.5302	0.5378	0.54544	0.53309	0.56077	0.57619	0.5917
3	0.3468	0.35353	0.36036	0.36721	0.37411	0.38105	0.38803	0.40211	0.41635
4	0.2626	0.26903	0.27549	0.28201	0.28859	0.29523	0.30192	0.31547	0.32923
5	0.2122	0.21835	0.22463	0.23097	0.2374	0.24389	0.25046	0.2638	0.27741
6	0.1785	0.18460	0.19076	0.19702	0.20336	0.2098	0.21632	0.22961	0.24323
7	0.1545	0.16051	0.16661	0.17282	0.17914	0.18555	0.19207	0.20541	0.21912
8	0.1365	0.14246	0.14853	0.15472	0.16104	0.16747	0.17401	0.18744	0.20130
9	0.1225	0.12843	0.13449	0.14069	0.14702	0.15349	0.16008	0.17364	0.18768
10	0.1113	0.11723	0.12329	0.12950	0.13587	0.14238	0.14903	0.16275	0.17698
11	0.1022	0.10808	0.11415	0.12039	0.12679	0.13336	0.14008	0.15396	0.16842
12	0.0946	0.10064	0.10655	0.11283	0.11928	0.12590	0.1327	0.14676	0.16144
13	0.0881	0.09403	0.10014	0.10646	0.11296	0.11965	0.12652	0.14078	0.15568
14	0.0826	0.08853	0.09467	0.10102	0.10758	0.11434	0.12130	0.13575	0.15087
15	0.0778	0.08377	0.08994	0.09634	0.10296	0.10979	0.11683	0.13147	0.14682
16	0.0737	0.07961	0.08582	0.09227	0.09895	0.10686	0.11298	0.12782	0.14339
17	0.07	0.07595	0.08220	0.08870	0.09544	0.10243	0.10963	0.12466	0.14046
18	0.0667	0.07271	0.07899	0.08555	0.09236	0.09941	0.10670	0.12193	0.13794
19	0.0638	0.06981	0.07614	0.08275	0.08962	0.09675	0.10413	0.11955	0.13576
20	0.0612	0.06722	0.07358	0.08024	0.08718	0.09439	0.10185	0.11746	0.13388
25	0.0512	0.05743	0.06401	0.07095	0.07823	0.08581	0.09368	0.11017	0.12750
30	0.0447	0.05102	0.05783	0.06505	0.07265	0.08059	0.08883	0.10608	0.12414
40	0.0366	0.04326	0.05052	0.05828	0.06646	0.07501	0.08386	0.10226	0.12130
50	0.0318	0.03887	0.04655	0.05478	0.06344	0.07246	0.08174	0.10086	0.12042
60	0.0288	0.03613	0.0442	0.05283	0.06188	0.07123	0.0808	0.10033	0.12013

(Source: Meel and Smulders,1989)

In order to find the average annual capital costs, the following three factors need to be considered: Investment cost, lifetime, and interest rate.

Investment Cost: The cost of investment for different pumping systems depends primarily on their size i.e. rotor area for wind pumps, peak power for solar pumps, rated power for engine pumps, etc. in determining specific cost (cost per unit size) it should include costs of all component of the system (Water source (well), Power source, (wind machine, solar panels, engine, etc.), Pump, Piping, Storage tank, - Distribution network, Field application system (in case of irrigation). Other cost aspects include: - Purchase (or manufacture), Packing, transport, Site preparation, installation, and Overhead cost (management, secretarial costs)

Lifetime: Realistic lifetimes must be used. Even if the (technical) lifetime of an installation is very long (e.g. 30 years for a concrete foundation), one must use a shorter (economic) lifetime, representing the period during which the installation will be effectively used (e.g. 15 years for a foundation). In 30 years' time circumstances may have changed and different solutions for water supply may have been found (such as a central pumping station with a piped distribution).

Different components of an installation may have different lifetimes. In that case the average annual capital cost must be determined for each component separately, and the annual costs added together. An economic life of 15 years was assumed for the solar pump, and 7 years for the diesel pump, corresponding to 10,000 hours of operation at 4 hours a day.

Calculating Annual Recurrent Costs (ARC): Recurrent costs are considered to consist of two parts: maintenance and repair costs, and costs of operation.

Maintenance and repair costs Depending on the character of the maintenance and repair activities to be carried out, one may distinguish three types of maintenance and repair costs: A constant annual amount, more or less independent of the size of the installation, reflecting for example a regular inspection visit to each installation (monthly, yearly). This type of cost is a component of the maintenance and repair cost of most types of pumping systems.

1. An annual amount proportional to the initial investment. This is the most important component of maintenance and repair costs of wind pumps and solar pumps. The time to be spent on maintenance and repair and the cost of spare parts is related to the size of the installation, which in its turn is related to the investment.
2. An amount proportional to the time of operation, which is typical for engine-driven pumps. For example, these pumps need maintenance after 1,000 running hours and overhaul after 8,000 hours. In contrast, for both wind and solar pumps the time of operation has little influence on the costs of maintenance and repair.

Operating Costs: For the different water pumping systems different types of operating costs are to be taken into account:

Wind and Solar Pumps: The cost of operation is mainly related to salaries for attendance, operation of the pump, and water distribution.

Fuel pumps: Here the fuel cost is the main cost of operation. Also salary costs are to be taken into account for attendance, starting and stopping the motor, and water distribution.

Calculating unit water costs: The unit water cost may be found by dividing the total average annual cost by the total annual water requirement. The total average annual cost is simply the sum of the average annual capital cost and the annual recurrent costs (steps 6 and 7):

AAC = AACC + ARC…………….3.6

With:

AAC: average annual cost

AACC: average annual capital cost

ARC: annual recurrent cost.

3.2.7 Multi-Criteria Analysis (MCA) Selection Module

The Selection criteria and comparison Indicators of evaluation includes:

1- Efficiencies of selected Pump model: These are:

b) Water Application Efficiency:

c) Power efficiency:

2- Economic Indicators: includes:

a- The average annual capital cost (AACC):

b- Unit water costs SDG/m^3:

c- Annual cost / Fadden

d- Cost HP-Hrs

3- System capacity

A- Output HP-Hrs

B- Max system capacity m^3

The model nature: It is based on five steps procedure as follows

2. System identification and data inventory: The data with respect to the identified evaluation criteria is that obtained from application of the selection procedure. (Table 3.7) shows the data for the Selected Indicators. In particular, this phase includes selection of: scenarios, indicators and max/min

Table 3.6: Output data for the selected indicator

Selection Indicators	Unit water costs	Annual cost / feddans	Output HP-Hrs	Cost HP-Hrs	Max system capacity	Average Annual capital cost	Water Application Efficiency	Power efficiency
Wind	0.66	265	3967	1.2	107	1514	31	33.4
Solar	2.93	1178	3950	5.37	129	17958	31	1.4
Diesel	0.1	42	3934	0.19	107	325	31	33.6
Electric	0.32	128	3950	0.59	107	1962	31	33.5

3. Analytical Phase: This step includes the establishment of diagnostic criteria (threshold levels), transforming parameter estimates into quality score and specification of the various decision making and weighting of indicators.

1. Select Scenarios
2. Select Indicators: Each indicator used represents only a part of the set of evaluation parameters. It is therefore, important to view these parts together as part of the whole evaluation system. In doing so, however, it must be recognized that some indicators are of lower importance than the others and they can be discarded. To reflect the relative importance of the evaluation indicators relative weights were distributed among the indicators.
3. Select Max/Min
4. Normalization Scale

Indicators are usually expressed with different units. Hence, normalization scheme is adopted for purpose of comparing indicators on common grounds. Normalization methods include:

i- Select max/min

ii- Select scale: In this model quality for soft indicators is defined by a scale of values between 0 and 10, where 0 denotes extremely poor quality and 10 denotes very good quality. This system will account for quality range and marginal changes without waiting until the standard is reached or exceeded. Additional benefit of this approach is the resulting common base necessary to express impacts in commensurate units regardless of the units used to measure the different indicators.

iii- Translation of row data

iv- Determine: Best and Worst

5. Decide on translated Values: determine: percentage of maximum, percentage of range and percentage of total, normalized by unit vector
6. Select normalization method:

a- Percentage of the maximum: $vi = (ai/\max ai)$

b- Percentage of range: $vi= (ai-\min ai)/ (\max ai-\min ai)$

c- Percentage of total: $vi = ai/\sum ai$

d- Unit vector: $vi = (ai/\sum ai^{2})$ ^½

Where:

a= measurement of criteria

ai = criteria measurement of plan i

vi = normalized value of ai

7. Normalized Weight: select rang: 0.0 to 1.0; 1.0 to 10.0; 1.0 to 100
8. Pre-Analysis
9. Weighting Method:

i- Apply Stakeholder Weights: select weighting method and the respective scale of each method:

a- Fixed Point Scoring: distribute from 10 to 100,

b- Rating: classified as Most Important - Least Important in scale of: 1 to 5,

c- Ranking: in scale of: 1 to 5,

d- Graphical Weighting, classified as Least Important – Most Important

e- Paired Comparisons: according to number of indicators

ii - Comparison of methods: is numerical result: Evaluation Phase: The quality scores developed in the previous step are arranged with their respective indicator weight in pay off matrix. The payoff matrix includes the performance scores of the project state at different time span. As such, the payoff matrix shows the objectives, parameters, indicator relative scores, and criteria weight. The overall performance index for each state of the project and for each alternative is calculated

iii - Normalized Weight: select rang: 0.0 to 1.0; 1.0 to 10.0; 1.0 to 100

10. Results: presentation of final ranking in tabular and graphical format: This is the implementation Phase: This is the final step of selecting the most

viable alternative technique to be physically implemented in the study site. This is achieved by ranking the alternatives to reflecting their overall impact. However, in case of presence of a tie Spars man rank correlation may be used.

CHAPTER FOUR

MATERIALS AND METHODS

4.1 Study Area:

Alosaylat Farm: Alosaylat Farm lies at Khartoum East - Nile, (37 Km North – East Khartoum City) at latitude 15° 25° N longitude 34° 32° E and 37.5 meters above sea level. The climate of the locality is semi-arid and topical. The rain fall is about 160mm, with great variation in amount and distribution along the season. The maximum temperature is more than 40°C and around 20°C in cool season.

The farm soil is montmorillonite with 48-54 % Clay, 25-29 % Silt, and 17-25 % Sand, reaction was moderately alkaline PH ranges from 7-8"(Saeed1978).

The farm total area is 25.2 ha (60 feddans). The supply groundwater for irrigation and domestic uses is from two wells. In one well a diesel pump (3 inches) is installed while the second pump in the second one is solar operated pump. The first well operated by the diesel pump while the second well is operated by solar pump. The specifications of the two wells are typical.

The specifications of the diesel pump are: Pump diameter = 0.1016 m (4 inches); Dug depth (coated) = 76 m; Filter pipe diameter = 0.219m (8 5/8 inches) of PVC type.

The results of Pumping test: Drawdown = 69 cm; Pumping test = 0.051 m (2 inches) submersible, Capacity = 45.42m^3 /hr (12.000 galls / hr), Static water head = 8m Drawdown = 4.6 m; Pump depth from soil surface = 8.2 m

The specifications of the solar pump are: Pump diameter= 0.076 m (3 inches); Size = 3Hp, Discharge=37.85 m^3 /hr (10.000 galls / hr).

The farm is irrigated using drip irrigation with specifications of: Mainline= (0.051 m) 2 inch, (16.4-17.7 m^3/hr; 60-65gall/min); Sub mainline= (0.025 m) 1inch, (7.4 m^3/hr, 27gall/min).

4.2 Data Collection:

4.2.1 Alosaylat Farm Data:

Climate data: The farm climate data is given in Table 4.1

Table 4.1: Farm Climate Data

Month	Max Temp (deg. C)	Mini Temp (deg. C)	Humidity (%)	Wind Sp (Km/d)	Sun Shine (Hours)	Solar Radiation (MJ/m2/d)	ETo (mm/d)
January	31.6	16.0	33	199	10.4	20.8	5.7
February	33.1	16.5	26	242	10.7	23.1	7.0
March	37.0	19.8	22	251	10.4	24.6	8.2
April	40.0	23.0	21	190	10.6	25.9	8.0
May	41.8	26.2	24	207	9.9	24.7	8.5
June	41.5	27.0	30	207	9.8	24.3	8.4
July	38.0	25.6	45	259	8.6	22.5	8.0
August	36.1	24.7	56	233	8.6	22.6	6.9
September	38.3	25.5	44	199	9.2	23.0	7.1
October	39.2	25.1	32	147	10.1	22.8	6.5
November	35.7	21.1	31	181	10.6	21.5	6.3
December	32.2	16.8	35	199	10.4	20.1	5.7

Source: (Crop wat)

i- Farm Cropping System

Types of crops and their respective areas are:

Table 4.2: Types of crops and their respective

Crops	All crops	Citrus	Date palms
Area in feddans	60	16	2
Area%	18	89	11

Source: (model data)

ii- Irrigation Operating Data

Table 4.3: Irrigation operating data

Working hr/day	8
Depth in m/day	0.006
mm/day	6.4
Q m3/hr	60
m^3/day	1451

Source: (model data)

iii- Water demand data

Table 4.4: Water demand of farm crops

Month	**Water requirements m³/day/fed**
Jan	17
Feb	21
March	26
April	26
May	27
Jun	17
July	17
August	12
Sept	18
Oct	19
November	19
Dec	17
Average	20

Source: (Crop wat)

iv- Domestic population and water demand

Table 4.5: Domestic population and water demand

Domestic population				
population cat	**liter of water /head**	**Numbers**	**liter of water /head**	
Human	**40**	**4**	**160**	
	liter of water /head	**Numbers**	**liter of water /head**	**lives stock demand**
species				
Camels	40 - 90	0	60	0
Horses	30 - 40	0	35	0
Cattle	20 - 40	0	30	0
Milk cow in production	70 - 100	0	85	0
Sheep and goats	1.0 - 5.0	0	3	0
Swine	3.0 - 6.0	0	5	0
Lactating sow	25	0	25	0
Poultry	0.2 - 0.3	0	0.17	0
Steers	20	0	20	0
pig	20	0	20	0

Source: (Crop wat)

Table 4.6: Water requirement

Month	m³/day	Lit/day	Total water requirement	m³/day
Jan	17	17425	17585	18
Feb	21	21055	21215	21
March	26	26138	26298	26
April	26	26138	26298	26
May	27	26864	27024	27
Jun	17	16699	16859	17
July	17	16699	16859	17
August	12	11980	12140	12
Sept	18	18151	18311	18
Oct	19	18877	19037	19
Nov	19	18877	19037	19
Dec	17	17062	17222	17
Average	20	19664	19824	20
Sum m³/hr				238

Source: (Crop wat)

V- Economic Data

Table 4.7: Wind pump economic data

Wind		
Input Data		Units
1.MAKE		Italy
2.Size	6	HP
3.power	6	HP
4.Data	15,7,2016	day, month
5.present cost	8500	SDG
6.Life time	10	year
7.Coef (K)	120	hrs/ fed/ year
8.Repair cost	3,000	SDG
9.Grease cost	75	SDG/100hrs
10.Salvag value	1500	SDG
11.Annual taxes	0	SDG
12.Interest rate	9	percent
13.Labor cost	250	SDG./Hr
14. Discharge	60	m^3/hr
16. Overall efficiency	65	%
16. Engine efficiency	65	%
17. Static head	8	meter
18.Dynamic head	8.2	meter
19. Water duty	7236	m^3/year
20. Max system capacity	4	m^3
21. Max time/day	8	day ,hr
22. Min. irrigation Interval	0.25	days
23. Max water irrigation	27	m^3
24. wind turbine cost	1500	SDG

Source: (model data)

Table 4.8: Solar pump economic data

Solar		
Input Data		Units
1.MAKE	Germany	
2.Size	5	HP
3.power	5	HP
4.Data,	15,7,2016	day, month
5.present cost	175,000	SDG
6.Life time	25	year
7.Coef (K)	150	hrs/ fed/ year
8.Repair cost	3000	SDG
9.Salvag value	0	SDG
10.Annual taxes	0	SDG
11.Interest rate	9	percent
12.Labor cost	0	SDG./Hr
13. Discharge	48	m^3/hr
14. Overall efficiency	80	%
15. Engine efficiency	70	%
16. Static head	8	meter
17. Dynamic head	8.8	meter
18.Water duty	7236	m^3
19. Max system capacity	4	m^3/year
20. Max time/day	0.25	m^3
21. Min. irrigation. interval	6	hr
22. Max water irrigation	27	m^3
23. photovoltaic cost	3000	SDG

Source: (model data)

Table 4.9: Diesel pump economic data

Diesel		
Input Data		Units
1.MAKE		India
2.Size	6	HP
3.power	diesel	HP
4.Data,	15,7,2016	day, month
5.present cost	1870	SDG
6.Life time	10	year
7.Coef (K)	120	hrs/ fed/ year
8.Repair cost	175	SDG
9.Salvag values	300	SDG
10.Annual taxes	0	SDG
11.Fuel consumption	1.4	Liters
12. Fuel cost	0.076	SD/ liter
13.Interest rate	9	percent
14.Labor cost	500	SDG./hr
15. Discharge	60	m^3/hr
16. Overall efficiency	80	%
17. Engine efficiency	65	%
18. Static head	8	meter
19. Dynamic head, meter	8.2	meter
20. Water duty	7236	m^3/year
21. Max system capacity	4	m^3
22. Max time/day	8	hr
23. Min. irrigation Interval	0.25	days
24. Max water irrigation	27	m^3

Source: (model data)

Table 4.10: Electric pump economic data

Electric		
Input Data		Units
1.Make		Italy
2.Size	6	HP
3.power	Electricity	HP
4.Data	15,7,2016	day, month
5.present cost	4880	SDG
6.Life time/year	10	Years
7.Coef (K)	120	hrs/ fed/ year
8.Repair cost	100	SDG
9. Elect. req.	4.3	Kw h
10.Electricty.cost	0.2	SDG
11.Salvag value	0	SDG
12.Annual taxes	0	SDG
13.Interest rate	9	percent
14.Labor cost	500	SDG/Hr
15. Discharge	60	m^3/hr
16. Overall efficiency	70	%
17. Engine efficiency	65	%
18. Static head	8	meter
19. Dynamic head	8.2	meter
20. Water duty	7236	m^3/year
21. Max system capacity	107	m^3
22. Min. irrigation. interval	0.25	days
23. Max water irrigation	27	m^3

Source: (model data)

2.8%; according to 1993 Population Census growth rates approximately 80% of the economic active group work in agriculture.

Agriculture is the single most important economic activity in the Sudan. From earliest historical times the banks of the Nile.

vi- Data for All Pumps

Table 4.11: Diesel pump input data

Model Inputs	
Total head (m)	8 meter
pipe diameter	150 mm
discharge	4 lit/sec
Pipe Type	165 (HDBE)
Life time	10 year
present cost	1870 SDG

Source: (model inputs)

Table 4.12: Solar pump input data

Model Inputs	
Total head (m)	8 meter
Extra-terrestrial irradiation	38 MJ/m²
Clearness index	0.6
Tital factor	1.05
pipe diameter	150 mm
discharge	4 lit/sec
Pipe Type)	165 (HDBE)
Life time	25 year
present cost	175000 SDG

Source: (model inputs)

4.3 Alosaylat Farm Data for Analysis of Model Sensitivity

Alosaylat tables of input data (Table 4.13 to 4.17) are used for operating the model to generate output (Farm, climate, pump data, economic data) data. These output data are considered as input for sensitivity analysis.

Table 4.13: Sensitivity input data

Model outputs	
hydraulic Power Requirement (Diesel)	25 W
hydraulic Power Requirement (Solar)	2.2 MJ/day
Pv array size	209 W
Required electrical energy	7.2 MJ
Rated flow rate	1.05 Lit
Total annual costs	21208 SDG
Unit water costs	3 SDG
Water Application Efficiency	31%
Power efficiency	1.4%

Source: (basic farm model outputs)

4.4 Alosaylat Farm Data for Pump Selection

Input data for selection of most suitable pump type for Alosaylat Farm includes the farm input data needed for running the model given in section 4.2 (Table 4.1 to 4.12) and the data needed to run multi-criteria analysis. The data needed for multi-criteria analysis is used for purpose of selection of pump type and includes:

Table 4.14: Multi-criteria analysis data of different pumps

Selection Indicators	Unit water costs	Annual cost / feddans	Output HP-Hrs	Cost HP-Hrs	Max system capacity	Average Annual capital cost	Water Application Efficiency	Power efficiency
Wind	0.66	265	3967	1.2	107	1514	31	33.4
Solar	2.93	1178	3950	5.37	129	17958	31	1.4
Diesel	0.10	42	3934	0.19	107	325	31	33.6
Electric	0.32	128	3950	0.59	107	1962	31	33.5

Source: (model out puts)

Table 4.15: Multi-criteria analysis resulted in ranking the different types of pumps

Rank	
1	Electric
2	Wind
3	Diesel
4	Solar

Source: (model out puts)

4.5 World Bank Data for Model Verification:

The data given by World Bank (Meel and Smulders,1989) for wind, solar, and diesel pumps is used to test validity of the model. These data include:

Table 4.16: Specification of example site

Location: Application: On slopes of the valley Consumption:	Flamingos, Republic of Cape Verde Drinking water supply to village situated on the 15 m3 /day throughout the year
Water source: floor Pumping): Storage tank: Pumping height: storage tank Wind situation: the prevailing	Tube well of 70 m depth, situated at the valley Static water level (i.e. level when not 4 m below ground level (valley floor) Dynamic level (i.e. level when pumping): approximately 10 m below ground level To be constructed on the slopes Height above valley floor: 12 m 22 m (dynamic level of well plus height of floor) above valley

Valley. The only 2 m. the wind speed	The well site is well exposed to the north-east, Wind direction, coinciding with that of the Obstacles are the crops, with heights less than The wind speed was estimated to be 0.7 times At the airport of Praia for which data is available.

(Source: Meel and Smulders,1989)

i. Wind Pump Data

Table 4.17: Wind pump data(basic farm model inputs)

Total head	24m
wind speed	3.3 m/s
pipe diameter	65 mm
discharge	6 lit/sec
Pipe Type	150
Life time	10 year
present cost	4943 $

ii. Solar Pump Data

Table 4.18: Solar pump data(basic farm model inputs)

Total head (m)	2.2 m
Extra-terrestrial irradiation	34 MJ/m²
Clearness index	0.5
Tital factor	0.92
pipe diameter	150 mm
discharge	20 lit/sec
Pipe Type	150
Life time	15 year
present cost	7570 $

iii. Diesel Pump Data

Table 4.19: Diesel pump data(basic farm model inputs)

head (m)	40 m
pipe diameter	65 mm
discharge	6 lit/sec
Pipe Type	150
Life time	3 year
present cost	2060 $

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Model Verification

Model verification is tested by comparing the technical and economic outputs generated with the model in comparison to the output calculated by World Bank for hypothetical farms using wind, solar and diesel pumps for smallholders. The input data used is detailed in chapter four (section4.2) and model application output data is shown in appendix 1 (Meel and Smulders,1989). The purpose of the verification tests is to certain variability in outputs generated by the model taking World Bank procedure as reference. Hereafter the analysis is detailed for each type of pump:

5.1.1 For Wind Pumps

Table 5.1 shows results of comparing sensitivity of technical (Hydraulic Power Requirement, Rotor Diameter Pump stork, Power efficiency, and Torque) and economic (Total annual costs, Unit water costs, and Water Application Efficiency) parameters for wind pump. From Table 5.1 it is evident that: the design month power requirement is 41 Watt and there are no differences in both technical and economic parameters obtained by the model and that obtained by the World Bank Study except for rotor diameter. With application of the model procedure, the obtained rotor diameter is 4.2 m while that obtained by World Bank is 4.3 m, and the difference is minor and is only -2%. The performance of the wind pump being a classical wind pump with high pumping head, is expected to lie somewhere between "low" and "medium". This is evident from the monograms in Figure 3.1 which indicate a rotor diameter between 3.8 and 5.4 m using input data given in chapter four (section4.2) and results of model application given in Appendix 1.

Table 5.1: Wind verification

Wind					
Specification	Units	Model Output	WB-Output	% Difference	Error
Technical					
Hydraulic Power Requirement	W	41	41	0.00	0.00
Rotor Diameter	m	4.2	4.3	-2.33	0.10
Pump stork	mm	305	305	0.00	0.00
Torque		72	72	0.00	0.00
Economics					
Total annual costs	SDG	1971	1971	0.00	0.00
Unit water costs	SDG/m3	0.36	0.36	0.00	0.00
Water Application Efficiency	%	31	31	0.00	0.00
Power efficiency	%	11.5	11.5	0.00	0.00

5.1.2 For Solar Pumps:

Table 5.2 shows results of comparing sensitivity of technical (Hydraulic Power Requirement, Rotor Diameter Pump stork, Power efficiency, and Torque) and economic (Total annual costs, Unit water costs, and Water Application Efficiency) parameters for solar pump. As shown in Table 5.2 no difference with respect to both technical and economic parameters obtained by the model and those obtained by World Bank.

According to World’s reports (2001) pump typical levels of performance can be classified into: - low performance, 25% - medium performance, 35% - high performance, 45%. The ratio of daily hydraulic energy output to the daily electrical energy input from the solar panel given in Table 5.2 indicate that the Ratio of daily hydraulic energy output to the daily electrical energy input 30.5%, which is a medium performance.

Table 5.2: Solar verification

Solar					
Technical	Units	Model Output	WB-Output	% Difference	Error
Design month hydraulic energy requirement	MJ/day	2.2	2.2	0.03	0.00
Pv array size	WP	541	540	0.19	1.00
Rated peak hydraulic power	W	216	215	0.47	1.00
Rated flow rate	lit/sec	10	10	0.00	0.00
Economics					
Total annual costs	SDG	80	80	0.00	0.00
Unit water costs	SDG/m3	9.5	9.5	0.00	0.00
Water Application Efficiency	%	31	31	0.00	0.00
Power efficiency	%	5	5	0.00	0.00
Ratio of daily hydraulic energy output to the daily electrical energy input= (2.2/7.2)*100	30%				

5.1.3 For Diesel Driven Pumps

The results given in Table 5.2 shows outcome of testing sensitivity of technical (Hydraulic Power Requirement, Rotor Diameter Pump stork, Power efficiency, and Torque) and economic (Total annual costs, Unit water costs, and Water Application Efficiency) parameters for diesel pump. As shown in Table 5.3 there is no difference with respect to both technical and economic parameters obtained by the model and those obtained by World Bank (2001).

Table 5.3: Diesel verification

Diesel					
Technical	Units	Model Output	WB-Output	% Difference	Error
Design month hydraulic energy requirement	W	82	82	0	0
Design month head	meter	40	40	0	0
Economics					
Total annual costs	SDG	750	750	0	0
Unit water costs	SDG/m^3	80.00	80	0	0
Water Application Efficiency	%	31	31	0	0
Power efficiency	%	9.6	9.6	0	0

5.2 Model Validation

The success of any model must be judged by how well it meets its objectives or requirements. With a predictive model this means deciding on the time and space scale for which predictions are required and the level of accuracy. When making a judgment on the utility of a model, it is necessary to distinguish between failures due to misuse, and those associated with the structure of the model or its operating functions. In the latter case, failure may result from poor conceptualization of the problem, omission of important factors or inaccurate representation of a particular element in the model by the operating function or equation employed.

The solution is to modify or in some instances completely rethink the model. The accuracy of model predictions is usually tested by comparing predicted with measured values and applying some measure of goodness-of-fit. The data used for validation is that of the World Bank which is different from those used to develop the model. Criteria for validation are by no means clear-cut and in many cases, a qualitative assessment is all that is required.

The efficiency coefficient (CE), proposed by Nash and Sutcliffe (1970), is now increasingly used as an alternative to the correlation coefficient to express the performance of a model:

$$CE = (\sum (X_{obs} - X_{mean})^2 - \sum (X_{pred} - X_{obs})^2) / (\sum (X_{obs} - X_{mean})^2) \text{ ------ } (5.1)$$

Xobs mean is the observed value, X^2 mean is the mean of a set of observed values and X is the predicted value. The efficiency parameter is thus a measure of the variance in the predictions from the one-to-one prediction line with the measured values. The results of CE calculation given in Tables 5.1, 5.2, and 5.3, and Appendix 2 indicated that the prediction has been arrived at is ideal values (1.0) for all types of pumps. The better result with the CE may be attributed to better input data.

5.3 Model Sensitivity Analysis

Sensitivity analysis is undertaken separately for three different outputs, hydraulic power requirement, total annual cost and power efficiency, by changing four inputs (head, speed, pipe diameter, and discharge) at positive and negative increments of ±10% up to ±30% for each one of the studied pumps.

5.3.1 For Wind Pump:

Hydraulic Power Requirement: As given in Figure5.1when sensitivity analysis is carried out for each input parameter individually the rate of change in the output is mild when all inputs are changed each individually, except that for operating head and the trend of change in all inputs is negative. Figure 5.1 is used to investigate the reality of the interaction of changing all input parameters at the same time on hydraulic requirement (Within All inputs).

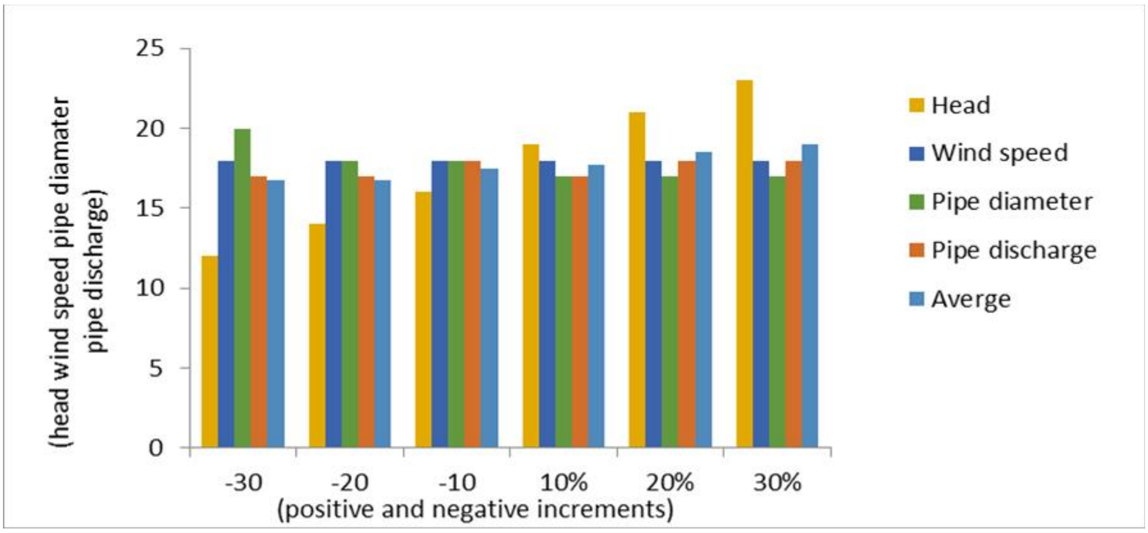


Figure 5.1 Hydraulic power requirement

It shows same trend as that obtained by the other input parameters and again except for the head. Such a case is more evident by calculating the values of average linear sensitivity index obtained with each input (Table5.4).

Table 5.4: Linear sensitivity index for variation of some inputs on energy, costs and efficiency of wind pump

1- hydraulic energy requirement	-30	-20	-10	10%	20%	30%	Average
Head	1.13	1.13	1.12	0.57	0.85	0.93	0.95
Wind speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe diameter	-0.30	0.00	0.00	-0.60	-0.31	-0.22	-0.24
Pipe discharge	0.16	0.26	0.00	-0.60	0.00	0.00	-0.03
Average	0.25	0.35	0.28	-0.16	0.13	0.18	0.17
2-Total annual costs							
Head	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe diameter	0.00	0.00	0.00	0.00	-0.04	0.00	-0.01
Pipe discharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
3-Power efficiency							
Head	-0.99	-8.86	-18.66	-1.00	-0.90	-0.91	-5.22
Wind speed	0.00	-8.82	-18.62	0.00	0.00	0.00	-4.57
Pipe diameter	0.27	-8.82	-18.62	0.31	0.16	0.11	-4.43
Pipe discharge	-0.08	-8.83	-18.63	0.00	0.00	0.00	-4.59
Average	-0.20	-8.83	-18.64	-0.17	-0.18	-0.20	-4.70

On average the highest variability is obtained by the head (0.95). This results call for putting high level of accuracy in collecting considering the values of the head parameter and should be considered as the most sensitive input.

However, the differences to changes in head are not misleading with respect to reality due to interaction of parameters. This because the differences between the within the model mean values of average linear sensitivity index (0.17) and that obtained by the head (0.95) indicate that it is logical to consider head as main controlling factor for variability. And other inputs are of low effect. This is due to their smaller values of average linear sensitivity index that range from 0.000 to - 0.024.

Total Annual Costs: Figure5.2shows that changing the four input parameters resulted in no variation in output of total annual costs. This is evident by the zero values obtained when inputs are changed individually or even collectively (Table5.4).

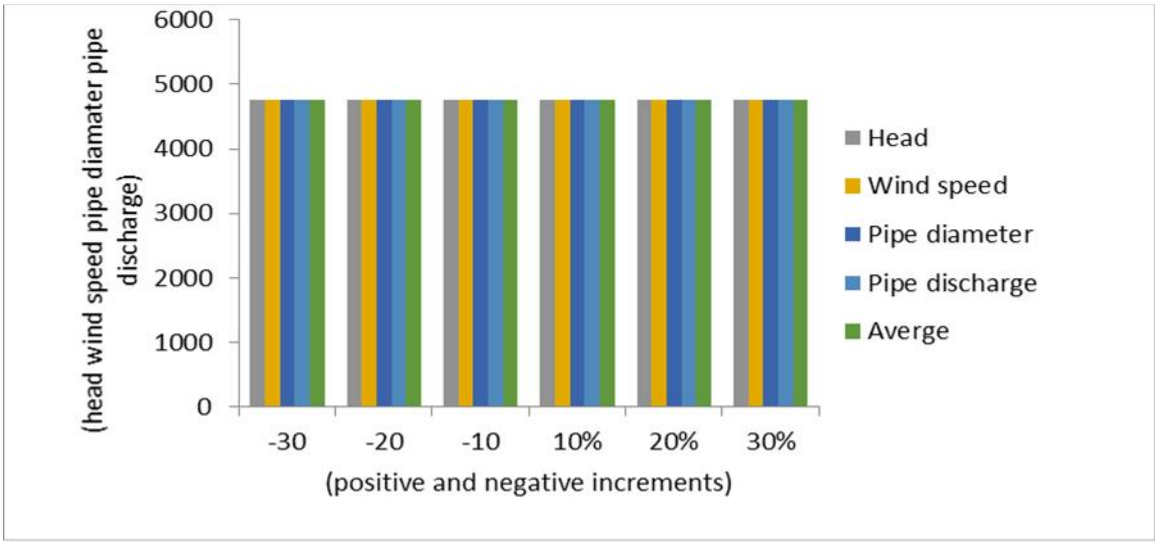


Figure 5.2 Total annual costs

Power Efficiency: As given in Table5.4 estimation of average linear sensitivity index indicate that very low values are obtained with changing all input parameter either collectively or individually. As such no high accuracy is needed in using the predictive model to give satisfactory estimates of the intended output of power efficiency. This result is supported by the same trend obtained by variation of the output values obtained by each or all input parameters given in Figure5.3

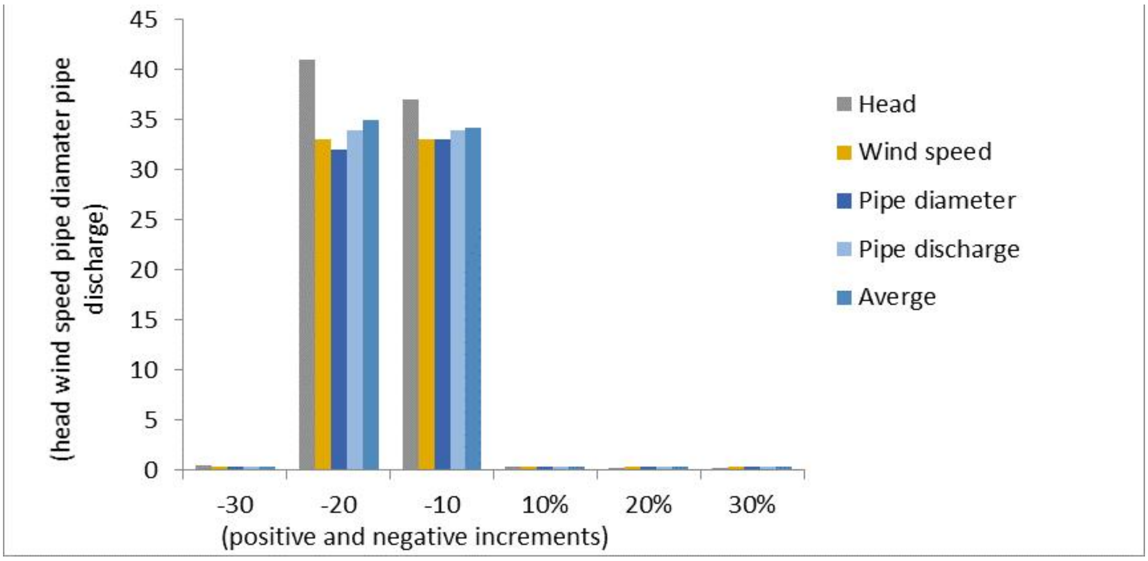


Figure 5.3 Power efficiency

5.3.2 For Solar pump:

Hydraulic power requirement: As given in Figure 5.4 when sensitivity analysis is carried out for each input parameter individually the rate of change in the output is mild when all inputs are changed each individually, except that for operating head and the trend of change in all inputs is negative. Figure 5.4 is used to investigate the reality of the interaction of changing all input parameters at the same time on hydraulic requirement (Within all inputs).

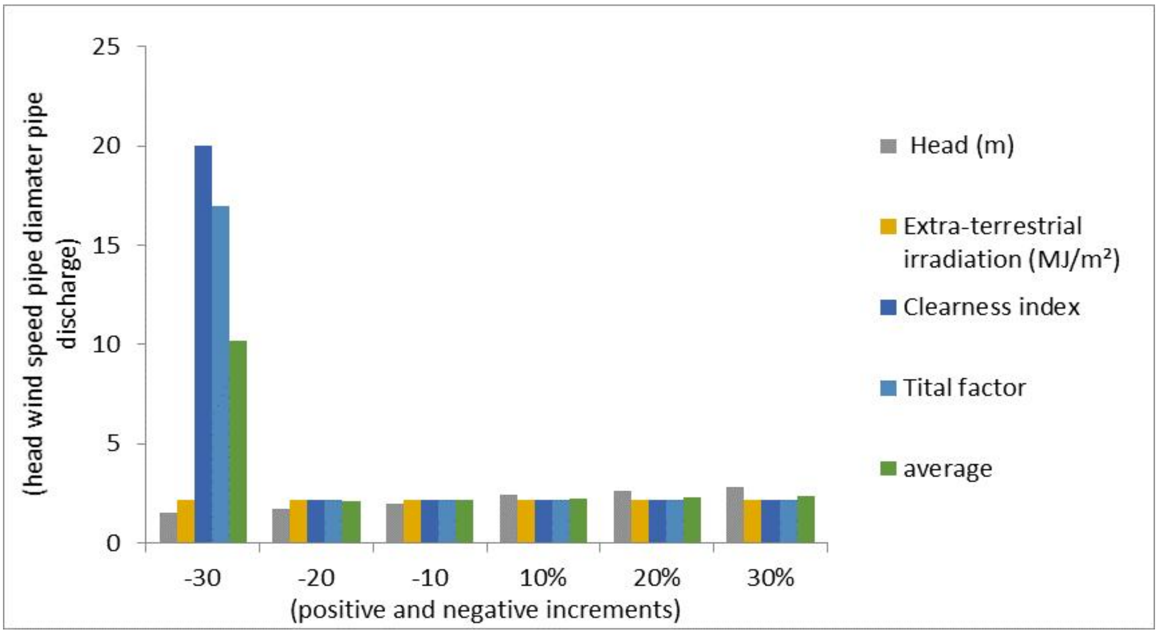


Figure 5.4 Hydraulic power requirement

It shows same trend as that obtained by the other input parameters and again except for the head. Such a case is more evident by calculating the values of average linear sensitivity index obtained with each input (Table).

Table 5.5: Linear sensitivity index for variation of some inputs on energy, costs and efficiency of wind pump

1- hydraulic energy requirement	-30	-20	-10	10%	20%	30%	Average
Head (m)	1.07	1.15	0.90	0.91	0.92	0.92	0.98
Extra-terrestrial irradiation (MJ/m²)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clearness index	-4.54	0.00	0.00	0.00	0.00	0.00	-0.76
Tital factor	-4.37	0.00	0.00	0.00	0.00	0.00	-0.73
Average	-1.96	0.29	0.23	0.23	0.23	0.23	-0.13
2-Total annual costs							
Head (m)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Extra-terrestrial irradiation (MJ/m²)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clearness index	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tital factor	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-Power efficiency							
Head (m)	0.00	0.00	0.00	0.00	-0.85	0.00	-0.14
Extra-terrestrial irradiation (MJ/m²)	0.00	0.00	0.00	0.00	-0.85	0.00	-0.14
Clearness index	0.00	0.00	0.00	0.00	-0.85	0.00	-0.14
Tital factor	-1.00	-0.87	-0.66	-0.78	-0.85	-0.92	-0.85
Average	-0.25	-0.22	-0.16	-0.19	-0.85	-0.23	-0.32

On average the highest variability is obtained by the head (0.98). This results call for putting high level of accuracy in collecting considering the values of the head parameter and should be considered as the most sensitive input. However, the differences to changes in head are not misleading with respect to reality due to interaction of parameters. This because the differences between the within the model mean values of average linear sensitivity index (-0.13) and that obtained by the head (0.98) indicate that it is logical to consider head as main controlling factor for variability. And other inputs are of low effect. This is due to their smaller values of average linear sensitivity index that range from 0.000 to - 0.13.

Total Annual Costs: Figure 5.5 shows that changing the four input parameters resulted in no variation in output of total annual costs. This is evident by the zero values obtained when inputs are changed individually or even collectively (Table5.5).

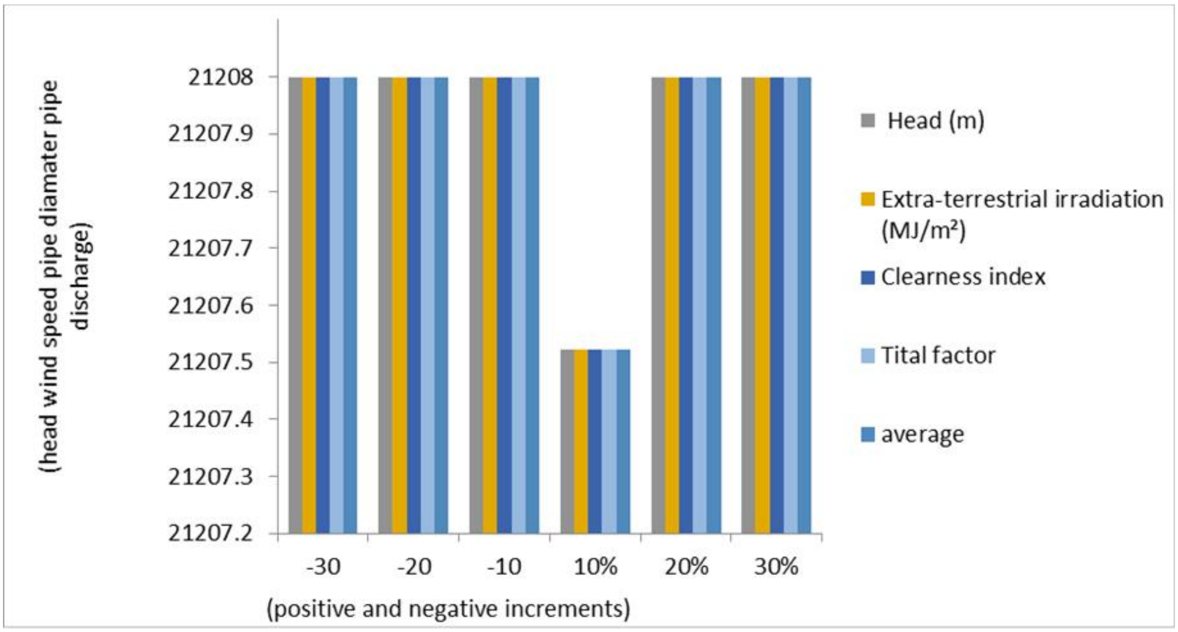


Figure 5.5 Total annual costs

Power Efficiency: As given in Table 5.5 estimation of average linear sensitivity index indicate that very low values are obtained with changing all input parameter either collectively or individually. As such no high accuracy is needed in using the predictive model to give satisfactory estimates of the intended output of power efficiency. This result is supported by the same trend obtained by variation of the output values obtained by each or all input parameters given in Figure 5.6

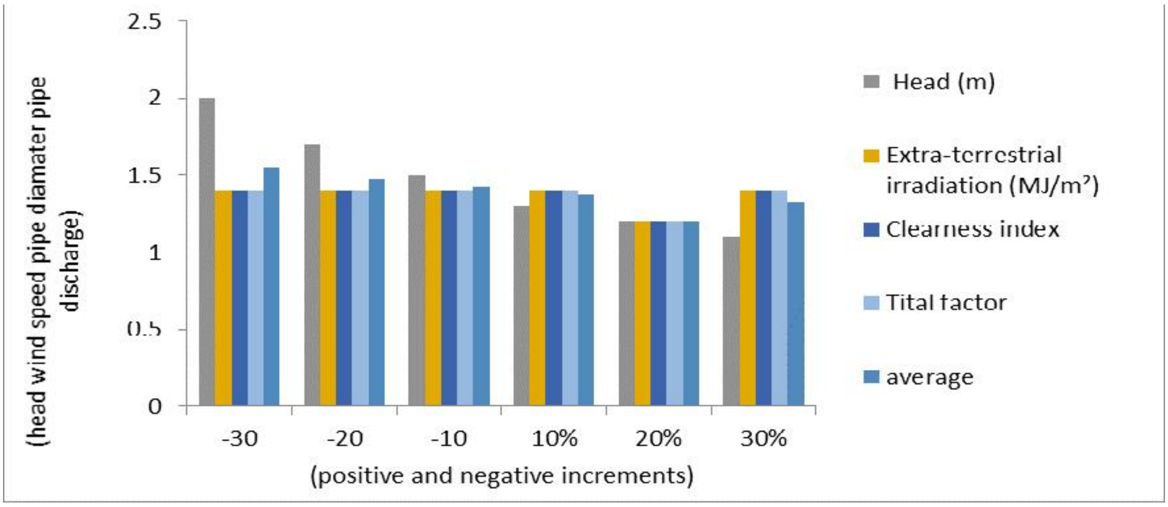


Figure 5.6 Power efficiency

5.3.3 For Diesel pump:

Hydraulic power requirement: As given in Figure 5.7 when sensitivity analysis is carried out for each input parameter individually the rate of change in the output is mild when all inputs are changed each individually, except that for operating head and the trend of change in all inputs is negative. Figure 5.7 is used to investigate the reality of the interaction of changing all input parameters at the same time on hydraulic requirement (Within all inputs).

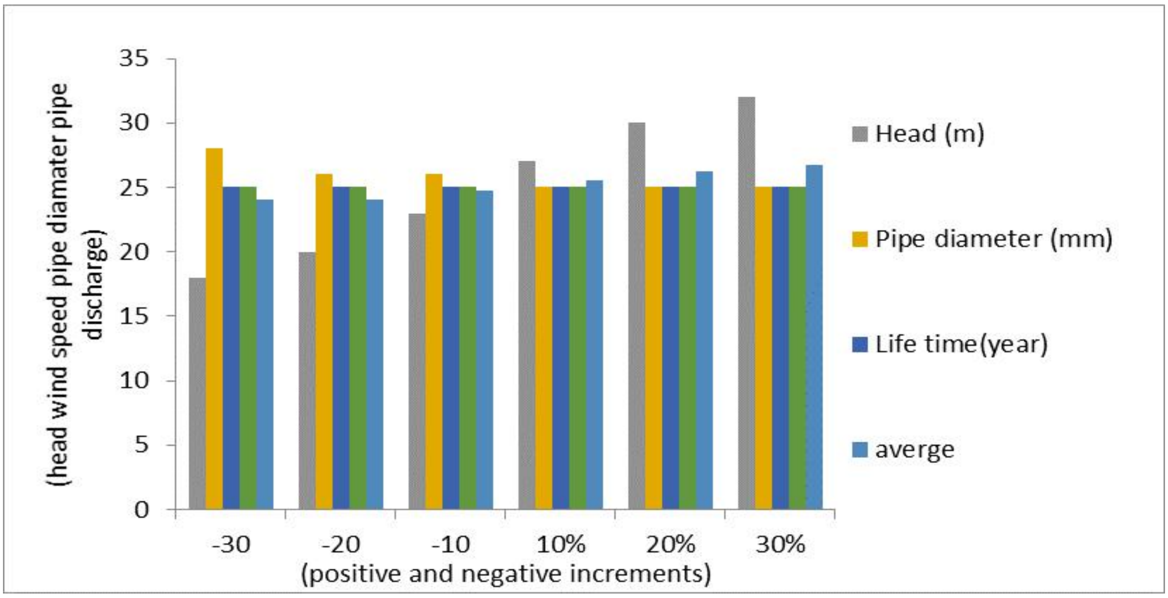


Figure 5.7 Hydraulic power requirement

It shows same trend as that obtained by the other input parameters and again except for the head. Such a case is more evident by calculating the values of average linear sensitivity index obtained with each input (Table).

Table 5.6:Linear sensitivity index for variation of some inputs on energy, costs and efficiency of wind pump

1- hydraulic energy requirement	-30	-20	-10	10%	20%	30%	Average
Head (m)	0.92	1.00	0.79	0.81	1.00	0.94	0.91
Pipe diameter (mm)	-0.32	-0.18	-0.37	0.00	0.00	0.00	-0.14
Life time(year)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe discharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.15	0.21	0.10	0.20	0.25	0.24	0.19
2-Total annual costs							
Head (m)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Pipe diameter (mm)	0.00	-0.18	0.00	0.00	0.00	0.00	-0.03
Life time(year)	-0.29	-0.01	-0.26	-0.23	-0.22	-0.22	-0.20
Pipe discharge	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
Average	-0.07	-0.05	-0.07	-0.06	-0.06	-0.05	-0.06
3-Power efficiency							
Head (m)	-0.95	-0.94	-0.89	-1.02	-11.00	-1.01	-2.63
Pipe diameter (mm)	0.36	0.26	0.23	0.06	-1.02	0.05	-0.01
Life time(year)	0.02	0.03	0.06	-0.03	0.05	-0.02	0.02
Pipe discharge	-0.03	-0.03	0.00	-0.06	-0.03	-0.07	-0.04
Average	-0.15	-0.17	-0.15	-0.26	-3.00	-0.26	-0.67

On average the highest variability is obtained by the head (0.91). This results call for putting high level of accuracy in collecting considering the values of the head parameter and should be considered as the most sensitive input. However, the differences to changes in head are not misleading with respect to reality due to interaction of parameters. This because the differences between the within the model mean values of average linear sensitivity index (0.19) and that obtained by the head (0.91) indicate that it is logical to consider head as main controlling factor for variability. And other inputs are of low effect. This is due to their smaller values of average linear sensitivity index that range from 0.000 to - 0.14.

Total Annual Costs: Figure 5.8 shows that changing the four input parameters resulted in no variation in output of total annual costs. This is evident by the zero values obtained when inputs are changed individually or even collectively (Table 5.6).

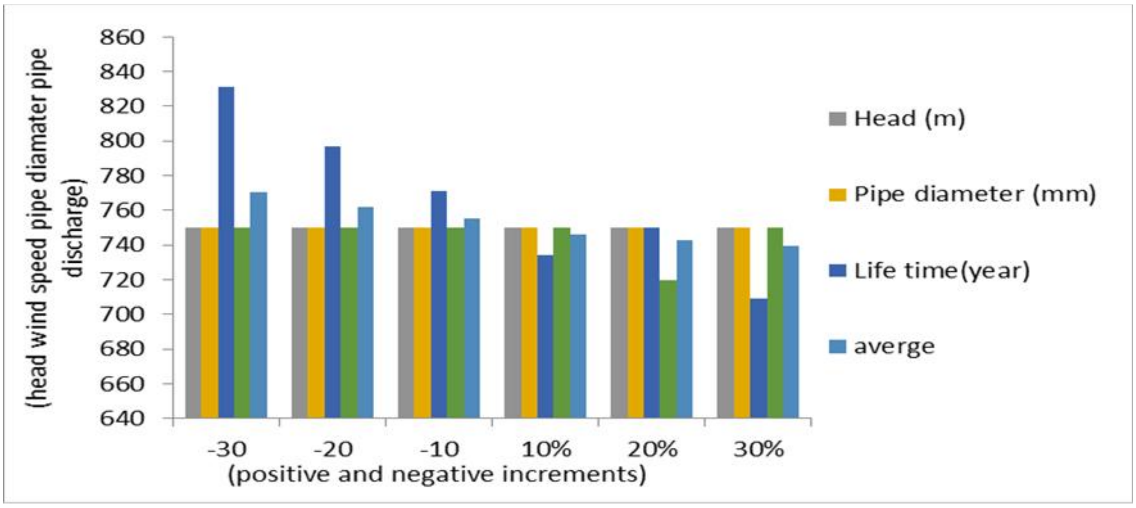


Figure 5.8 Total annual costs

Power Efficiency: As given in Table 5.6 estimation of average linear sensitivity index indicate that very low values are obtained with changing all input parameter either collectively or individually. As such no high accuracy is needed in using the predictive model to give satisfactory estimates of the intended output of power efficiency. This result is supported by the same trend obtained by variation of the output values obtained by each or all input parameters given in Figure 5.9

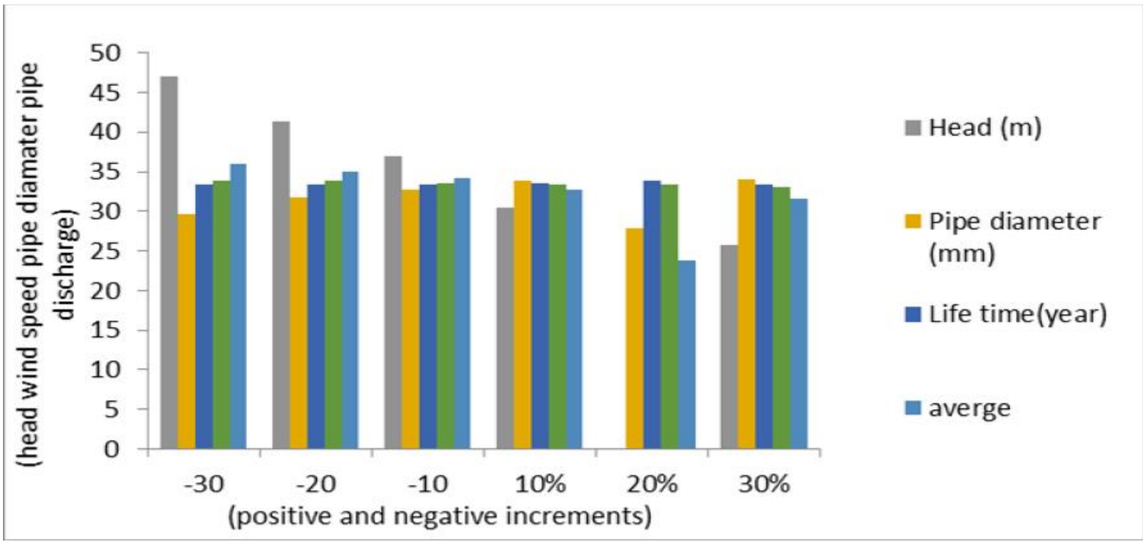


Figure 5.9 Power efficiency

5.3.4 For Electric Pump:

Hydraulic Power Requirement: As given in Figure 5.10 when sensitivity analysis is carried out for each input parameter individually the rate of change in the output is mild when all inputs are changed each individually, except that for operating head and the trend of change in all inputs is negative. Figure 5.10 is used to investigate the reality of the interaction of changing all input parameters at the same time on hydraulic requirement (Within all inputs).

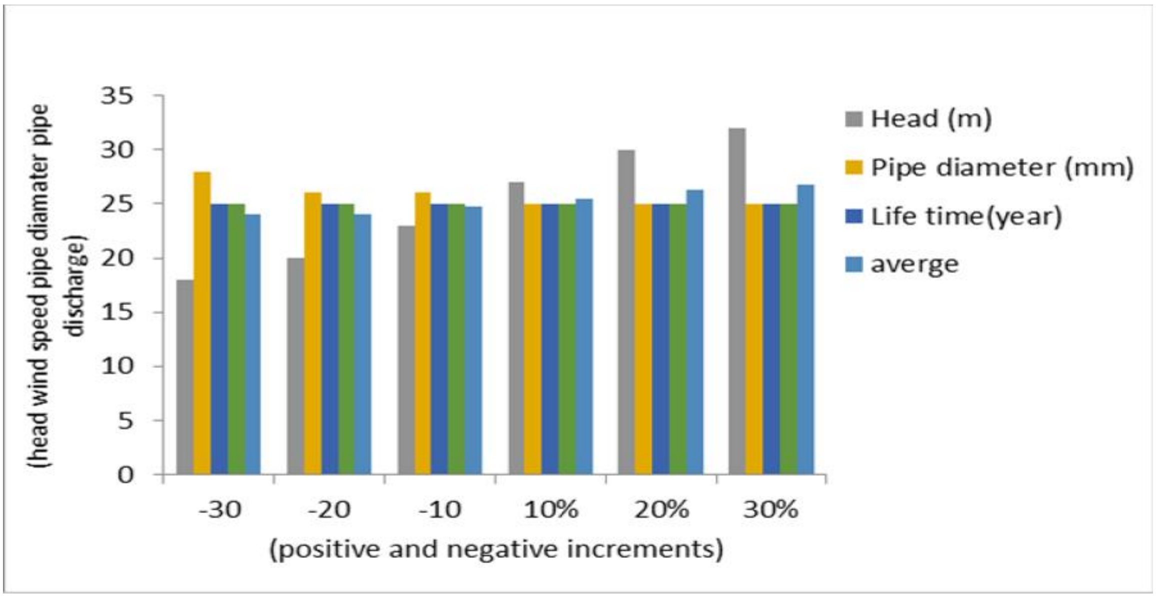


Figure 5.10 Hydraulic power requirement

It shows same trend as that obtained by the other input parameters and again except for the head. Such a case is more evident by calculating the values of average linear sensitivity index obtained with each input (Table 5.7).

Table 5.7: Linear sensitivity index for variation of some inputs on energy, costs and efficiency of wind pump

1- hydraulic energy requirement	-30	-20	-10	10%	20%	30%	Average
Head (m)	0.92	1.00	0.79	0.81	1.00	1.64	1.03
Pipe diameter (mm)	-0.32	-0.18	-0.37	0.00	0.00	0.00	-0.14
Life time(year)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe discharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.15	0.21	0.10	0.20	0.25	0.41	0.22
2-Total annual costs							
Head (m)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe diameter (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Life time(year)	2.89	4.59	9.69	-10.71	-5.61	0.00	0.14
Pipe discharge	2.89	-0.04	9.69	-10.71	-5.61	0.00	-0.63
Average	1.45	1.14	4.85	-5.36	-2.81	0.00	-0.12
3-Power efficiency							
Head (m)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe diameter (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Life time(year)	-0.96	-0.95	-0.92	-0.98	-1.00	-2.38	-1.20
Pipe discharge	0.35	0.25	0.20	0.09	0.07	0.11	0.18
Average	-0.15	-0.18	-0.18	-0.22	-0.23	-0.57	-0.25

On average the highest variability is obtained by the head (1.03). This results call for putting high level of accuracy in collecting considering the values of the head parameter and should be considered as the most sensitive input. However, the differences to changes in head are not misleading with respect to reality due to interaction of parameters. This because the differences between the within the model mean values of average linear sensitivity index (0.22) and that obtained by the head (1.03) indicate that it is logical to consider head as main controlling factor for variability. And other inputs are of low effect. This is due to their smaller values of average linear sensitivity index that range from 0.000 to - 0.14.

Total Annual Costs: Figure 5.11shows that changing the four input parameters resulted in no variation in output of total annual costs. This is evident by the zero values obtained when inputs are changed individually or even collectively (Table 5.7).

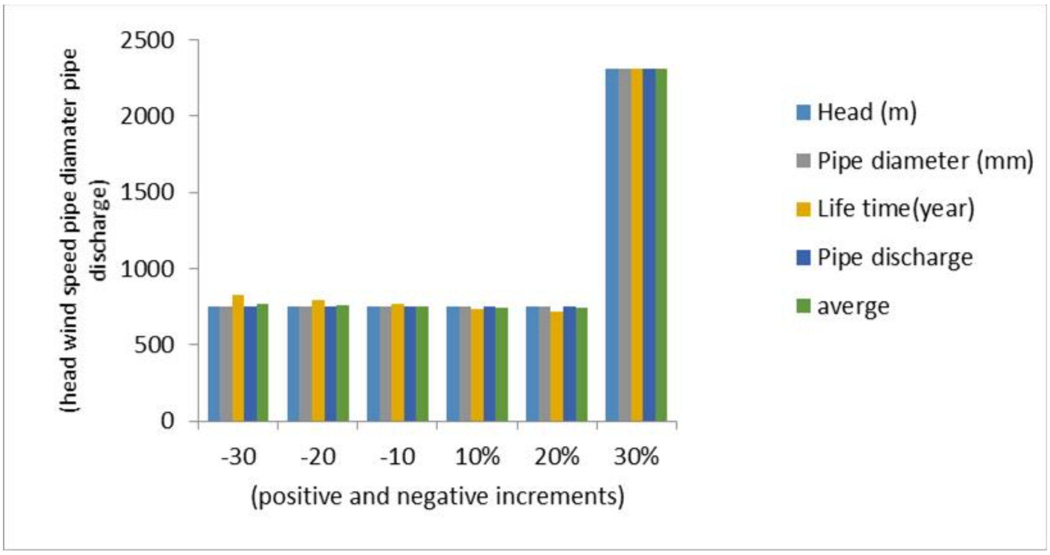


Figure 5.11 Total annual costs

Power Efficiency: As given in Table 5.7 estimation of average linear sensitivity index indicate that very low values are obtained with changing all input parameter either collectively or individually. As such no high accuracy is needed in using the predictive model to give satisfactory estimates of the intended output of power efficiency. This result is supported by the same trend obtained by variation of the output values obtained by each or all input parameters given in Figure 5.12

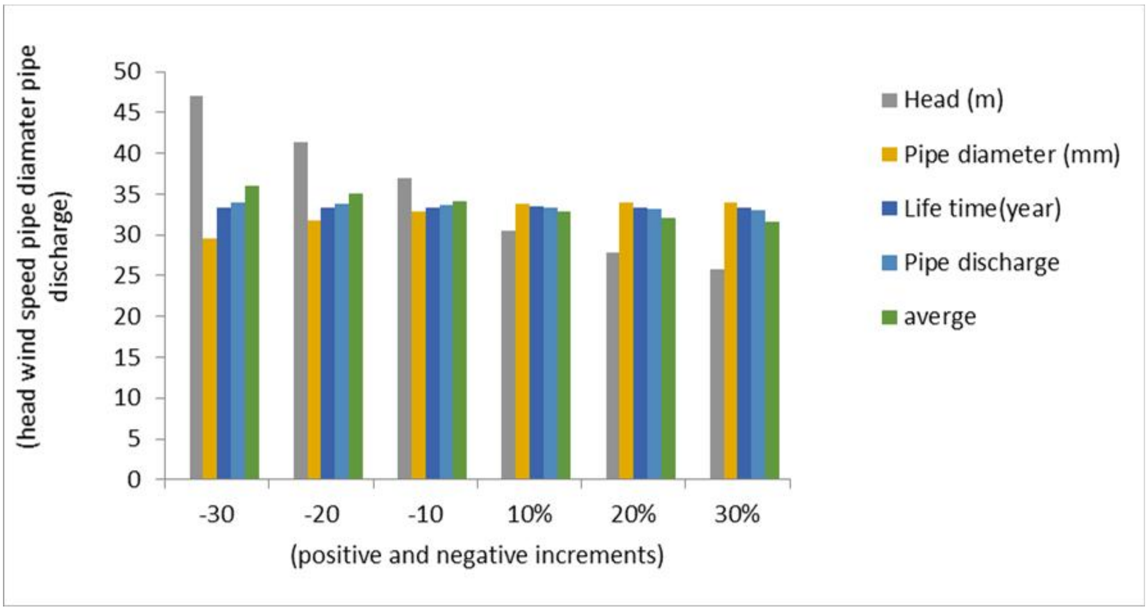


Figure 5.12 Power efficiency

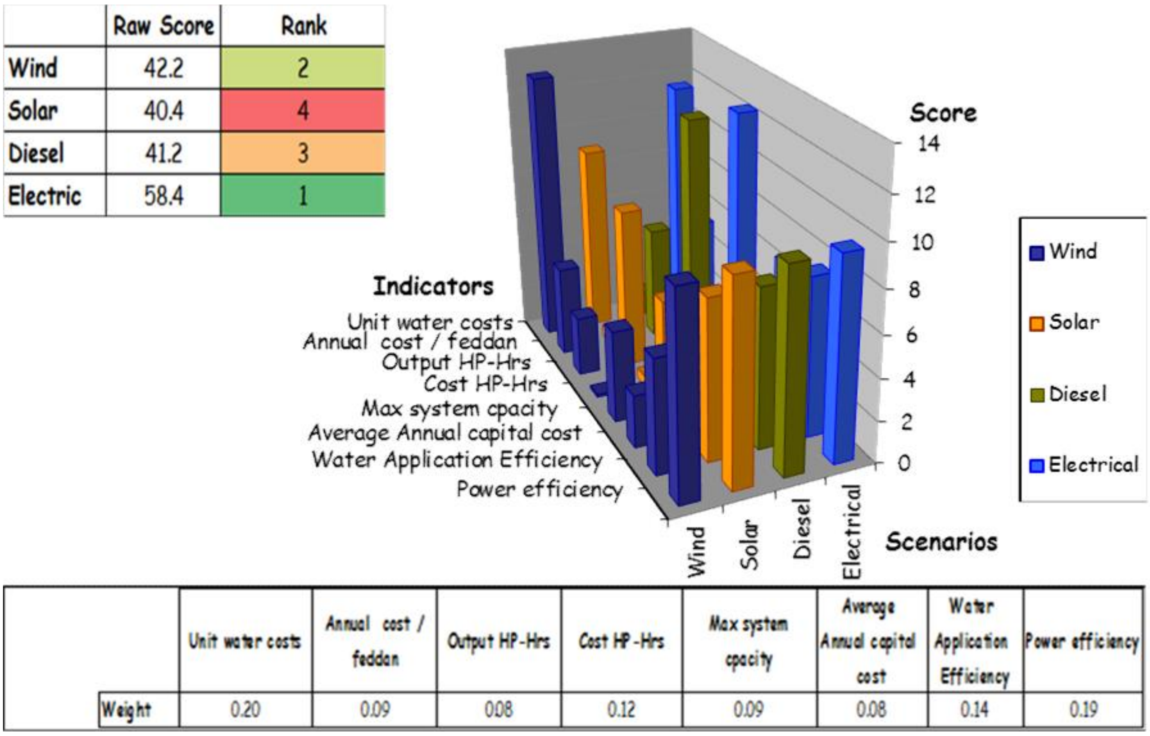
5.4 Model Application and Pump Selection for Alosaylat Farm

Using input data of Alosaylat Farm (given in chapter 4) the application of the model multi-criteria analysis resulted in ranking the different types of pumps (Table4.15). Farm reveled the ranking of pump types in descending order of: electric, wind, diesel and solar. The order is based on the facts that:

- The electric pump: is highest score (best choice) of pump with unit water rate of 0.32, unfortunately, the farm is located in remote area outside of the layout of electrical grid lines. But not actually installed in the farm. However, this is not included in the evaluation indicators of the selection model.
- For wind pump: also not actually installed in the farm. This may be due to the fact that wind distribution along each month of the year is not studied and the probability of its occurrence needs to be specified.
- For pump the specifications of the diesel pump selected by the model
- For solar pump: The solar pump is most expensive type of pump but it is actually installed in the farm.

Table 5.8: Results of multi-criteria analysis for selection of the different types of pump

Pump Type	Unit water costs	annual cost / feddan	Output HP-Hrs	Cost HP-Hrs	Max system capacity	Average Annual capital cost	Water Application Efficiency	Power efficiency
Wind	12.94	4.34	2.87	0.12	4.39	2.52	5.45	9.59
Solar	9.02	0.55	7.71	0.50	5.33	0.08	7.61	9.59
Diesel	1.18	5.45	0.41	12.44	4.39	0.15	7.61	9.59
Electric	11.57	5.45	0.16	12.44	4.39	7.17	7.61	9.59



	Raw Score	Rank
Wind	42.2	2
Solar	40.4	4
Diesel	41.2	3
Electric	58.4	1

	Unit water costs	Annual cost / feddan	Output HP-Hrs	Cost HP-Hrs	Max system cpacity	Average Annual capital cost	Water Application Efficiency	Power efficiency
Weight	0.20	0.09	0.08	0.12	0.09	0.08	0.14	0.19

Figure 5.13 Ranking of different types of pumps based on evaluation indicators

Comparison and the specifications of each type of pump that can be employed in the farms (Table 5.9)

Table 5.9: Comparison of the specifications of each type of pump generated by the model with that actually used in Alosaylat Farm

Pump Type	**solar**		**diesel**	
Parameter	Model	Actual	Model	Actual
discharge(m^3/hr.)	48	37.85	60	45.42
size(hp)	5	3	6	10
diameter(inch)	3	3	3	4
Pump Type	**Wind**		**Electric**	
Parameter	Model	Units	Model	Units
Pumping Rate	590	m3/month	838	m3/month
Pumping height	8	m	8	m
Power Requirement	18	W	25	W
power	6	hp	6	hp

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This study is directed to analyze the economic and technical feasibility of different energy sources for smallholder pump used for Plantation and domestic supply. To reach such goal the study explores the background information and literature overview regarding the problem faced when the smallholders is confronted with the dilemma of selecting the most preferred watering pump prime mover with constraint of rising prices of energy and lack of electricity in remote areas, and what suitable pump design to use under the prevailing environment. The methodology used to answer these questions includes secondary sources, data analysis, and development of selection and specification model on techno-economic grounds coded in Excel and Visual Basic. The process of model development includes: programming techniques and style, structure, limitation, iterative logic and calculation procedures

Analysis of results covers areas of: model validation in comparison with data supplied by World Bank and model verification and application with respect to a real case study farm.

6.2 Conclusions

The study outcomes can be summarized in the followings:

1- Model Development: A hydraulic design scheme using Excel spread sheet for sizing and setting the specification of smallholder pump operated by: wind or diesel or electricity or solar power was made to be user-friendly.

2- Model verification: Statistical comparison of model outputs for solar, wind and diesel pumps was found typical to the data of smallholder farm reported by World Bank. This confirms model validity.

3- Model Sensitivity Analysis : Effect of changing model inputs (For Wind pump: Head, wind speed, pipe diameter, and discharge; For Solar pump: Head (m), Extra-terrestrial irradiation (MJ/m²) Clearness index, Tital factor; For Diesel pump: Head (m), Pipe diameter (mm), Life time(year), Pipe discharge; For Electric pump: Head (m), Pipe diameter (mm), Life time(year), Pipe discharge) on model out puts (Hydraulic Power Requirements , Design month hydraulic energy requirement, Economic parameters of total annual cost, and unit costs, Water Application Efficiency, Power Efficiency) for each type of pump.

The results indicate that using linear sensitivity index for all pump types changing head input had clear effect on the three outputs while no effect was obtained when other inputs are changed.

4- Model Application: Using input data of Alosaylat Farm the application of the model multi-criteria analysis resulted in ranking the different types of pumps in descending order of: electric, wind, diesel and solar. However, reasons governing such results and the specifications of each type of pump that can be employed are (The electric pump: is highest score (best choice) of pump with unit water rate of 0.32, unfortunately, the farm is located in remote area outside of the layout of electrical grid lines. But not actually installed in the farm. However, this is not included in the evaluation indicators of the selection model, for wind pump: also not actually installed in the farm. This may be due to the fact that wind distribution along each month of the year is not studied and the probability of its occurrence needs to be specified, for pump the specifications of the diesel pump selected by the model, for solar pump: The solar pump is most expensive type of pump and the farmers cannot buy it).

6.3 Recommendations

6.3.1 For Policy Making

1- It is recommended to employ pump type selection and specification Model for irrigating small farms
2- When applying the developed selection model special care to be taken For the sensitivity of input data as given above (section 6.2 c) to use with each type of pump.
3- For the case of Alosaylat Farm it is recommended to install wind Pump but after detailed analysis of wind variation with season months.

6.3.2 For Future Research

In future it is recommended employing the model in each climate zone of Sudan to set priority levels of pump types according to model multi-objective analysis. Recall that this requires developing probability analysis module to analyze the climate elements to be added to the structure of the developed computer model.

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APPENDICES

Appendix1

Figure A1. Clearness Index Map for January

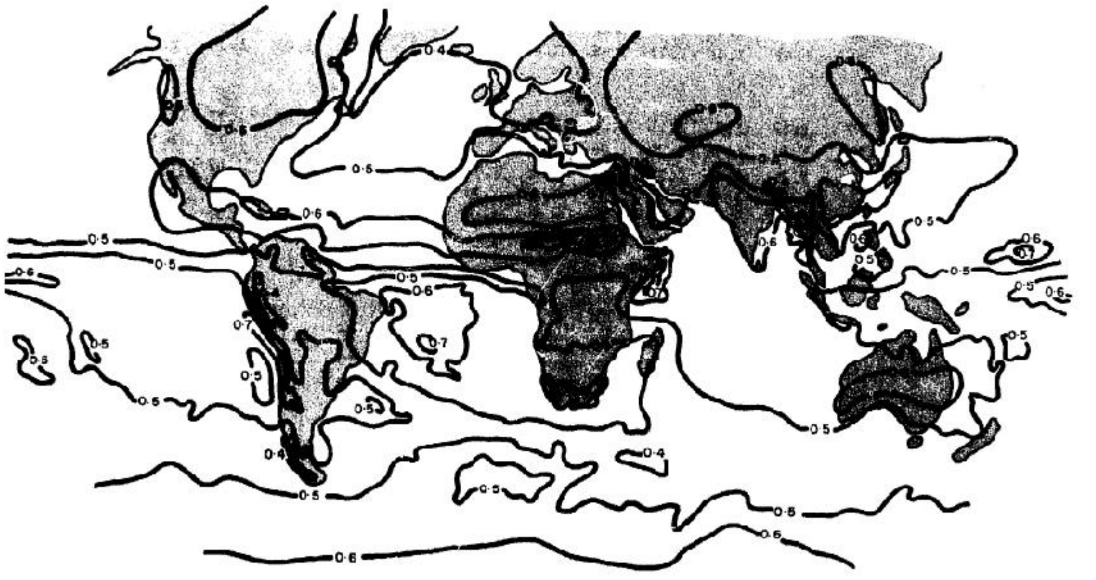

Figure A2. Clearness Index Map for February

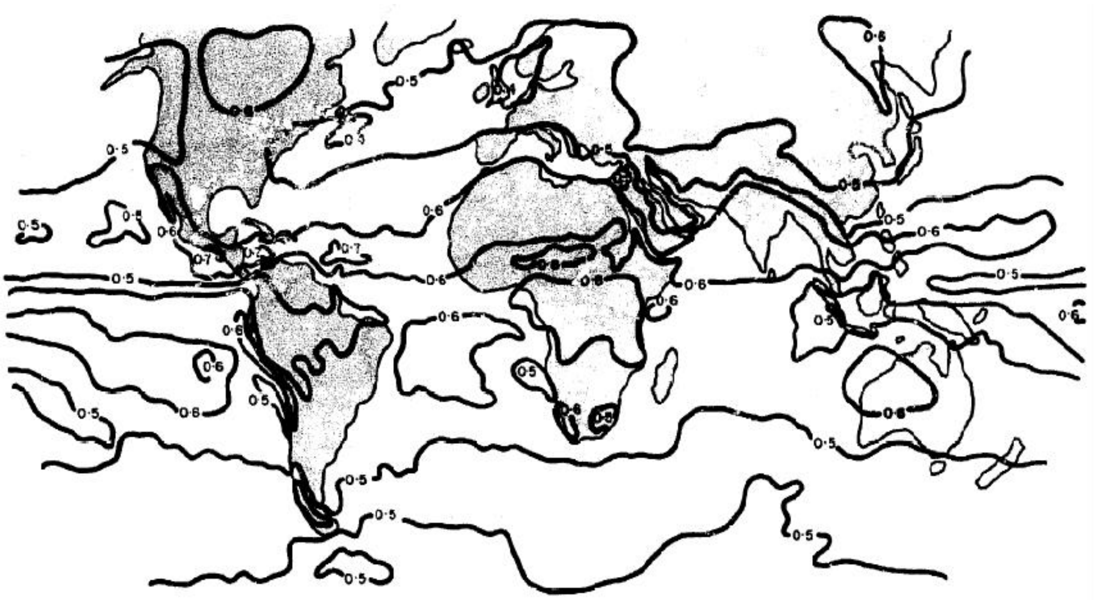

Figure A3. Clearness Index Map for March

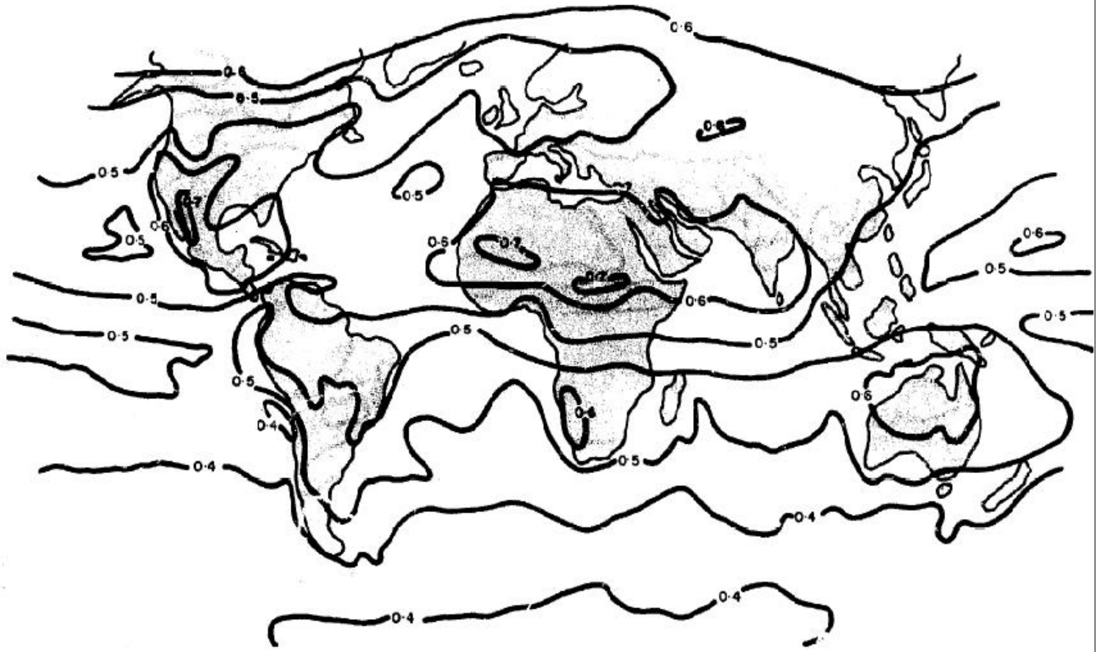

Figure A4. Clearness Index Map for April

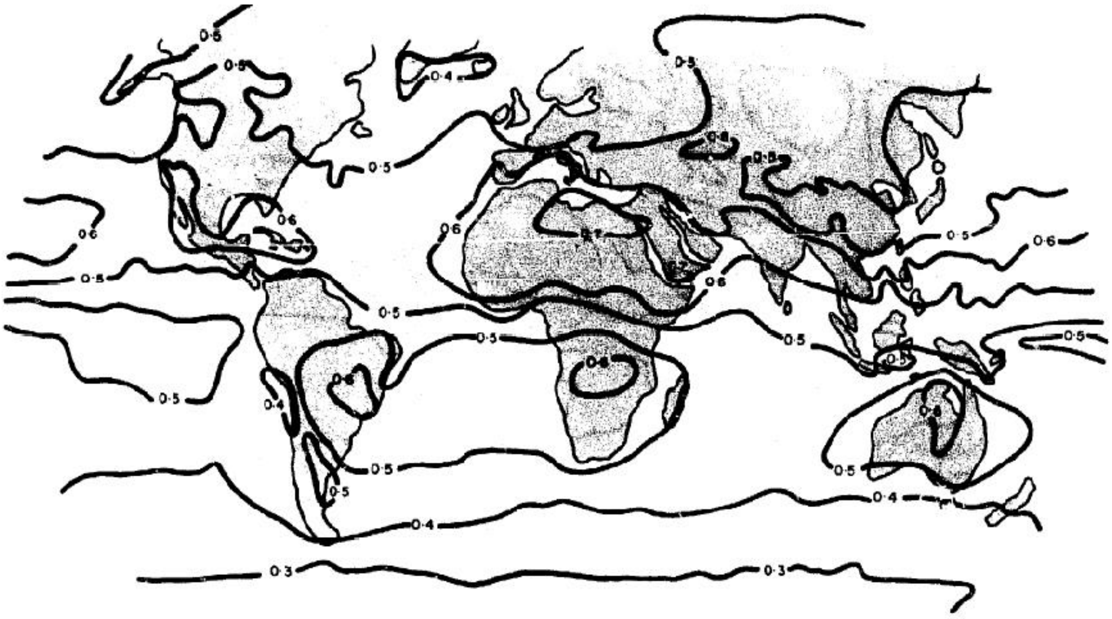

Figure A5. Clearness Index Map for May

Figure A6. Clearness Index Map for June

Figure A7. Clearness Index Map for July

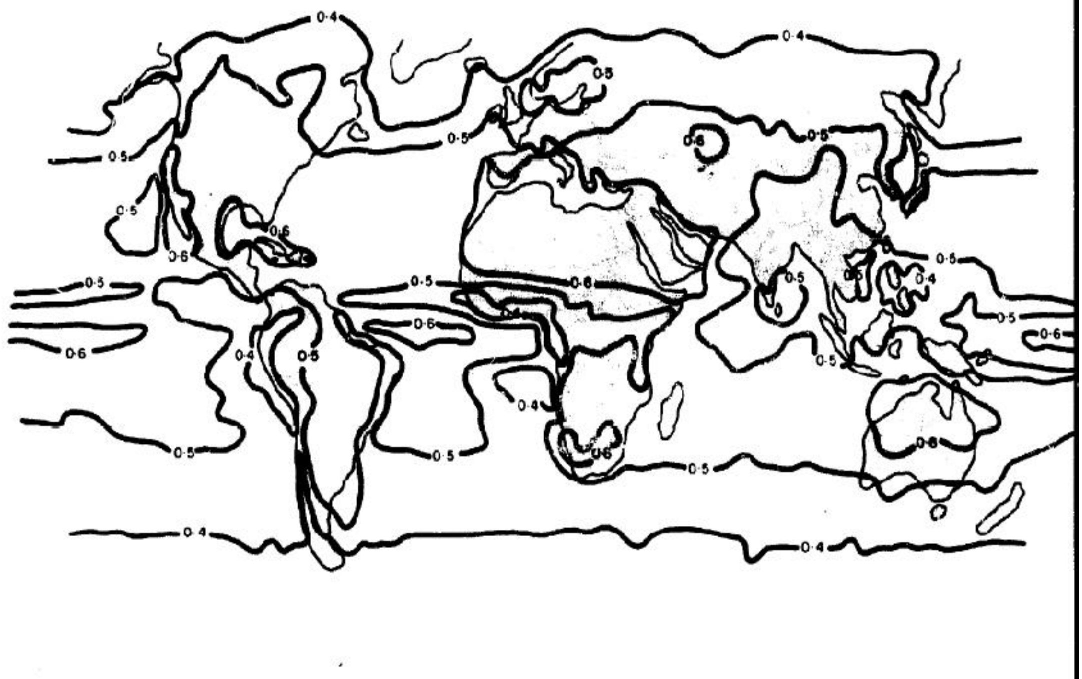

Figure A8. Clearness Index Map for August

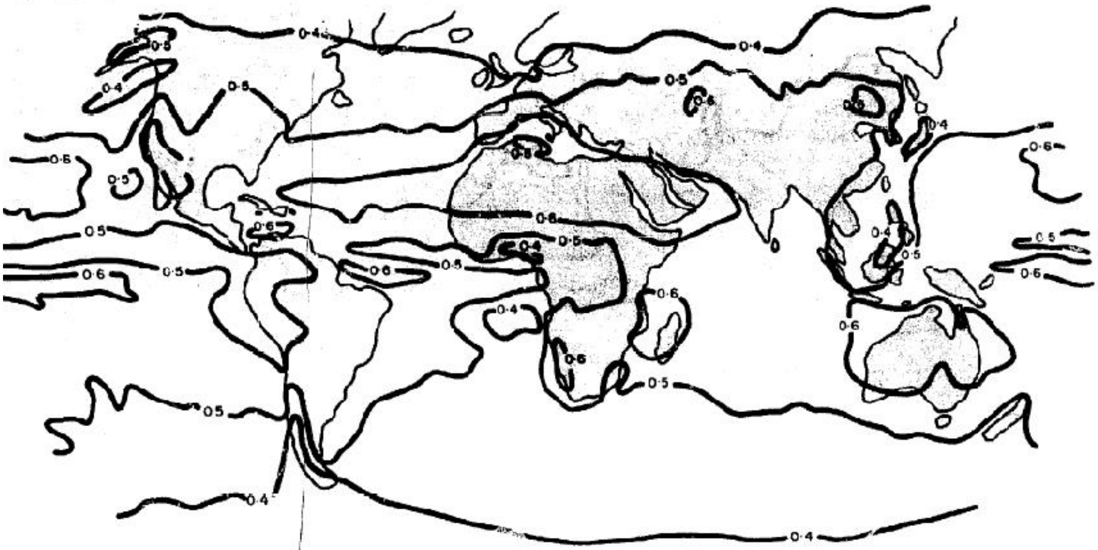

Figure A9. Clearness Index Map for September

Figure A10. Clearness Index Map for October

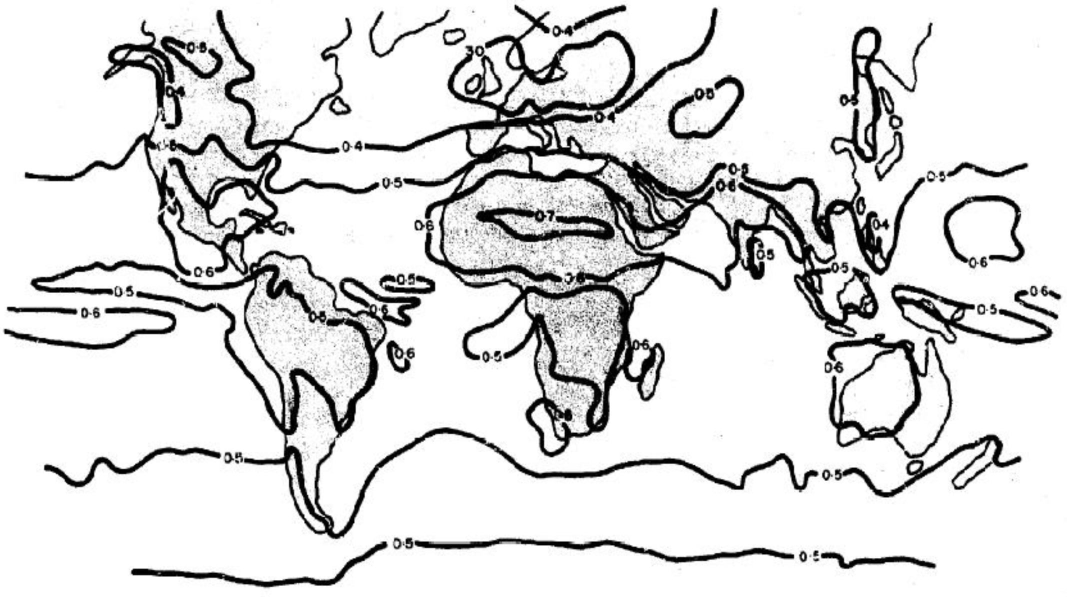

Figure A11. Clearness Index Map for November

Figure A12. Clearness Index Map for December

Appendix 2(Kenna and Gillett ,1985)

	Month for Northern Hemisphere												
Latitude Degrees	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Latitude Degrees
0	36	37	38	36	34	33	34	35	37	37	36	35	0
5	34	36	37	37	36	35	35	36	37	36	34	33	5
10	32	34	37	38	37	37	37	37	37	35	32	31	10
15	29	32	36	38	38	38	38	38	36	33	30	28	15
20	27	30	34	38	39	39	39	38	35	31	27	25	20
25	24	28	33	37	39	40	40	38	34	29	25	23	25
30	21	26	31	37	40	41	40	37	33	27	22	20	30
35	18	23	29	36	40	41	40	37	31	25	19	17	35
40	15	20	27	34	39	41	40	36	29	22	16	14	40
45	12	18	25	33	39	41	40	35	27	19	13	11	45
50	9	15	22	31	38	41	40	34	25	16	10	8	50
55	6	12	20	29	37	41	39	32	23	14	7	5	55
60	3	9	17	27	36	41	38	30	20	11	4	2	60
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	
	Month for Southern Hemisphere												

Table A1. Average Daily Global Irradiation for a horizontal surface outside the earth's atmosphere.

Clearness Index	Tilt (degrees)	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.3	10	1.03	1.01	1.00	0.97	0.96	0.95	0.95	0.97	0.99	1.01	1.03	1.04
	20	1.04	1.01	0.97	0.93	0.90	0.88	0.89	0.92	0.96	1.00	1.04	1.05
	30	1.04	0.99	0.93	0.87	0.82	0.80	0.81	0.85	0.91	0.97	1.03	1.05
	40	1.01	0.95	0.88	0.80	0.74	0.71	0.73	0.78	0.85	0.93	1.00	1.03
	50	0.96	0.89	0.81	0.71	0.65	0.62	0.64	0.69	0.77	0.87	0.95	0.99
	60	0.90	0.82	0.72	0.62	0.56	0.54	0.55	0.60	0.69	0.80	0.89	0.93
0.4	10	1.05	1.02	1.00	0.96	0.94	0.93	0.93	0.95	0.98	1.02	1.04	1.06
	20	1.07	1.03	0.97	0.91	0.86	0.84	0.85	0.89	0.95	1.01	1.06	1.09
	30	1.08	1.01	0.93	0.84	0.77	0.73	0.75	0.81	0.89	0.99	1.06	1.10
	40	1.06	0.97	0.86	0.75	0.66	0.63	0.64	0.72	0.82	0.94	1.04	1.08
	50	1.01	0.91	0.78	0.65	0.55	0.51	0.53	0.61	0.73	0.87	0.99	1.05
	60	0.95	0.83	0.69	0.54	0.45	0.41	0.43	0.50	0.63	0.79	0.92	0.99
0.5	10	1.06	1.03	1.00	0.95	0.92	0.90	0.91	0.94	0.98	1.02	1.06	1.07
	20	1.10	1.04	0.97	0.89	0.82	0.79	0.81	0.86	0.94	1.02	1.09	1.12
	30	1.12	1.03	0.92	0.80	0.71	0.67	0.69	0.77	0.88	1.00	1.10	1.14
	40	1.10	0.99	0.85	0.70	0.59	0.54	0.56	0.66	0.80	0.95	1.08	1.14
	50	1.06	0.93	0.76	0.59	0.46	0.41	0.44	0.54	0.70	0.88	1.03	1.10
	60	1.00	0.84	0.65	0.46	0.34	0.30	0.32	0.41	0.58	0.79	0.96	1.04
0.6	10	1.08	1.04	1.00	0.95	0.90	0.88	0.89	0.93	0.98	1.03	1.07	1.09
	20	1.14	1.06	0.97	0.87	0.79	0.75	0.77	0.84	0.93	1.03	1.12	1.16
	30	1.16	1.05	0.91	0.77	0.65	0.60	0.63	0.72	0.86	1.01	1.13	1.19
	40	1.15	1.01	0.83	0.65	0.51	0.45	0.48	0.60	0.77	0.96	1.12	1.19
	50	1.11	0.94	0.74	0.52	0.37	0.30	0.33	0.46	0.66	0.89	1.08	1.16
	60	1.04	0.85	0.62	0.38	0.23	0.17	0.20	0.32	0.53	0.79	1.00	1.10
0.7	10	1.10	1.06	1.00	0.93	0.88	0.86	0.87	0.91	0.98	1.04	1.09	1.12
	20	1.17	1.08	0.97	0.84	0.74	0.70	0.72	0.80	0.92	1.05	1.15	1.20
	30	1.21	1.07	0.91	0.73	0.59	0.52	0.56	0.67	0.84	1.03	1.18	1.25
	40	1.21	1.03	0.82	0.59	0.42	0.35	0.38	0.53	0.74	0.97	1.17	1.26
	50	1.17	0.96	0.71	0.44	0.25	0.17	0.21	0.37	0.61	0.89	1.13	1.23
	60	1.1	0.87	0.58	0.28	0.10	0.03	0.06	0.21	0.47	0.79	1.05	1.17

Table A2 Tilt factors for latitude 0 degrees

Clearness Index	Tilt (degrees)	Month for Northern Hemisphere											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	10	1.04	1.02	1.00	0.98	0.96	0.95	0.96	0.97	0.99	1.02	1.03	1.04
	20	1.06	1.02	0.98	0.94	0.91	0.89	0.90	0.93	0.97	1.01	1.05	1.07
0.3	30	1.06	1.01	0.95	0.89	0.84	0.82	0.83	0.87	0.93	0.99	1.05	1.07
	40	1.04	0.97	0.90	0.82	0.76	0.74	0.75	0.80	0.87	0.95	1.02	1.06
	50	1.00	0.92	0.83	0.74	0.68	0.65	0.66	0.72	0.80	0.90	0.98	1.02
	60	0.94	0.85	0.75	0.65	0.59	0.56	0.57	0.63	0.72	0.83	0.92	0.97
	10	1.06	1.03	1.00	0.97	0.95	0.94	0.94	0.96	0.99	1.03	1.05	1.07
	20	1.10	1.05	0.99	0.93	0.88	0.86	0.87	0.91	0.97	1.03	1.08	1.11
0.4	30	1.11	1.04	0.95	0.86	0.79	0.76	0.78	0.83	0.92	1.01	1.09	1.13
	40	1.10	1.00	0.89	0.78	0.70	0.66	0.68	0.75	0.85	0.97	1.08	1.13
	50	1.06	0.95	0.82	0.69	0.59	0.55	0.57	0.65	0.77	0.92	1.04	1.10
	60	1.01	0.88	0.73	0.58	0.49	0.45	0.47	0.54	0.68	0.84	0.98	1.04
	10	1.08	1.05	1.01	0.97	0.93	0.92	0.93	0.95	0.99	1.04	1.07	1.09
	20	1.13	1.07	0.99	0.91	0.85	0.82	0.83	0.89	0.96	1.05	1.12	1.15
0.5	30	1.16	1.06	0.95	0.84	0.75	0.71	0.73	0.80	0.91	1.03	1.14	1.19
	40	1.16	1.03	0.89	0.74	0.63	0.59	0.61	0.70	0.84	0.99	1.13	1.19
	50	1.12	0.98	0.81	0.63	0.51	0.46	0.49	0.59	0.75	0.93	1.09	1.17
	60	1.07	0.90	0.71	0.52	0.39	0.34	0.37	0.47	0.64	0.85	1.03	1.12
	10	1.10	1.06	1.01	0.96	0.92	0.90	0.91	0.94	0.99	1.05	1.09	1.11
	20	1.17	1.09	0.99	0.89	0.82	0.78	0.80	0.86	0.96	1.06	1.15	1.19
0.6	30	1.21	1.09	0.95	0.81	0.70	0.65	0.67	0.77	0.90	1.05	1.18	1.25
	40	1.22	1.07	0.89	0.70	0.57	0.51	0.54	0.65	0.82	1.02	1.18	1.26
	50	1.19	1.01	0.80	0.58	0.43	0.36	0.40	0.52	0.72	0.95	1.15	1.25
	60	1.13	0.93	0.69	0.45	0.29	0.23	0.26	0.38	0.60	0.86	1.09	1.20
	10	1.12	1.07	1.01	0.95	0.90	0.88	0.89	0.93	0.99	1.06	1.11	1.14
	20	1.21	1.12	1.00	0.88	0.78	0.74	0.76	0.84	0.96	1.08	1.19	1.24
0.7	30	1.27	1.13	0.95	0.78	0.64	0.58	0.61	0.72	0.89	1.08	1.24	1.31
	40	1.29	1.10	0.88	0.65	0.49	0.42	0.45	0.59	0.80	1.04	1.25	1.34
	50	1.27	1.05	0.78	0.52	0.33	0.25	0.29	0.44	0.69	0.97	1.22	1.33
	60	1.21	0.96	0.66	0.37	0.17	0.10	0.14	0.29	0.55	0.88	1.15	1.29
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A3 Tilt factors for latitude 5 degrees

Clearness Index	Tilt (degrees)	Month for Northern Hemisphere											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.3	10	1.05	1.03	1.01	0.99	0.97	0.96	0.96	0.98	1.00	1.02	1.04	1.05
	20	1.07	1.04	1.00	0.95	0.92	0.91	0.91	0.94	0.98	1.03	1.07	1.09
	30	1.08	1.03	0.97	0.90	0.86	0.84	0.85	0.89	0.94	1.01	1.07	1.10
	40	1.07	1.00	0.92	0.84	0.79	0.76	0.77	0.82	0.89	0.98	1.05	1.09
	50	1.03	0.95	0.86	0.77	0.70	0.68	0.69	0.74	0.82	0.93	1.02	1.06
	60	0.98	0.89	0.78	0.68	0.61	0.59	0.60	0.65	0.75	0.86	0.96	1.01
0.4	10	1.07	1.04	1.01	0.98	0.96	0.95	0.95	0.97	1.00	1.04	1.07	1.08
	20	1.12	1.07	1.00	0.94	0.90	0.87	0.88	0.92	0.98	1.05	1.11	1.14
	30	1.14	1.07	0.98	0.89	0.82	0.79	0.80	0.86	0.94	1.04	1.13	1.17
	40	1.14	1.04	0.93	0.81	0.73	0.69	0.71	0.78	0.89	1.01	1.12	1.17
	50	1.12	1.00	0.86	0.72	0.63	0.59	0.61	0.69	0.81	0.96	1.09	1.15
	60	1.07	0.93	0.78	0.62	0.53	0.49	0.51	0.58	0.72	0.89	1.04	1.11
0.5	10	1.09	1.06	1.02	0.98	0.94	0.93	0.94	0.96	1.00	1.05	1.09	1.11
	20	1.16	1.09	1.01	0.93	0.87	0.84	0.86	0.91	0.98	1.07	1.15	1.18
	30	1.20	1.10	0.98	0.87	0.78	0.74	0.76	0.83	0.94	1.07	1.18	1.24
	40	1.21	1.08	0.93	0.78	0.68	0.63	0.65	0.74	0.88	1.04	1.18	1.25
	50	1.19	1.04	0.86	0.68	0.56	0.51	0.53	0.63	0.80	0.99	1.16	1.24
	60	1.15	0.97	0.77	0.57	0.44	0.39	0.42	0.52	0.70	0.91	1.11	1.20
0.6	10	1.12	1.08	1.02	0.97	0.93	0.91	0.92	0.96	1.01	1.06	1.11	1.13
	20	1.21	1.12	1.02	0.92	0.84	0.81	0.83	0.89	0.99	1.09	1.19	1.24
	30	1.27	1.14	0.99	0.85	0.74	0.69	0.71	0.81	0.94	1.10	1.24	1.31
	40	1.29	1.13	0.94	0.75	0.62	0.56	0.59	0.70	0.87	1.07	1.25	1.34
	50	1.28	1.08	0.86	0.64	0.49	0.42	0.46	0.58	0.78	1.02	1.23	1.34
	60	1.23	1.01	0.76	0.51	0.35	0.29	0.32	0.45	0.67	0.94	1.18	1.30
0.7	10	1.15	1.09	1.03	0.97	0.92	0.90	0.91	0.95	1.01	1.08	1.14	1.17
	20	1.26	1.16	1.03	0.91	0.81	0.77	0.79	0.87	0.99	1.12	1.24	1.30
	30	1.34	1.18	1.01	0.82	0.69	0.63	0.66	0.77	0.94	1.13	1.31	1.39
	40	1.38	1.18	0.95	0.72	0.55	0.48	0.52	0.65	0.86	1.11	1.33	1.44
	50	1.37	1.14	0.86	0.59	0.40	0.33	0.36	0.52	0.76	1.06	1.32	1.45
	60	1.33	1.06	0.75	0.45	0.25	0.17	0.21	0.37	0.64	0.97	1.27	1.42
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A4 Tilt factors for latitude 10 degrees

Clearness Index	Tilt (degrees)	Month for Northern Hemisphere											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.3	10	1.06	1.04	1.01	0.99	0.97	0.97	0.97	0.98	1.01	1.03	1.05	1.06
	20	1.09	1.05	1.01	0.96	0.93	0.92	0.92	0.95	0.99	1.04	1.08	1.11
	30	1.11	1.05	0.98	0.92	0.88	0.86	0.87	0.90	0.96	1.03	1.10	1.13
	40	1.10	1.03	0.94	0.86	0.81	0.78	0.79	0.84	0.91	1.00	1.09	1.13
	50	1.08	0.99	0.89	0.79	0.73	0.70	0.71	0.77	0.85	0.96	1.06	1.10
	60	1.03	0.93	0.81	0.71	0.64	0.61	0.62	0.68	0.77	0.90	1.01	1.06
0.4	10	1.09	1.06	1.02	0.99	0.96	0.95	0.96	0.98	1.01	1.05	1.08	1.09
	20	1.15	1.09	1.02	0.96	0.91	0.89	0.90	0.94	1.00	1.07	1.13	1.17
	30	1.18	1.10	1.00	0.91	0.84	0.81	0.83	0.88	0.97	1.07	1.16	1.21
	40	1.19	1.08	0.96	0.84	0.76	0.72	0.74	0.81	0.92	1.05	1.17	1.23
	50	1.18	1.05	0.90	0.76	0.67	0.63	0.65	0.72	0.85	1.00	1.15	1.22
	60	1.14	0.99	0.82	0.66	0.56	0.52	0.54	0.62	0.76	0.94	1.10	1.18
0.5	10	1.11	1.07	1.03	0.99	0.96	0.94	0.95	0.98	1.02	1.06	1.10	1.13
	20	1.2	1.12	1.04	0.95	0.89	0.87	0.88	0.93	1.01	1.10	1.18	1.22
	30	1.26	1.14	1.02	0.90	0.81	0.77	0.79	0.86	0.98	1.11	1.23	1.29
	40	1.28	1.14	0.98	0.82	0.71	0.67	0.69	0.78	0.92	1.09	1.25	1.33
	50	1.28	1.10	0.91	0.73	0.61	0.56	0.58	0.68	0.85	1.05	1.24	1.33
	60	1.24	1.04	0.83	0.62	0.49	0.44	0.47	0.57	0.75	0.98	1.19	1.30
0.6	10	1.14	1.09	1.04	0.99	0.95	0.93	0.94	0.97	1.02	1.08	1.13	1.16
	20	1.25	1.16	1.05	0.95	0.87	0.84	0.85	0.92	1.01	1.13	1.23	1.28
	30	1.33	1.19	1.04	0.89	0.78	0.73	0.75	0.84	0.98	1.15	1.30	1.38
	40	1.37	1.20	1.00	0.80	0.67	0.61	0.64	0.75	0.92	1.14	1.33	1.43
	50	1.38	1.17	0.93	0.70	0.55	0.48	0.51	0.64	0.84	1.10	1.33	1.45
	60	1.35	1.10	0.84	0.58	0.42	0.35	0.38	0.51	0.74	1.03	1.29	1.42
0.7	10	1.18	1.12	1.05	0.98	0.94	0.91	0.92	0.97	1.03	1.10	1.16	1.20
	20	1.32	1.20	1.07	0.94	0.85	0.81	0.83	0.91	1.02	1.16	1.29	1.35
	30	1.42	1.25	1.06	0.87	0.74	0.68	0.71	0.82	0.99	1.19	1.38	1.47
	40	1.48	1.26	1.02	0.78	0.61	0.54	0.58	0.71	0.93	1.19	1.43	1.55
	50	1.50	1.24	0.94	0.66	0.47	0.40	0.43	0.59	0.84	1.15	1.44	1.58
	60	1.47	1.17	0.84	0.53	0.33	0.25	0.29	0.45	0.73	1.08	1.40	1.56
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A5 Tilt factor for latitude 15 degrees

		Month for Northern Hemisphere											
Clearness Index	Tilt (degrees)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	10	1.07	1.04	1.02	1.00	0.98	0.97	0.98	0.99	1.01	1.04	1.06	1.07
	20	1.11	1.07	1.02	0.98	0.94	0.93	0.94	0.96	1.00	1.06	1.10	1.13
0.3	30	1.14	1.07	1.00	0.94	0.89	0.87	0.88	0.92	0.98	1.05	1.13	1.16
	40	1.14	1.06	0.97	0.88	0.83	0.80	0.81	0.86	0.94	1.03	1.12	1.17
	50	1.13	1.02	0.92	0.82	0.75	0.72	0.74	0.79	0.88	0.99	1.10	1.16
	60	1.08	0.97	0.85	0.74	0.66	0.64	0.65	0.71	0.81	0.94	1.06	1.12
	10	1.10	1.07	1.03	1.00	0.97	0.96	0.97	0.99	1.02	1.06	1.09	1.11
	20	1.18	1.11	1.04	0.98	0.93	0.91	0.92	0.96	1.02	1.09	1.16	1.20
0.4	30	1.23	1.13	1.03	0.93	0.87	0.84	0.85	0.91	0.99	1.10	1.21	1.26
	40	1.25	1.13	1.00	0.87	0.79	0.75	0.77	0.84	0.95	1.09	1.23	1.29
	50	1.25	1.10	0.94	0.80	0.70	0.66	0.68	0.76	0.89	1.06	1.22	1.30
	60	1.22	1.05	0.87	0.71	0.60	0.56	0.58	0.66	0.81	1.00	1.18	1.27
	10	1.13	1.09	1.04	1.00	0.97	0.95	0.96	0.99	1.03	1.08	1.12	1.15
	20	1.24	1.16	1.06	0.97	0.91	0.89	0.90	0.95	1.03	1.13	1.22	1.27
0.5	30	1.32	1.19	1.06	0.93	0.84	0.80	0.82	0.89	1.01	1.15	1.29	1.36
	40	1.36	1.20	1.02	0.86	0.75	0.71	0.73	0.82	0.97	1.15	1.32	1.41
	50	1.37	1.18	0.97	0.78	0.65	0.60	0.63	0.73	0.90	1.12	1.32	1.43
	60	1.34	1.13	0.89	0.68	0.54	0.49	0.51	0.62	0.81	1.06	1.29	1.41
	10	1.17	1.11	1.06	1.00	0.96	0.94	0.95	0.98	1.04	1.10	1.16	1.19
	20	1.31	1.2	1.08	0.97	0.90	0.86	0.88	0.94	1.04	1.17	1.28	1.34
0.6	30	1.41	1.25	1.08	0.92	0.81	0.77	0.79	0.88	1.03	1.20	1.37	1.46
	40	1.47	1.27	1.05	0.85	0.72	0.66	0.69	0.80	0.98	1.21	1.43	1.54
	50	1.49	1.26	1.00	0.76	0.60	0.54	0.57	0.70	0.91	1.18	1.44	1.57
	60	1.48	1.21	0.91	0.65	0.48	0.41	0.44	0.58	0.81	1.12	1.41	1.56
	10	1.21	1.14	1.07	1.00	0.95	0.93	0.94	0.98	1.05	1.12	1.19	1.23
	20	1.38	1.25	1.11	0.97	0.88	0.84	0.86	0.94	1.06	1.21	1.35	1.42
0.7	30	1.51	1.32	1.11	0.92	0.78	0.73	0.76	0.87	1.04	1.26	1.47	1.58
	40	1.60	1.35	1.09	0.84	0.67	0.60	0.64	0.77	1.00	1.28	1.54	1.68
	50	1.64	1.35	1.03	0.74	0.54	0.46	0.50	0.66	0.92	1.25	1.57	1.74
	60	1.63	1.30	0.94	0.61	0.41	0.32	0.36	0.53	0.82	1.20	1.56	1.74
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A6 Tilt factors for latitude 20 drgrees

Clearness Index	Tilt (degrees)	Month for Northern Hemisphere											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.3	10	1.08	1.05	1.03	1.00	0.98	0.98	0.98	1.00	1.02	1.05	1.07	1.09
	20	1.14	1.09	1.04	0.99	0.95	0.94	0.95	0.97	1.02	1.07	1.13	1.16
	30	1.18	1.10	1.02	0.95	0.91	0.89	0.90	0.93	1.00	1.08	1.16	1.20
	40	1.19	1.10	1.00	0.90	0.85	0.82	0.83	0.86	0.96	1.07	1.17	1.23
	50	1.18	1.07	0.95	0.84	0.77	0.75	0.76	0.81	0.91	1.03	1.16	1.22
	60	1.15	1.02	0.88	0.76	0.69	0.66	0.68	0.73	0.84	0.98	1.12	1.19
0.4	10	1.12	1.08	1.04	1.01	0.98	0.97	0.97	1.00	1.03	1.07	1.11	1.13
	20	1.22	1.14	1.06	0.99	0.94	0.92	0.93	0.97	1.04	1.12	1.20	1.24
	30	1.29	1.18	1.06	0.96	0.89	0.86	0.87	0.93	1.02	1.14	1.26	1.32
	40	1.33	1.18	1.04	0.90	0.82	0.78	0.80	0.87	0.99	1.14	1.29	1.37
	50	1.34	1.17	0.99	0.83	0.73	0.69	0.71	0.79	0.93	1.11	1.30	1.39
	60	1.31	1.12	0.92	0.75	0.64	0.60	0.62	0.70	0.86	1.06	1.27	1.38
0.5	10	1.16	1.11	1.06	1.01	0.98	0.96	0.97	1.00	1.04	1.09	1.15	1.18
	20	1.29	1.19	1.09	1.00	0.93	0.91	0.92	0.97	1.06	1.16	1.27	1.32
	30	1.39	1.25	1.10	0.96	0.87	0.83	0.85	0.92	1.05	1.20	1.36	1.44
	40	1.45	1.27	1.08	0.90	0.79	0.74	0.77	0.86	1.01	1.21	1.41	1.52
	50	1.48	1.26	1.03	0.83	0.70	0.64	0.67	0.77	0.95	1.19	1.43	1.55
	60	1.47	1.22	0.96	0.73	0.59	0.54	0.56	0.68	0.87	1.14	1.41	1.55
0.6	10	1.20	1.14	1.07	1.01	0.97	0.95	0.96	1.00	1.05	1.12	1.19	1.22
	20	1.37	1.25	1.12	1.00	0.92	0.89	0.90	0.97	1.07	1.21	1.34	1.41
	30	1.50	1.32	1.13	0.96	0.85	0.80	0.83	0.92	1.07	1.26	1.46	1.56
	40	1.59	1.36	1.12	0.90	0.76	0.70	0.73	0.85	1.04	1.29	1.53	1.67
	50	1.63	1.36	1.07	0.82	0.66	0.59	0.62	0.75	0.98	1.27	1.57	1.73
	60	1.63	1.32	1.00	0.72	0.54	0.47	0.50	0.64	0.89	1.23	1.56	1.74
0.7	10	1.25	1.17	1.09	1.02	0.97	0.94	0.96	1.00	1.06	1.15	1.23	1.27
	20	1.46	1.31	1.15	1.01	0.91	0.87	0.89	0.97	1.10	1.26	1.42	1.51
	30	1.63	1.40	1.18	0.97	0.83	0.77	0.80	0.91	1.10	1.34	1.57	1.70
	40	1.74	1.46	1.17	0.90	0.73	0.66	0.69	0.83	1.07	1.37	1.68	1.84
	50	1.81	1.47	1.12	0.6[illegible]	0.61	0.53	0.57	0.73	1.00	1.37	1.73	1.93
	60	1.83	1.44	1.05	0.70	0.48	0.40	0.44	0.61	0.91	1.33	1.74	1.95
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A7 Tilt factors for latitude 25 degrees

Clearness Index	Tilt (degrees)	Month for Northern Hemisphere											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.3	10	1.10	1.07	1.04	1.01	0.99	0.98	0.99	1.00	1.03	1.06	1.09	1.11
	20	1.17	1.11	1.05	1.00	0.96	0.95	0.96	0.98	1.03	1.09	1.16	1.19
	30	1.23	1.14	1.05	0.97	0.92	0.90	0.91	0.95	1.02	1.11	1.20	1.26
	40	1.25	1.14	1.02	0.93	0.86	0.84	0.85	0.90	0.99	1.10	1.23	1.29
	50	1.26	1.12	0.98	0.87	0.80	0.77	0.78	0.84	0.94	1.08	1.22	1.30
	60	1.23	1.08	0.92	0.79	0.72	0.69	0.70	0.76	0.87	1.03	1.20	1.29
0.4	10	1.14	1.10	1.05	1.01	0.99	0.98	0.98	1.00	1.04	1.09	1.13	1.16
	20	1.26	1.17	1.09	1.01	0.96	0.94	0.95	0.99	1.06	1.15	1.24	1.30
	30	1.36	1.22	1.09	0.98	0.91	0.88	0.89	0.95	1.05	1.19	1.32	1.40
	40	1.41	1.25	1.08	0.94	0.85	0.81	0.83	0.90	1.03	1.20	1.37	1.47
	50	1.44	1.24	1.04	0.87	0.77	0.73	0.75	0.83	0.98	1.18	1.39	1.51
	60	1.43	1.21	0.98	0.79	0.68	0.63	0.65	0.74	0.91	1.14	1.38	1.51
0.5	10	1.19	1.13	1.07	1.02	0.99	0.97	0.98	1.01	1.05	1.11	1.18	1.21
	20	1.35	1.23	1.12	1.02	0.95	0.92	0.94	0.99	1.08	1.20	1.32	1.39
	30	1.48	1.31	1.14	0.99	0.90	0.86	0.88	0.96	1.08	1.26	1.44	1.54
	40	1.57	1.35	1.13	0.95	0.83	0.78	0.80	0.90	1.06	1.28	1.52	1.64
	50	1.62	1.36	1.10	0.88	0.74	0.69	0.71	0.82	1.01	1.28	1.56	1.71
	60	1.62	1.33	1.04	0.79	0.64	0.58	0.61	0.73	0.94	1.24	1.55	1.73
0.6	10	1.24	1.16	1.09	1.03	0.98	0.97	0.97	1.01	1.07	1.14	1.22	1.26
	20	1.44	1.30	1.15	1.03	0.95	0.91	0.93	1.00	1.11	1.26	1.41	1.49
	30	1.61	1.40	1.19	1.00	0.89	0.84	0.86	0.96	1.12	1.33	1.56	1.68
	40	1.73	1.46	1.19	0.95	0.81	0.75	0.78	0.90	1.10	1.38	1.67	1.83
	50	1.80	1.48	1.16	0.88	0.71	0.64	0.68	0.81	1.05	1.38	1.73	1.92
	60	1.83	1.46	1.09	0.79	0.60	0.53	0.56	0.71	0.98	1.35	1.74	1.95
0.7	10	1.30	1.20	1.11	1.04	0.98	0.96	0.97	1.01	1.08	1.18	1.27	1.33
	20	1.55	1.37	1.20	1.04	0.94	0.90	0.92	1.00	1.14	1.32	1.51	1.61
	30	1.76	1.50	1.24	1.02	0.87	0.81	0.84	0.96	1.16	1.42	1.70	1.85
	40	1.92	1.58	1.25	0.97	0.78	0.71	0.75	0.89	1.14	1.48	1.84	2.04
	50	2.02	1.62	1.22	0.89	0.68	0.59	0.63	0.80	1.10	1.50	1.93	2.16
	60	2.06	1.61	1.16	0.78	0.56	0.47	0.51	0.69	1.02	1.48	1.95	2.22
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A8 Tilt factors for latitude 35 degrees

Clearness Index	Tilt (degrees)	Month for Northern Hemisphere											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	10	1.12	1.08	1.04	1.01	0.99	0.99	0.99	1.01	1.03	1.07	1.11	1.13
	20	1.21	1.14	1.07	1.01	0.97	0.96	0.97	1.00	1.05	1.12	1.20	1.24
0.3	30	1.29	1.18	1.07	0.99	0.94	0.91	0.93	0.97	1.04	1.14	1.26	1.32
	40	1.33	1.19	1.06	0.95	0.88	0.86	0.87	0.92	1.02	1.15	1.30	1.38
	50	1.35	1.18	1.02	0.89	0.82	0.79	0.80	0.86	0.97	1.13	1.31	1.41
	60	1.34	1.15	0.97	0.82	0.74	0.71	0.73	0.79	0.91	1.09	1.29	1.40
	10	1.18	1.12	1.07	1.02	1.00	0.98	0.99	1.01	1.05	1.10	1.16	1.20
	20	1.32	1.21	1.11	1.03	0.97	0.95	0.96	1.00	1.08	1.18	1.30	1.36
0.4	30	1.44	1.28	1.13	1.01	0.93	0.90	0.92	0.98	1.08	1.24	1.40	1.50
	40	1.53	1.32	1.13	0.97	0.87	0.83	0.85	0.93	1.07	1.26	1.48	1.60
	50	1.57	1.33	1.10	0.91	0.80	0.76	0.78	0.87	1.03	1.26	1.52	1.66
	60	1.58	1.31	1.05	0.84	0.71	0.67	0.69	0.79	0.96	1.23	1.52	1.68
	10	1.23	1.16	1.09	1.03	1.00	0.98	0.99	1.02	1.07	1.14	1.21	1.26
	20	1.43	1.29	1.15	1.04	0.97	0.94	0.96	1.01	1.11	1.25	1.39	1.48
0.5	30	1.59	1.38	1.19	1.03	0.93	0.89	0.91	0.99	1.13	1.32	1.54	1.67
	40	1.72	1.45	1.19	0.99	0.86	0.81	0.84	0.94	1.12	1.37	1.65	1.81
	50	1.79	1.47	1.17	0.93	0.78	0.73	0.75	0.87	1.08	1.38	1.71	1.91
	60	1.82	1.46	1.12	0.85	0.69	0.63	0.66	0.78	1.01	1.36	1.73	1.95
	10	1.29	1.2	1.11	1.04	1.00	0.98	0.99	1.02	1.09	1.17	1.27	1.32
	20	1.54	1.36	1.20	1.06	0.97	0.93	0.95	1.02	1.14	1.31	1.50	1.61
0.6	30	1.75	1.49	1.25	1.05	0.92	0.87	0.90	1.00	1.17	1.42	1.69	1.85
	40	1.91	1.58	1.27	1.01	0.85	0.79	0.82	0.95	1.17	1.48	1.83	2.03
	50	2.02	1.62	1.25	0.95	0.77	0.69	0.73	0.87	1.13	1.51	1.92	2.17
	60	2.07	1.62	1.20	0.86	0.66	0.59	0.62	0.78	1.07	1.49	1.96	2.24
	10	1.30	1.20	1.11	1.04	0.98	0.96	0.97	1.01	1.08	1.18	1.27	1.33
	20	1.55	1.37	1.20	1.04	0.94	0.90	0.92	1.00	1.14	1.32	1.51	1.61
0.7	30	1.76	1.50	1.24	1.02	0.87	0.81	0.84	0.96	1.16	1.42	1.70	1.85
	40	1.92	1.58	1.25	0.97	0.78	0.71	0.75	0.89	1.14	1.48	1.84	2.04
	50	2.02	1.62	1.22	0.89	0.68	0.59	0.63	0.80	1.10	1.50	1.93	2.16
	60	2.06	1.61	1.16	0.78	0.56	0.47	0.51	0.69	1.02	1.48	1.95	2.22
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Month for Southern Hemisphere											

Table A9 Tilt factors for latitude 40 degrees

Discount Rate (d)	Inflation Rate (i)	Factor Pr for given number of year				
		5	10	15	20	30
	0.00	1.00	1.00	1.00	1.00	1.00
	0.05	1.21	1.55	1.98	2.53	4.12
0.0	0.10	1.46	2.36	3.78	6.11	15.86
	0.15	1.75	3.53	7.07	14.23	57.57
	0.20	2.07	5.16	12.84	31.95	197.81
	0.00	0.78	0.61	0.48	0.38	0.23
	0.05	0.95	0.95	0.95	0.95	0.95
0.05	0.10	1.15	1.45	1.82	2.30	3.67
	0.15	1.37	2.16	3.40	5.36	13.37
	0.20	1.62	3.17	6.17	12.04	23.47
	0.00	0.62	0.39	0.24	0.15	0.06
	0.05	0.75	0.60	0.47	0.37	0.23
0.10	0.10	0.91	0.91	0.91	0.91	0.91
	0.15	1.08	1.36	1.69	2.11	3.30
	0.20	1.29	1.99	3.07	4.75	11.34
	0.00	0.50	0.25	0.12	0.06	0.02
	0.05	0.60.	0.38	0.24	0.15	0.08
0.15	0.10	0.73	0.58	0.47	0.37	0.24
	0.15	0.87	0.87	0.87	0.87	0.87
	0.20	1.03	1.27	1.58	1.95	2.99
	0.00	0.40	0.16	0.06	0.03	0.00
	0.05	0.49	0.25	0.13	0.06	0.02
0.20	0.10	0.59	0.38	0.25	0.16	0.07
	0.15	0.70	0.57	0.46	0.37	0.24
	0.20	0.83	0.83	0.83	0.83	0.83

Table A11 Present Worth Factor Pr for selected values of inflation rate, discount rate and number of year