SMALL SCALE SOLAR POWERED DRIP IRRIGATION

BY

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B.S. UNIVERSIDAD NACIONAL DE INGENIERIA (2003)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
ENERGY ENGINEERING, SOLAR
UNIVERSITY OF MASSACHUSETTS LOWELL

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ABSTRACT OF A THESIS SUBMITTED TO THE FACULTY OF THE ENERGY
ENGINEERING PROGRAM IN PARTIAL FULLFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF THE MASTER OF SCIENCE
ENERGY ENGINEERING, SOLAR
UNIVERSITY OF MASSACHUSETTS LOWELL
2008

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ABSTRACT

The aim of this study is to provide small farmers in developing countries with an affordable irrigation method that promotes the sustainable use of water and energy. To sustain the world in the future, 60% of the food required must come from irrigated agriculture; and developing countries hold three quarters of the total world's irrigated area where small farmers cultivate half of this agricultural land and 80% of this population lacks electricity services. This study presents a solar drip irrigation design and installation of a 5000m^2 asparagus plot in Turripampa, Huarmey, Peru. The Penman-Monteith method was used to match the plant's water requirement with the photovoltaic pumping. The system was designed based on finding low cost (but robust) components that can make it affordable. A cost/benefit comparison is made between the system proposed and the base scenario of the agricultural common practices such as gravity fed systems and diesel pumping.

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I. INTRODUCTION

The aim of this study is to provide small farmers in developing countries with an affordable, eco-friendly and easy to maintain irrigation method that promotes the sustainable use of photovoltaic energy. Sixty percent of the extra food required to sustain the world in the future must come from irrigated agriculture (FAO, 1999)[1]. Irrigated agriculture provides 40% of world food production on only 17% of total cultivated land. Third world countries hold three quarters of the total world's irrigated area (260 million hectares), where small farmers (average 3-4 hectares per farm) cultivate more than half of this agricultural land (FAO, 1999). New sites for development are scarce; therefore, the world's food security relies largely on the improvements of irrigation techniques for smallholder agriculture.

According to the International Labor Organization (ILO-FAO, 2008), 3 of every 4 poor people in developing countries live in rural areas—2.1 billion living on less than $2 a day and 880 million on less than $1 a day, and agriculture is a source of livelihoods for an estimated 86% of rural people. Eighty percent of the agricultural land in the developing countries, which compromises 2 billion people, lack energy services (World Bank, 2000). Alternative sources of power for irrigation include the use of gasoline and diesel powered water pumps. It is important to distinguish the gravity fed systems as the most common watering method for irrigated fields when

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[1] These were the latest statistics of irrigation, energy and poverty by the time this thesis was defended.

seasonal superficial water is available. It is risky for small farmers to rely on oil for food production given the fluctuations of prices. Also, diesel and gasoline motors are high maintenance, and polluting source of energy. The use of photovoltaics to provide electricity eliminates the need to use gasoline or diesel, which saves money for maintenance and runs cleaner than internal combustion engines.

Photovoltaic energy in rural areas of developing countries has made significant inroads for household lighting. The World Bank expressed in its publication “Renewable Energy Markets in the Developing World” (2002), that although electricity certainly provides improvements in the quality of life through these household applications, it is the "productive uses" of electricity that can increase incomes and provide development benefits to rural areas. This benefit applies to small scale solar powered drip irrigation which when well designed and implemented presents great potential for productive uses of photovoltaic since the irrigated area can generate enough income to pay for the system. An important advantageous characteristic of the photovoltaic technology is its modularity, that is one can add PV modules to a system as needed. As incomes increase, rural populations will be better able to afford greater levels of solar energy service even for domestic use. Nevertheless, the high initial cost of implementing such beneficial system in developing countries, and the low cash flow and credit access of small farmers remain a barrier (Barreto, Kinne, & Komp, 2005).

Appropriate low-cost pumps are required in other for the technology affordable for small farmers. A number of manufacturers make efficient DC and AC pumps suitable for being powered by photovoltaic modules, but in general these pumps are costly and relatively large, requiring an expensive array of photovoltaic modules and a complex control system. One of the challenges of this study is to design a suitable system that can make the technology sustainable for third world small farmers.

Another challenge is to pair the water distribution method with solar water pumps, but as irrigation is currently practiced (flooding being the most common), there are several drawbacks. First, the usual flood type irrigation is only 60% efficient if a good design and technical assessment are provided to the farmer. Unfortunately, in most of the developing countries flooding irrigation systems are empirical and lack techniques that could reduce the water losses such as percolation below the root zone due to non-uniform application or over-application water runoff from the field, seepage and evaporation, among others. In most cases this systems barely reach 40% of total irrigation efficiency (Burt & Styles, 1999), which includes water conveyance and water application efficiency. This leads to a high water requirement, and therefore high energy demand. If there is not a reliable local water source uphill that can feed the fields by gravity, the system will require a large amount of energy for pumping to provide water to the irrigation ditches, and eventually to flood the fields.

Sprinkler irrigation is more efficient than furrow irrigation; however, sprinkler irrigation requires a large cash investment in the pipes, moving spray machines and large pumps. Both flooding and spray irrigation systems require more energy to pump higher flows compared to drip irrigation. In the case of sprinkler irrigation, pressures from 1 to 2 bar are required to deliver water with a diameter between 6m to 35m. This adds to the system an additional hydraulic head of 10 to 20 meters representing a higher hydraulic energy with respect from furrow and drip (Burt & Styles, 1999). The energy supplied to meet this high pressure requirement comes usually from using fossil fuels in engine driven pumps because of the lack of electrification in small farms. Also the most of the diesel-powered pumps in developing countries are overdesigned using more fuel than needed and pumping more water than the amount required, and in many areas where ground water is used these conditions have lead to a drastic drop in the local water table.

Drip irrigation is the system that can take better advantage of photovoltaic pumping. Over the past few decades, drip irrigation systems have been developed which deliver drops of water directly to the soil at the plant roots, requiring a small fraction of the water needed to grow the same crops by conventional irrigation techniques (FAO, 1997). Drip irrigation has an efficiency (water savings) of 90%, and because of its target, the plant roots, evapotranspiration and percolation water losses are minimized. The use of drip irrigation in small parcels, has proved to generate higher crop yield. As a result, farmers do not need extensive access to land.

The smaller amount of water required for drip irrigation in small plots make it possible to consider hand pumps and solar powered pumps to meet the daily water volume needs. Depending on the crop cycle, drip irrigation could allow up to three crops per year to be harvested instead of only a single crop in the rainy season of many tropical locations.

There is a good match between irrigation and photovoltaic technology given that both: irrigation as consumption and PV as generation are directly dependant to the solar radiations. This means that when it rains or is cloudy, irrigation is not needed because there is less evapotranspiration due to the irradiation decrease. This is convenient because under the same rainy and cloudy conditions, the solar pumping would not generate as much energy. The same applies to the opposite: on sunny clear days the water demand of the plant increase and at the same time there is more water pumped.

I.1. Objective

The overall objective of this work is to design, model, and test a solar powered drip irrigation system for remote regions of the world.

I.2. Approach

The approach is the following:

- To design a photovoltaic irrigation system which will use less energy and water than the common practice.
- Install a prototype that delivers water to a small plot of asparagus in a farm of the community of Turripampa, Huarmey, Peru.
- To review and compare information of the different alternatives of irrigation in order to determine the efficiency performance in terms of energy

- To estimate the payback time and economic performance measures of the solar drip irrigation system.
- To propose sustainability strategies to transfer the proposed technology to small farmers in developing countries

I.3. The scope

This study presents the design and installation of a small asparagus plot in Turripampa, Huarmey, Peru. The watering method chosen is drip irrigation powered by a diaphragm pump with a150 watt photovoltaic array. The Penman-Monteith method was used to match the plant's water requirement with the photovoltaic pumping. The criteria selection of the system was made based on finding low cost (but robust) components that can make the system affordable to small farmers. An economical comparison is made between the system proposed and the base scenario of the agricultural actual common practices, such as gravity fed systems and diesel pumping. Recommendations on risks and sustainability strategies are made to appropriately transfer of the technology to the users.

II. BACKGROUND OF THE DIFFERENT COMPONENTS AND APPROACHES: PV PUMPS, DIESEL MOTORS, FLOODING, SPRAY AND DRIP IRRIGATION.

II.1.Rural electricity in developing countries

Some 1.6 billion people (Figure II-1), about one quarter of the world's population, have no access to electricity today. Eighty percent of these people live in rural areas of the developing world, mainly in developing countries where rapid urban migration and population growth will occur over the next several decades (IEA, 2002). Without adequate supplies of affordable energy, it is virtually impossible to carry out productive economic activity or improve health and education. Poverty becomes inescapable.

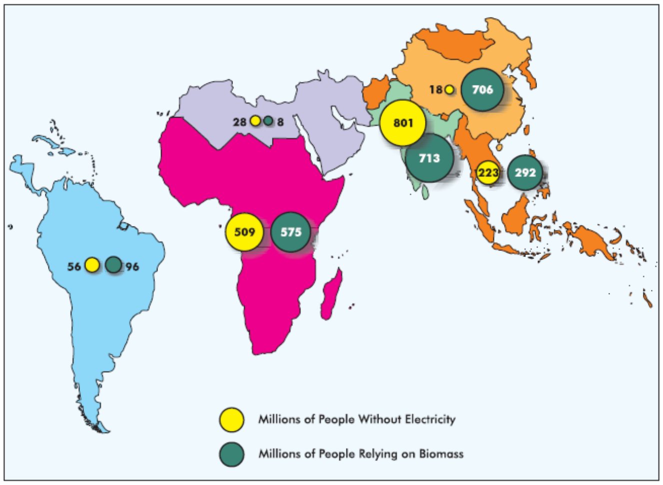

Figure II-1 Global energy poverty (IEA, 2002)

Lack of access to electricity remains the clearest indicator of poverty in general. Yet, even if the $5 trillion of necessary investment were to be secured over the next 30 years, there is a very real likelihood that electricity access would still be denied to some 1.4 billion people, frustrating economic development, hindering critical quality of life and environmental improvements, and condemning billions of people to continued poverty (World Bank, 2000). Lack of electricity exacerbates poverty and contributes to its perpetuation, as it precludes most industrial activities and the jobs they create.

Access to modern energy is a key factor for economic growth and poverty reduction. Lack of access to modern energy services hinders people in meeting their basic needs, limits enterprise development and results in lower productivity and hence less scope for economic growth. People do not want energy in itself, but the energy services, i.e., the activity it enables, such as cooking, heating, water pumping, transport, etc. Shortages cause problems, just as with any other production factor in short supply.

Lack of electricity is strongly correlated to the number of people living below $2 per day Figures II-2 and II-3 shows the strong correlation between electricity supply and income. Income, however, is not the only determinant in electricity access. China, with 56% of its people still poor, has managed to supply electricity to more than 98% of its population (IEA, 2002).

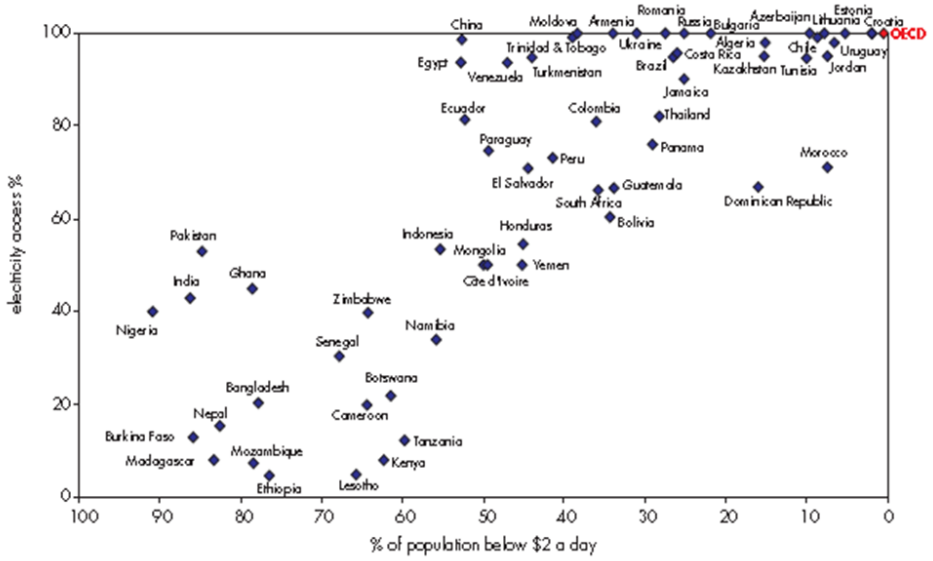

Figure II-2 The link between poverty and electricity access (IEA, 2002).

Rural electricity supply in many developing countries is often hampered by low population densities, the limited purchasing power of rural people and the absence of decentralized supply options. While electricity is essential for conserving vaccines and medicines in village dispensaries, in the home, electric lighting has no cost-benefit in a poor rural household, except when the system is being used to generate an income in the household. For instance, using electricity that will generate income, such as solar drip irrigation, is more appropriate than having a few lights in a house. In rural areas, over 85% of energy is consumed by households mainly in the form of traditional energy sources used for cooking and heating (Kijne, Molden, & Barker, 2003).

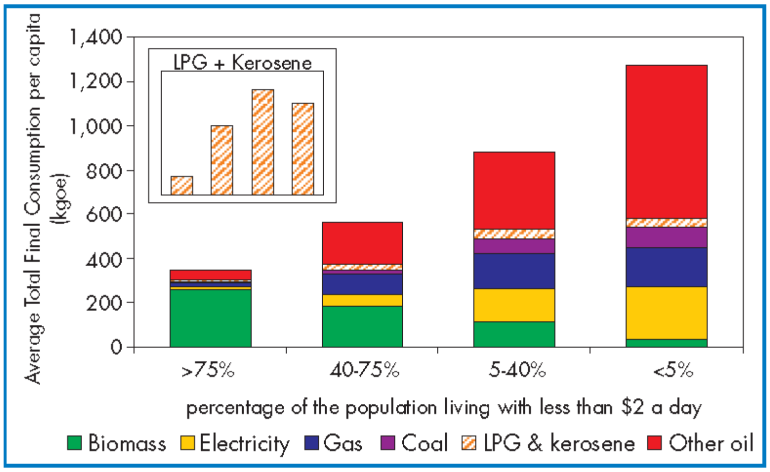

Figure II-3. Average per capita final energy consumption and share of population living under poverty line (IEA, 2002).

Figure II-3 plots average final energy consumption per capita for 100 developing and transition countries, grouped according to the percentage of their population under the poverty line ($2 a day). In countries where less than 5% of the population is poor, per capita energy consumption is four times higher than in countries where more than 75% of the population lives under the poverty line. Consumption of commercial fuels, especially oil products, is much higher in the richest group of countries, partly because transport demand rises with income. LPG and kerosene are transition fuels in households: their consumption is higher for the intermediate groups, but lower for the richest citizens, who replace them with natural gas and electricity (see insert in Figure II-4). Electricity consumption is very strongly correlated with wealth. The share of biomass in final energy consumption is lowest in countries where the percentage of poor people is lowest (IEA, 2002).

Depending on levels of mechanization, agricultural activities account for about 2 to 8% of all energy consumption, mainly in the form of commercial energy used to power mechanical equipment and irrigation pump-sets. Commercial energy, often kerosene and electricity where available, is mainly used for lighting, which on average constitutes about 2 to 10% of total rural consumption. Small amounts of electricity are used to operate radios, television sets and small appliances in electrified villages. The energy consumption of rural industries, including both cottage industries and village level enterprises, amounts to less than 10% of the rural aggregates in most countries. In a few cases in Asia and Africa, the share of traditional fuels in rural household energy rises to more than 95% (Kijne, Molden, & Barker, 2003).

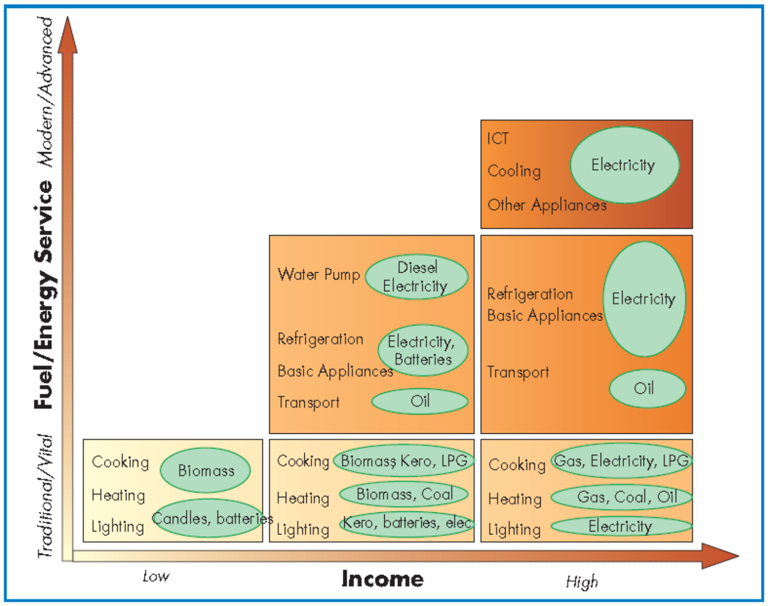

Figure II-4. Illustrative example of household fuel transition (IEA, 2002).

Figure II-4 from the IEA analysis shows that at higher income levels, better lighting is one of the first energy services sought to improve living standards and, frequently, to extend the working day. At still high incomes, water heating, refrigeration and cooling begin to play an important role. In addition, at these higher income levels, the need for space heating may decline because houses may be better constructed. The provision of an adequate modern energy supply for water-related activities in rural areas of developing countries offers many advantages, including time saved not having to travel to collect water, thus increasing productivity; easier access to water through pumping of drinking water, irrigation water and water for animal husbandry; health benefits (ranging from water purification through filtration to reduced medical costs when boiling water for sterilization is unnecessary); and health and environmental benefits through the discharge of wastewater from canals, septic tanks and latrines. Energy also allows wastewater to be treated through aeration.

II.1.1. Energy and Irrigation in small holder agriculture in developing countries

The link between water and energy is frequently disregarded. Energy is essential for freshwater supplies, for instance, in groundwater pumping, desalination technology and delivery and distribution systems. Reducing the inefficiencies that occur in energy production (during electricity generation, transmissions, distribution and usage) will reduce electric power requirements leading to greater water savings. Equally, diminishing the inefficiencies and leaks that occur in water distribution systems (for agriculture and municipalities in particular, as well as other human activities) makes efficiency gains possible in the electricity sector and offers big potential water savings. Older power plants in many developing countries consume from 18% to 44% more fuel per kilowatt hour of electricity produced than those in industrialized nations. Third world countries also suffer transmission and distribution losses two to four times higher. In fact, technical and nontechnical transmission and distribution system losses in the delivery of electricity are commonly greater than 20% and occasionally approaching 40%. (World Bank, 1992).

Increasing the productivity of agriculture through better water control clearly makes a significant impact. Farmers can use a variety of simple and affordable water management techniques to increase their yields and reduce their vulnerability to erratic rainfall or drought. Figure II-5 shows the results of a report presented by the International Water Management Institute (IWMI) comparing of yields and water productivity of wheat in USA, India and Pakistan where the water productivity in developing countries is inferior with respect to industrialized countries. Two indicators are presented to analyze the water productivity: the yield in tons per hectare and the evapotranspiration of the crop per drop in kilograms per cubic meters of water needed to meet the crop water requirement. In the USA case both the yield and water crop per drop are higher than India and Punjab. It is important to notice the disparity of these two indicators in the case of the developing countries and the inefficiency of the water applied to the crop directly affects the yield. This case is a mirror of the problems of inefficiency of water application in developing countries where there are higher water applications but lower yields.

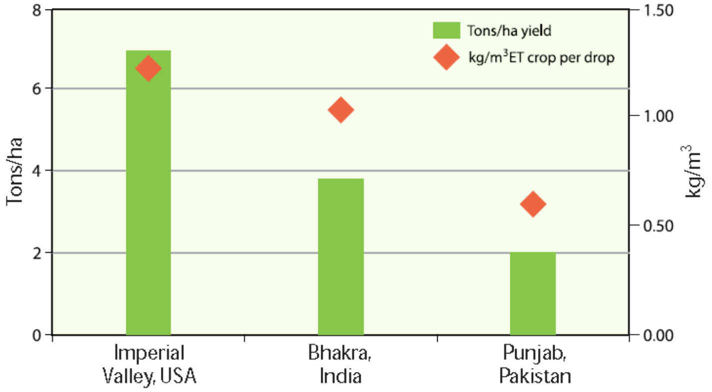

Figure II-5 Comparison of yields and water productivity of wheat in USA, India and Pakistan (Kijne, Molden, & Barker, 2003)

Agriculture is the predominant user of the available freshwater resource in many parts of the world, using between 75 to 82% (Figure II-6). At present most of the water used to grow crops is derived from rainfed soil moisture, with non-irrigated agriculture accounting for some 60% of production in developing countries. Although irrigation provides only 10% of agricultural water use and covers just around 20% of the cropland, it can vastly increase crop yields, improve food security and contribute 40% of total food production since the productivity of irrigated land is three times higher than that of rainfed land. The Food and Agriculture Organization (FAO) predicts a net expansion of irrigated land of some 45 million hectares in 93 developing countries (for a total of 242 million hectares in 2030) and project that agricultural water withdrawals will increase by approximately 14% during 2000-2030 to meet food demand.[2]

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[2] http://www.fao.org/newsroom/en/focus/2006/1000252/index.html

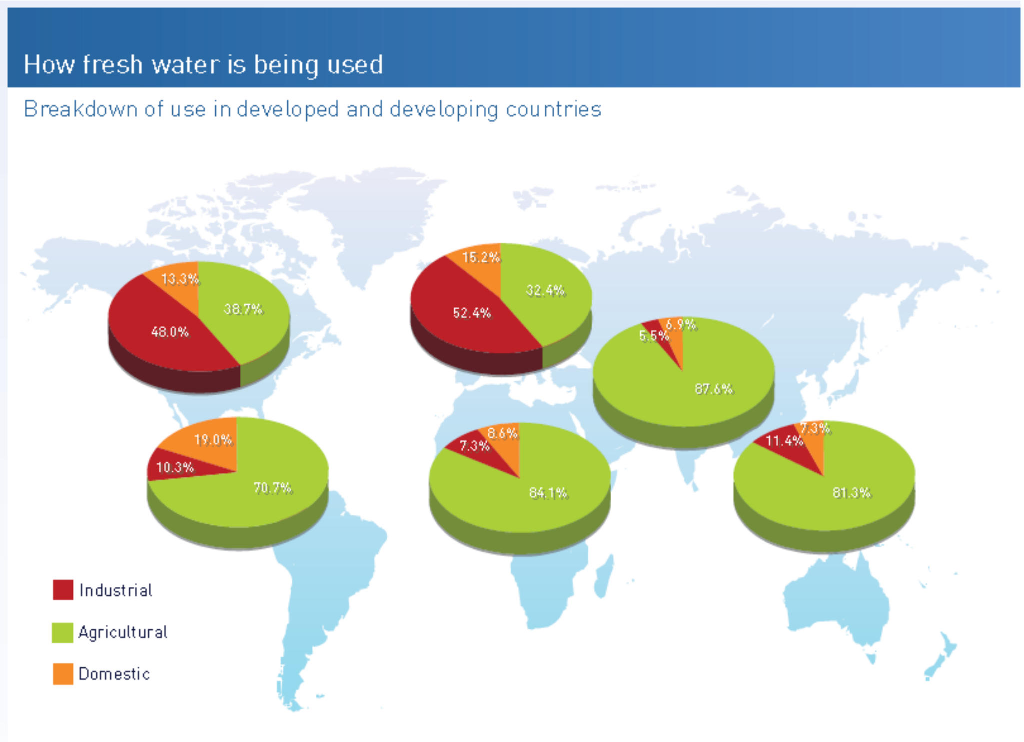


Figure II-6 Competing water uses for main income groups of countries (The United Nations, 2003)

Mitigating the effects of short-term drought is a key step in achieving higher yields and water productivity in rain-fed areas. On figure II-7 it is showed that supplemental irrigation reduces vulnerability to drought and helps farmers to get the most out of the scarce resources; however it needs to be combined with on-farm water-harvesting practices, such as mulching or bunding.

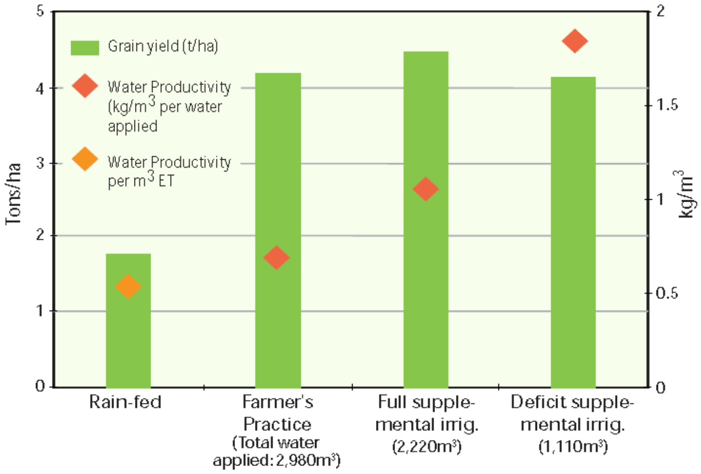


Figure II-7 Comparison of yields and productivity for rainfed, irrigation and supplemental irrigation (Kijne, Molden, & Barker, 2003)

As figure II-7 shows, increasing water application does not necessarily improve the water productivity, and yields will increase per hectare but not at the same rate as the kilograms per cubic meter of water use for the crop. Small farmers in developing countries find them self at a high risk if they invest in productivity enhancement inputs when the water supply is uncertain.

The world contains an estimated 1 400 million cubic km of water. Only 0.003% of this vast amount, about 45 000 cubic km, are what is called “fresh water resources” - water that theoretically can be used for drinking, hygiene, agriculture and industry. However, not all of this water is accessible. For instance, seasonal flooding makes water extremely difficult to capture before it flows into remote rivers. Only about 9 000-14 000 cubic km are economically available for human use - a mere teaspoon in a full bathtub when compared to the total amount of water on earth. For this reason it is imperative to improve the application efficiencies of irrigation technologies since irrigation accounts for 70% of the water withdrawals and up to 95% in developing countries (Kijne, Molden, & Barker, 2003)

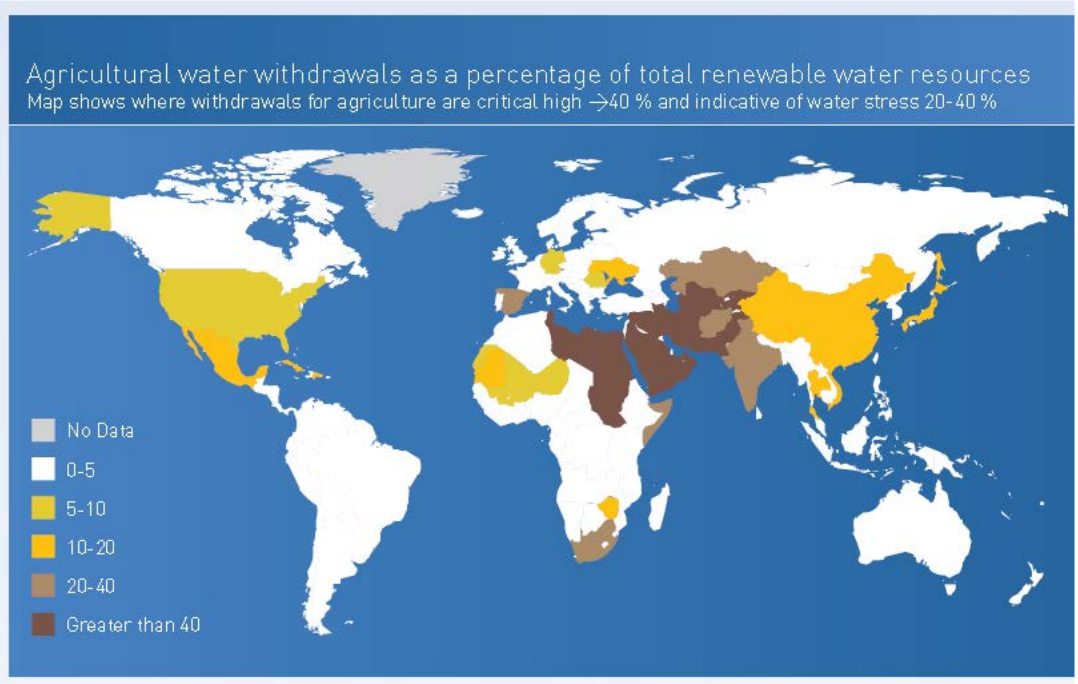


Figure II-8 Critical fresh water withdrawals in developed and developing countries. (Kijne, Molden, & Barker, 2003)

It is estimated that poor drainage and irrigation practices have led to waterlogging and salinization of about 10 percent of the world's irrigated lands, thereby reducing productivity. In India's Tamil Nadu state, overpumping in certain areas has lowered the water level in wells by 25 to 30 meters in one decade. Since water and population are unevenly distributed, water supply is critical in various countries and regions. Countries could be defined as "water-stressed" if they abstract more than 20 percent of their renewable water resources. By this definition, 36 out of 159 countries (23 percent) were already water-stressed in 1998 (Figure II-8).

Water & food security

Water is important for food security, which is defined as the regular access of people to enough high-quality food to lead active, healthy lives. This is especially true in developing countries. People who have better access to water tend to have lower levels of undernourishment. If water is a key ingredient to food security, lack of it can be a major cause of famine and undernourishment, especially in areas where people depend on local agriculture for food and income.

The availability of water varies dramatically by region. But even in areas with limited or erratic water supplies, maximizing their use can increase agricultural productivity enormously. That is the key to improving food security and reducing poverty, especially in the rural areas that are home to three-quarters of the world's hungry people.

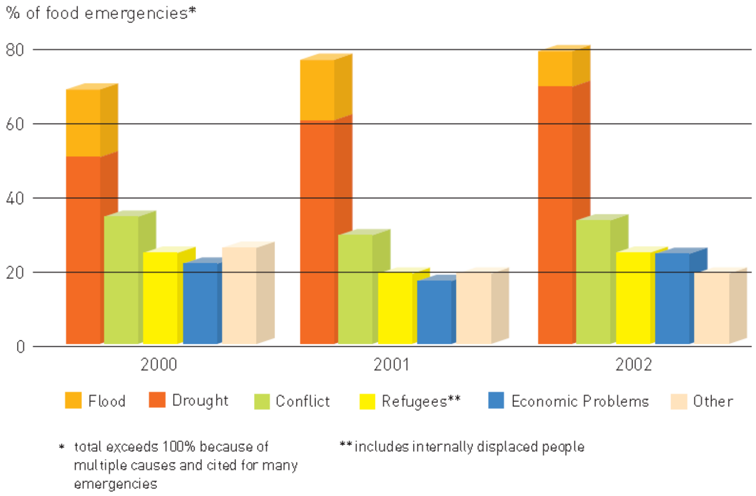


Figure II-9. Causes of food emergencies in developing countries (Kijne, Molden, & Barker, 2003)

Erratic rainfall and seasonal differences in water availability can cause temporary food shortages; floods and droughts can cause some of the most intensive food emergencies. Figure II-9 shows flood and draught as a result of climate change and poor water management practices are the main component for food emergency in the developing countries. It is for this reason that good irrigation practices are imperative to reduce water withdrawals in fragile ecosystems and mitigate effects of climate change, especially in the developing world. If water is a key to food security and poverty reduction, then managing it wisely is essential. Improving the management of water resources is a question of getting more "crop for the drop". These improvements hinge largely on raising the water productivity of rainfed and irrigation systems.

II.2.Watering methods for irrigation

Choosing a new irrigation system is about choosing the various components which make up the system. Below is a schematic of the main components and steps on how to choose, for preliminary design purposes, between the various options and component configurations available. Figure II-10 illustrates the process of preliminary design and the decisions to be made.

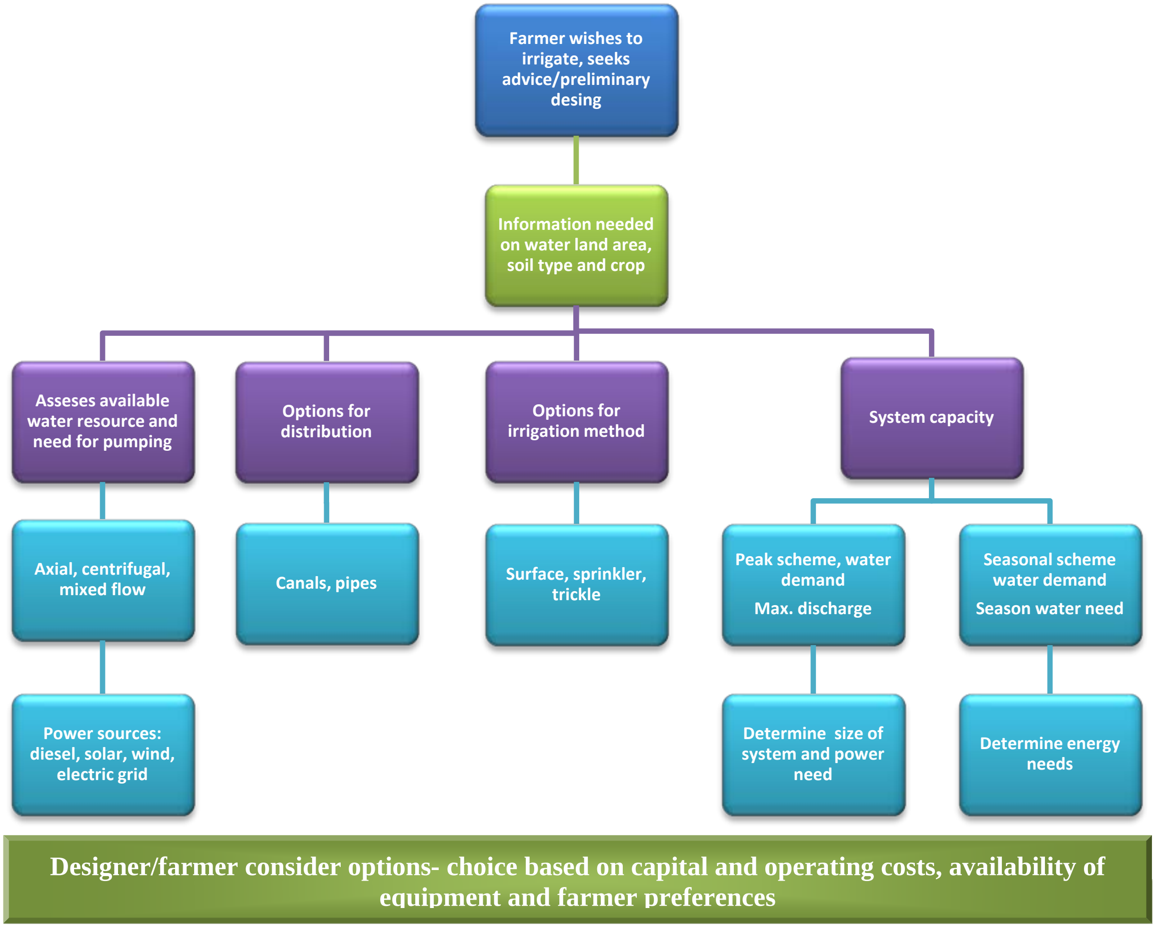


Figure II-10 Choosing irrigation system components

Small-scale pumped irrigation systems are made up of the following components:

- Water source;
- Pump and power unit;
- Distribution system; and
- Method of irrigation.

♦ The water source, the distribution system and the method of irrigation determine the energy demand.

♦ The pump and power unit provide the energy supply.

Water source

The water source may be a river or lake (surface water) or a shallow well or borehole (groundwater). In some cases, water can be abstracted from rivers by gravity, but in many cases pumping will be needed. In the case of groundwater abstraction, pumping is essential.

The amount of water abstracted and the height through which it must be lifted from the river or borehole add to the energy demand.

Pump and power unit

The pump may be driven by a power unit such as a diesel or petrol engine, or an electric motor in which case it can be powered by solar, wind or grid power when available. Hand or animal power, may be used to provide the power source for the pump, but they are generally limited to very small irrigated plots. In this thesis the primary concern is with the use of pumps driven by diesel engines as these are usually the main sources of energy supply available to most small-scale farmers, as well as solar pump which is the alternative proposed to the base case.

Distribution system

The distribution system conveys water from the pump to the fields and may consist of pipes or open channels. Some systems are a combination of both. The choice of distribution system has a significant effect on the *energy demand*.

Method of irrigation

The method of irrigation may be surface, sprinkler or trickle irrigation. This may also affect the choice of distribution system and is also significant in determining the energy demand. Surface irrigation may be supplied by either pipe or open channel systems. Sprinkler and Drip irrigation systems would normally use piped distribution systems.

Typical systems

The most common combinations of components for an irrigation system are:

- Pump open channel surface irrigation.
- Pump pipe supply surface irrigation.
- Pump pipe supply sprinkler or trickle irrigation.

The first system is the most common for small-scale irrigation, although the advantages of the second are now being more fully realized. Sprinkle, and especially trickle, irrigation are growing in importance in some areas where soils are very sandy and water is scarce, or energy costs are high, or both, but surface irrigation is the dominant method and is likely to remain so in many countries for the foreseeable future.

II.2.1. Water sources

Rivers and lakes

Many small irrigation schemes are located close to natural river channels and lakes and obtain water by pumping from these sources. They provide a supply which can be seen by the farmer and be judged whether sufficient or not for the seasonal needs of the farm. Usually, the pumping pressures, and hence energy requirements, needed to use such sources are small because the difference in elevation between the source water level and the level of the field are usually not large.

Shallow groundwater

This is an ideal source of supply for farms located some distance from a river or lake. Usually the groundwater table is fed by seepage from a river or lake and may be only a few meters below ground level. This source may be less reliable than surface water because except through pumping experience there is no easy way of assessing whether there is a sufficient reserve of water to ensure adequate irrigation. However, the farmer can save the cost of an expensive canal or pipe system to bring water from a more distant surface supply. As with surface supplies, the energy costs involved in pumping are relatively low.

Deep groundwater

This may be water which has permeated through the ground from a surface source many kilometers away or water which has been trapped in the ground by impermeable soils for many thousands of years (fossil water). Pumping deep groundwater which may be 20 - 100 m or more below ground level can be expensive in terms of energy use, as well as in the cost of drilling the borehole, and requires special, deep borehole, pumping equipment, which may also be expensive to buy.

II.2.2. Methods of irrigation

There are three methods of irrigation commonly used on small schemes:

- Surface irrigation
- Sprinkler irrigation
- Trickle irrigation

The main objectives of these methods are to:

- Apply an adequate amount of water to meet crop needs
- Apply water uniformly across the field
- Ensure there are no long-term problems (e.g., soil erosion, salinization).

II.2.2.1. Surface irrigation

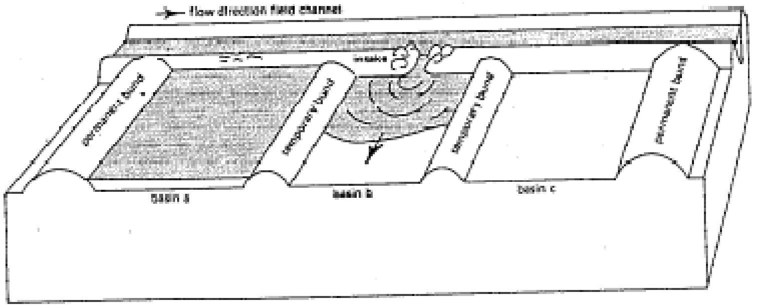
This is the most common method used on small schemes and involves flooding water across the soil surface so that it can infiltrate into the root zone and be used by the crop. Basin irrigation, border irrigation and furrow irrigation are all surface methods (Figure II-11). The choice of surface method depends on the crop, cultivation practices, soils and topography, and farmer preferences (Kay & Hatcho, 1992) .

Although surface irrigation is considered to be a simple method of irrigation, this can be very misleading. Surface irrigation design and construction is relatively simple and little or no imported specialist materials are needed. However, the proper management of the method is very complex. The efficient use of irrigation water all depends on the skill of the farmer, who must decide when to irrigate and how much to apply, and then provide the right discharge into the field so that water infiltrates adequately and uniformly into the root zone. This is not an easy task, as the soil and topographic conditions can be very variable and the farmer may not have the necessary degree of control over the discharge and timing of the application. Potentially, surface irrigation can be very efficient if all the factors involved are under the careful control of an experienced irrigator. More often however, the water management skills are lacking and efficiency tends to be low. As the designer will not know the level of field application efficiency that the farmer will achieve once the scheme is built, a typical value is used for design purposes (Table II-1). If the actual efficiency is less than the typical value once the scheme is operating, then the farmer will need to operate the system for longer each day, or to reduce the cropped area to compensate. This fall in efficiency will increase the energy demand.

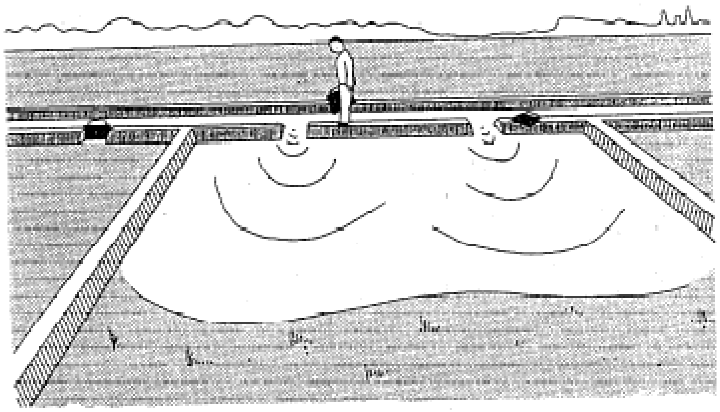
Table II-I Typical field application efficiencies for irrigation methods (Kay & Hatcho, 1992)

Irrigation method	Efficiency (%)
Surface	60
Sprinkler	75
Trickle	90

basin irrigation



border irrigation



furrow irrigation

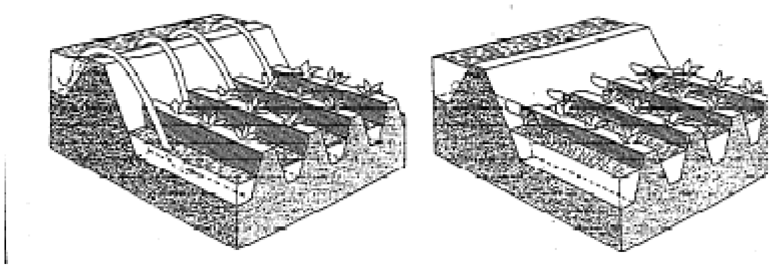


Figure II-11 Basin, border and furrow irrigation (Kay & Hatcho, 1992)

II.2.2.2. Sprinkler irrigation

Sprinkler irrigation involves distributing water in pipes under pressure and spraying it into the air so that it breaks up into small droplets and falls to the ground like natural rainfall. Sprinkler systems are generally more efficient and use less labor than surface irrigation and can be adapted more easily to sandy and erodible soils on undulating ground. There are many types of sprinkler system available, but the most common is a system using portable pipes (aluminum or plastic) supplying rotary impact sprinklers (Figure II-12).

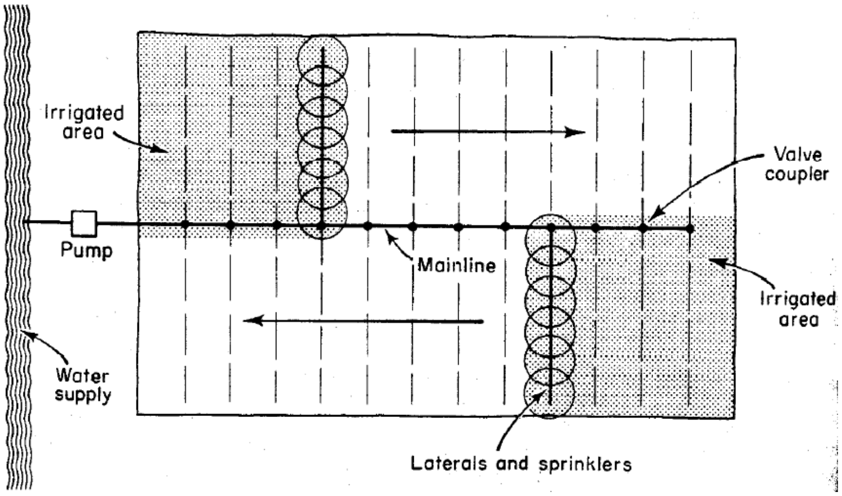


Figure II-12 Sprinkler irrigation (Kay & Hatcho, 1992)

An individual rotary impact sprinkler produces a circular wetting pattern with poor uniformity. To obtain good uniformity, several sprinklers are always operated close together so that the patterns overlap. Pressure is an important factor in successful sprinkler operation. Typical operating pressures range from 2 to 6 bar, and so energy requirements can be much greater than for surface irrigation. If sprinklers are working at the pressure recommended by the manufacturer then the distribution will be good. If the pressure is above or below this value, then the distribution will be adversely affected. The most common problem is when pressure is too low and this happens when pump and pipes wear, increasing friction and so reducing pressure.

Typical data for rotary impact sprinklers are shown in Table II-2. It is usually assumed that sprinkler irrigation is more efficient than surface irrigation. Potentially this is the case, but it largely depends on how well the system is operated and maintained. If pipe seals leak or burst, and if sprinklers are left running for longer than necessary, then wastage is inevitable. For design purposes, a field application efficiency of 75% is generally used.

Table II-II Typical sprinkler data (Kay & Hatcho, 1992)

Nozzle diameter (mm)	Pressure (bar)	Diameter of wetted circle (m)	Flow (m^3/h)	Application rate (mm/h) for spacings:		
				18 x 18 m	18 x 24 m	24 x 24 m
4	3.0	29	1.02	3.2	..	..
5	3.0	32	1.67	5.2	3.8	..
6	3.0	35	2.44	7.5	5.7	4.2
8	4.0	43	4.96	15.3	11.4	8.6
10	4.5	48	8.13	52.1	18.9	14

Traditional sprinkler irrigation is not so well suited to small farms. Typical spacings for sprinklers are 18 m × 18 m, and so they are not so flexible and adaptable to the multitude of small plots usually found on many farms. An alternative which may be more applicable to small farms is the use of smaller sprinklers connected to the mainline by flexible hoses (Figure III-13). This is often called a hose-pull system. These sprinklers have great flexibility in operation and are easily re-located around the farm.

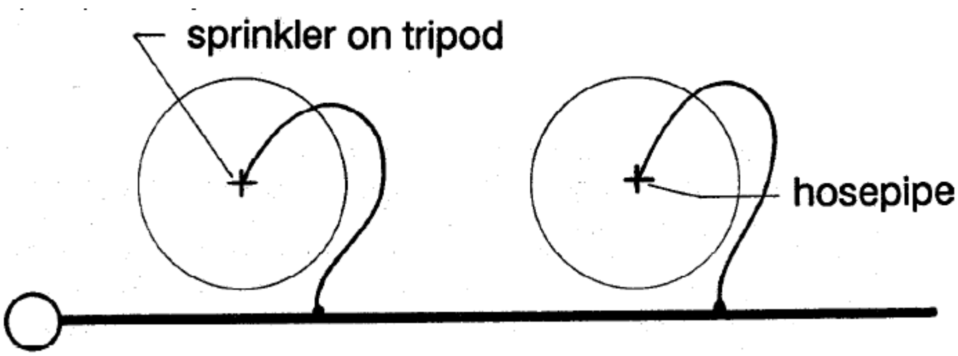


Figure II-13 Hose-pull sprinkler system (Kay & Hatcho, 1992)

II.2.2.3. Trickle irrigation

Trickle irrigation involves dripping water onto the soil at very low flow rates (1-20 l/h) from a system of small diameter plastic pipes fitted with outlets called emitters. Water is applied close to the plants so that only the part of the soil volume in which the roots develop is wetted. Applications are usually frequent (every 2-3 days) and this can provide a favourable high moisture level condition in which the plants can flourish. Many other claims are made about the method, including increased crop yields, greater efficiency of water use, possible use of saline water, reduced labour requirements and its adaptability to poor soils. An important advantage is the ease with which nutrients can be applied with the irrigation water. The relative importance of each of these attributes will vary depending on the situation (Kay & Hatcho, 1992) .

A typical trickle irrigation system is shown in Figure II-14

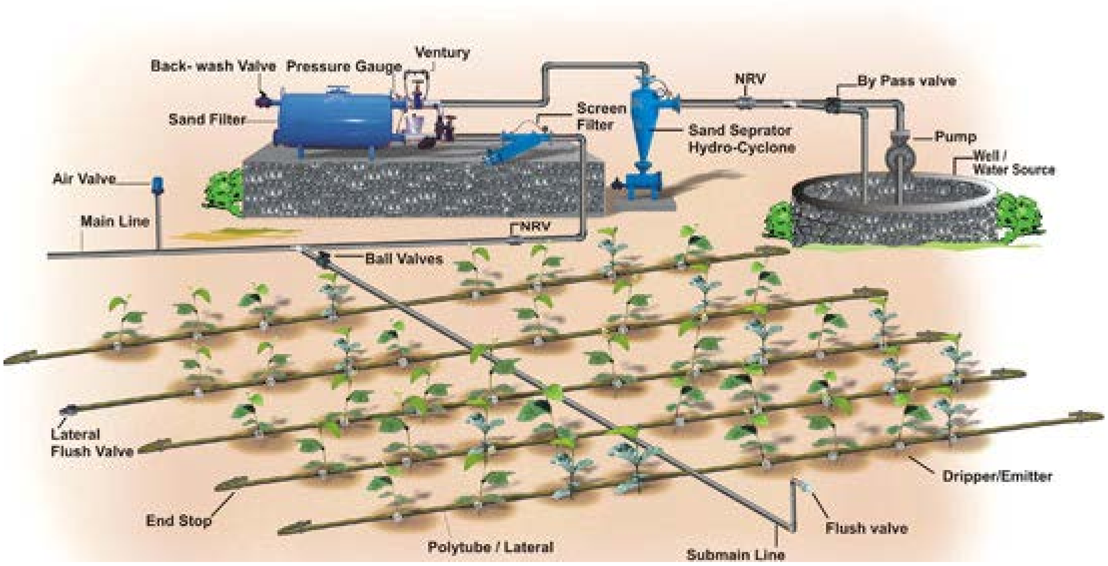


Figure II-14 Drip irrigation layout[3]

Trickle irrigation is potentially a very efficient method of applying water to crops. Field application efficiency can be as high as 90%, but like any other method it relies very much on the skill of the irrigator to achieve this. Field measurements on trickle systems have shown application efficiencies as low as 25%. This was the result of poor system management rather than design. The farmers had not fully understood the concept of partial wetting of the root zone and so they wasted a lot of water trying to wet up the entire area (Kay & Hatcho, 1992).

Because of the potentially higher efficiency and the operating pressure of only 1-2 bar this method can use less energy than sprinkler irrigation and in some cases less than surface irrigation.

Trickle irrigation is very adaptable to small-scale irrigation. It can be ideal for small plots of trees and row crops requiring different amounts of water. Trickle laterals may also be moved from one crop row to another to reduce the cost of the system.

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[3] www.yuvaengineers.com

Many claims are made about trickle irrigation, such as that it saves irrigation water, increases yield, etc., but care should be taken in accepting such claims. Crops need a certain amount of water to grow and generally they are not aware of where the water is coming from. If it comes from surface flooding, sprinkling or trickle, it makes little difference to the plants — they respond to water. The saving in water comes from the efficiency with which the water can be applied and it is here that trickle has a distinct advantage. Some yield increases have been shown with trickle and this may be due to the favourable soil water conditions and the nutrients added to the water (Kay & Hatcho, 1992).

II.2.3. Crop’s water requirement

The concept of evapotranspiration

This section of the chapter explains the concepts of and the differences between reference crop evapotranspiration (ETo) and crop evapotranspiration under standard conditions (ETc) and various management and environmental conditions (ETc adj). It also examines the factors that affect evapotranspiration, the units in which it is normally expressed and the way in which it can be determined.

Evapotranspiration process

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (ET).

Evaporation

Evaporation is the process whereby liquid water is converted to water vapour (vaporization) and removed from the evaporating surface (vapour removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Energy is required to change the state of the molecules of water from liquid to vapour. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy.

The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.

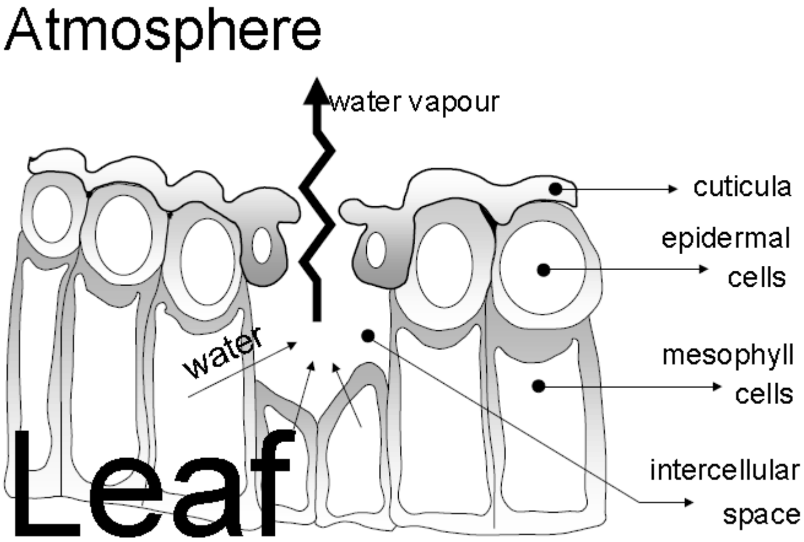

Figure II-15 Schematic representation of a stoma (Allen & Pereira, 1998)

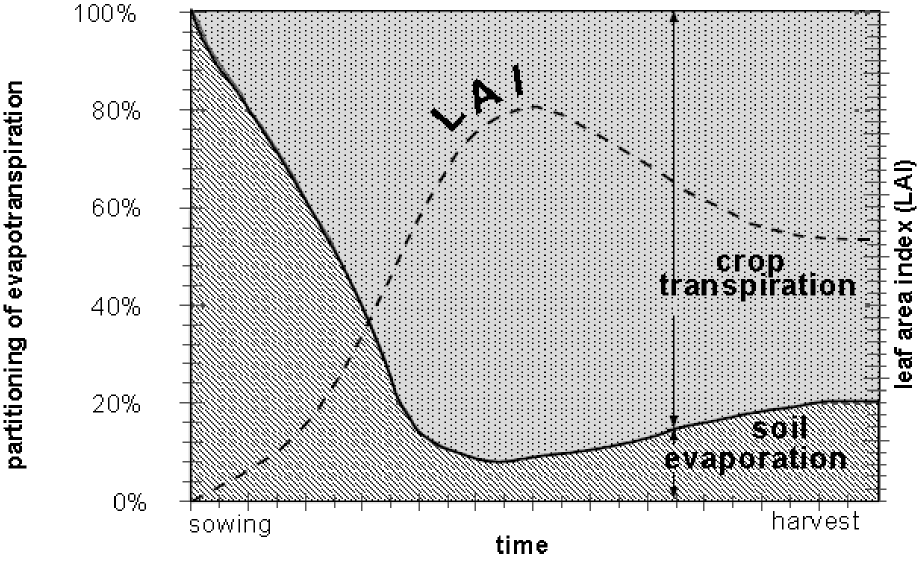

Figure II-16 The partitioning of evapotranspiration into evaporation and transpiration over the growing period for an annual field crop (Allen & Pereira, 1998)

Transpiration

The vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere is known as transpiration. Crops lose their water in majority through the stomata. These are small openings on the plant leaf through which gases and water vapor pass (Figure II-15). The water, together with some nutrients, is taken up by the roots and transported through the plant. The vaporization occurs within the leaf, namely in the intercellular spaces, and the vapor exchange with the atmosphere is controlled by the stomata aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant. Transpiration, like direct evaporation, depends on the energy supply, vapor pressure gradient and wind. Hence, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do water logging and soil water salinity.

The transpiration rate is also influenced by crop characteristics, environmental aspects and cultivation practices. Different kinds of plants may have different transpiration rates. Not only the type of crop, but also the crop development, environment and management should be considered when assessing transpiration.

II.2.3.1. Evapotranspiration (ET)

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process. In Figure II-16 the partitioning of evapotranspiration into evaporation and transpiration is plotted in correspondence to leaf area per unit surface of soil below it. At sowing nearly 100% of ET comes from evaporation, while at full crop cover more than 90% of ET comes from transpiration.

Units

The evapotranspiration rate is normally expressed in millimeters (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth. The time unit can be an hour, day, decade, month or even an entire growing period or year. As one hectare has a surface of 10 000 m^2 and 1 mm is equal to 0.001 m, a loss of 1 mm of water corresponds to a loss of 10 m^3 of water per hectare. In other words, 1 mm day^{-1} is equivalent to 10 m^3 ha^{-1} day^{-1}. Water depths can also be expressed in terms of energy received per unit area. The energy refers to the energy or heat required to vaporize free water. This energy, known as the latent heat of vaporization (λ), is a function of the water temperature. At 20°C, λ is about 2.45 MJ kg^{-1}. In other words, 2.45 MJ are needed to vaporize 1 kg or 0.001 m^3 of water. Hence, an energy input of 2.45 MJ per m^2 is able to vaporize 0.001 m or 1 mm of water, and therefore 1 mm of water is equivalent to 2.45 MJ m^{-2}. The evapotranspiration rate expressed in units of MJ m^{-2} day^{-1} is represented by λET, the latent heat flux.

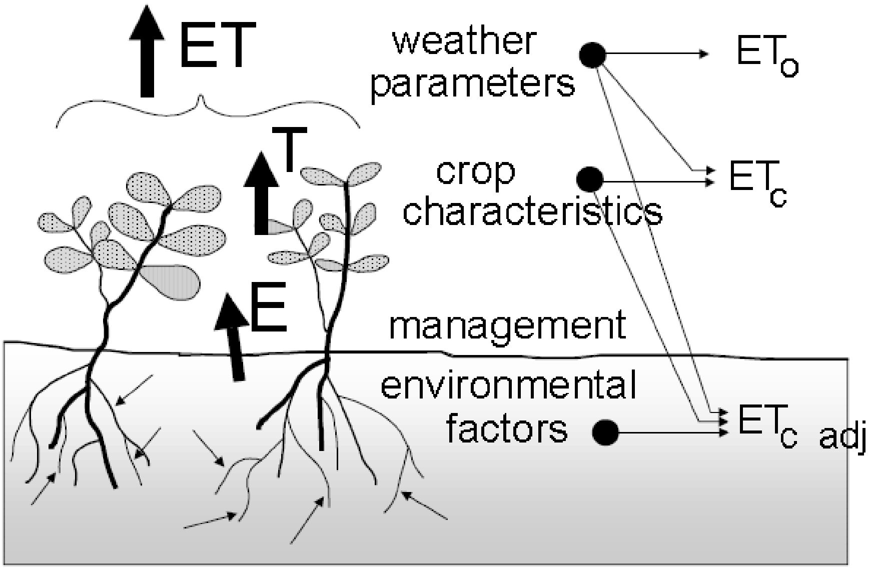

Figure II-17 Factors affecting evapotranspiration with reference to related ET concepts (Allen & Pereira, 1998)

Factors affecting evapotranspiration (Allen & Pereira, 1998)

Weather parameters, crop characteristics, management and environmental aspects are factors affecting evaporation and transpiration. The related ET concepts presented in Figure II-17 are discussed in the section on evapotranspiration concepts.

Weather parameters

The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed. Several procedures have been developed to assess the evaporation rate from these parameters. The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration (ETo). The reference crop evapotranspiration represents the evapotranspiration from a standardized vegetated surface.

Crop factors

The crop type, variety and development stage should be considered when assessing the evapotranspiration from crops grown in large, well-managed fields. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels in different types of crops under identical environmental conditions. Crop evapotranspiration under standard conditions (ETc) refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full production under the given climatic conditions.

Management and environmental conditions

Factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. Other factors to be considered when assessing ET are ground cover, plant density and the soil water content. The effect of soil water content on ET is conditioned primarily by the magnitude of the water deficit and the type of soil. On the other hand, too much water will result in waterlogging which might damage the root and limit root water uptake by inhibiting respiration.

When assessing the ET rate, additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the ET process. Cultivation practices and the type of irrigation method can alter the microclimate, affect the crop characteristics or affect the wetting of the soil and crop surface. A windbreak reduces wind velocities and decreases the ET rate of the field directly beyond the barrier. The effect can be significant especially in windy, warm and dry conditions although evapotranspiration from the trees themselves may offset any reduction in the field. For instance, soil evaporation in a young orchard, where trees are widely spaced, can be reduced by using a well-designed drip or trickle irrigation system. The drippers apply water directly to the soil near trees, thereby leaving the major part of the soil surface dry, and limiting the evaporation losses. The use of mulches, especially when the crop is small, is another way of substantially reducing soil evaporation. Anti-transpirants, such as stomata-closing, film-forming or reflecting material, reduce the water losses from the crop and hence the transpiration rate.

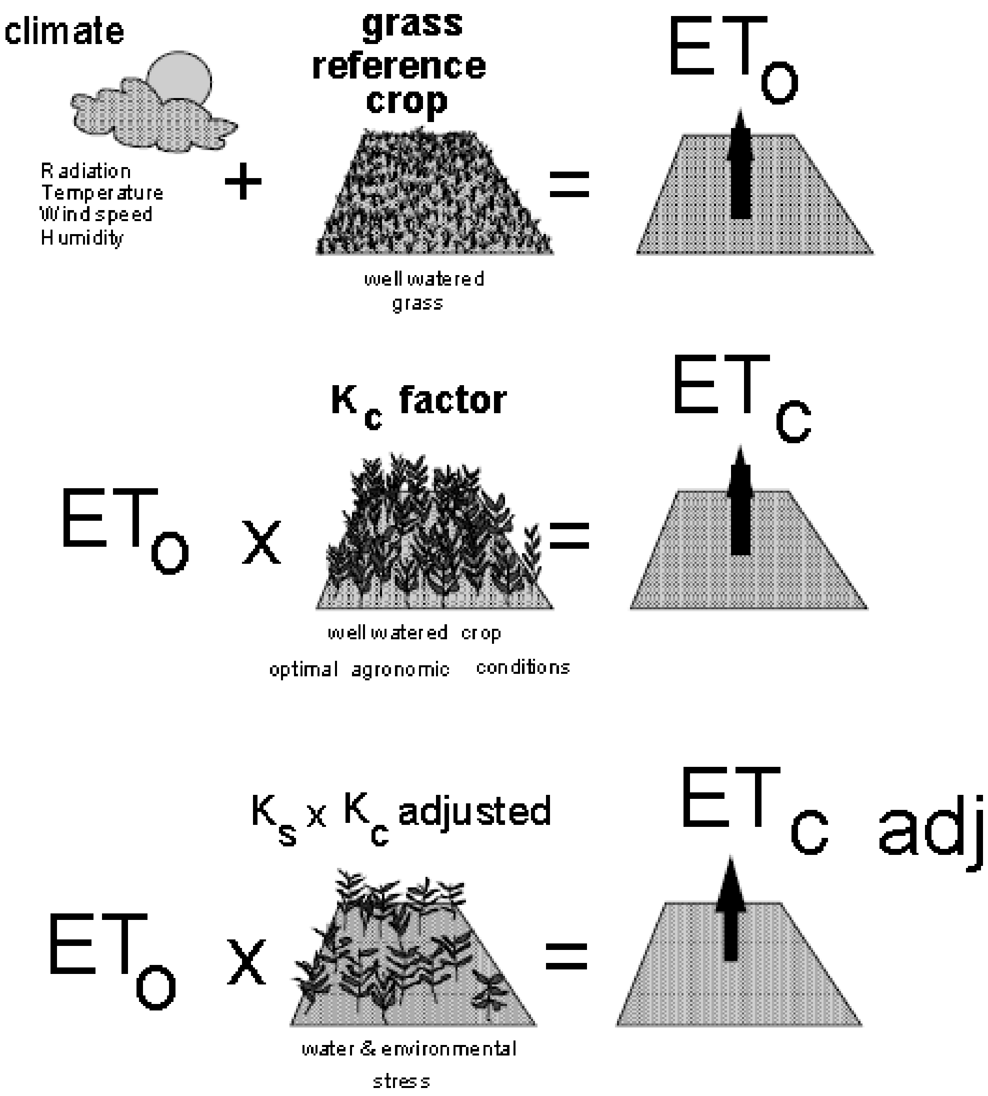

Figure II-18 Reference (ETo) crop evapotranspiration under standard (Etc) and non standard conditions (Etc adj) (Allen & Pereira, 1998).

Where field conditions differ from the standard conditions, correction factors are required to adjust ETc. The adjustment reflects the effect on crop evapotranspiration of the environmental and management conditions in the field.

Evapotranspiration concepts (Allen & Pereira, 1998)

Distinctions are made (Figure II-18) between reference crop evapotranspiration (ETo), crop evapotranspiration under standard conditions (ETc) and crop evapotranspiration under nonstandard conditions (ETc adj). ETo is a climatic parameter expressing the evaporation power of the atmosphere. ETc refers to the evapotranspiration from excellently managed, large, well-watered fields that achieve full production under the given climatic conditions. Due to suboptimal crop management and environmental constraints that affect crop growth and limit evapotranspiration, ETc under non-standard conditions generally requires a correction (Allen & Pereira, 1998).

II.2.3.2. Reference crop evapotranspiration (ETo)

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ETo. The reference surface is a hypothetical grass reference crop with specific characteristics. The use of other denominations such as potential ET is strongly discouraged due to ambiguities in their definitions (Allen & Pereira, 1998).

The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect ET. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It obviates the need to define a separate ET level for each crop and stage of growth. ETo values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface.

The only factors affecting ETo are climatic parameters. Consequently, ETo is a climatic parameter and can be computed from weather data. ETo expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The FAO Penman-Monteith method is recommended as the sole method for determining ETo. The method has been selected because it closely approximates grass ETo at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters. Moreover, procedures have been developed for estimating missing climatic parameters.

Typical ranges for ETo values for different agroclimatic regions are given in Table II-3. These values are intended to familiarize inexperienced users with typical ranges, and are not intended for direct application.

II.2.3.3. Crop evapotranspiration under standard conditions (ETc)

The crop evapotranspiration under standard conditions, denoted as ETc, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions.

Table II-III Average ETo for different agroclimatic regions in mm/day

Regions	Mean daily temperature (°C)		
	Cool ~10°C	Moderate 20°C	Warm >30°C
Tropics and subtropics			
• Humid and sub-humid	2-3	3-5	5-7
• Arid and semi-arid	2-4	4-6	6-8
Tropics region			
• Humid and sub-humid	1-2	2-4	4-7
• Arid and semi-arid	1-3	4-7	6-9

The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement basically represents the difference between the crop water requirement and effective precipitation. The irrigation water requirement also includes additional water for leaching of salts and to compensate for non-uniformity of water application. Calculation of the irrigation water requirement is not covered in this study. Crop evapotranspiration can be calculated from climatic data and by integrating directly the crop resistance, albedo and air resistance factors in the Penman-Monteith approach. As there is still a considerable lack of information for different crops, the Penman-Monteith method is used for the estimation of the standard reference crop to determine its evapotranspiration rate, i.e., ETo. Experimentally determined ratios of ETc/ETo, called crop coefficients (Kc), are used to relate ETc to ETo or ETc = Kc ETo.

Differences in leaf anatomy, stomatal characteristics, aerodynamic properties and even albedo cause the crop evapotranspiration to differ from the reference crop evapotranspiration under the same climatic conditions. Due to variations in the crop characteristics throughout its growing season, Kc for a given crop changes from sowing till harvest.

II.2.4. Crop evapotranspiration under non-standard conditions (ETc adj)

The crop evapotranspiration under non-standard conditions (ETc adj) is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. When cultivating crops in fields, the real crop evapotranspiration may deviate from ETc due to non-optimal conditions such as the presence of pests and diseases, soil salinity, low soil fertility, water shortage or waterlogging. This may result in scanty plant growth, low plant density and may reduce the evapotranspiration rate below ETc. The crop evapotranspiration under non-standard conditions is calculated by using a water stress coefficient Ks and/or by adjusting Kc for all kinds of other stresses and environmental constraints on crop evapotranspiration.

ET measurement

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. Although the methods are inappropriate for routine measurements, they remain important for the evaluation of ET estimates obtained by more indirect methods.

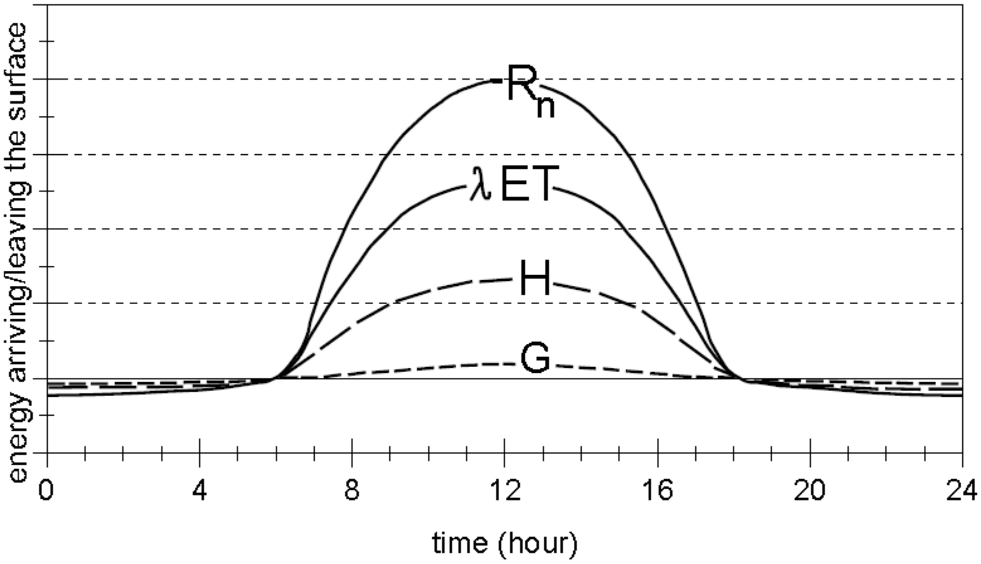

Figure II-19 Schematic presentation of the diurnal variation of the components of the energy balance above a well-watered transpiring surface on a cloudless day

II.2.4.1. Energy balance and microclimatological methods

Evaporation of water requires relatively large amounts of energy, either in the form of sensible heat or radiant energy. Therefore the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available.

Because of this limitation, it is possible to predict the evapotranspiration rate by applying the principle of energy conservation. The energy arriving at the surface must equal the energy leaving the surface for the same time period.

All fluxes of energy should be considered when deriving an energy balance equation. The equation for an evaporating surface can be written as:

$$R_n - G - \lambda ET - H = 0 \qquad (1)$$

Where Rn is the net radiation, H the sensible heat, G the soil heat flux and λET the latent heat flux. The various terms can be either positive or negative. Positive Rn supplies energy to the surface and positive G ,λET and H remove energy from the surface (Figure II-19).

In Equation 1 only vertical fluxes are considered and the net rate at which energy is being transferred horizontally, by advection, is ignored. Therefore the equation is to be applied to large, extensive surfaces of homogeneous vegetation only. The equation is restricted to the four components: Rn, λET, H and G. Other energy terms, such as heat stored or released in the plant, or the energy used in metabolic activities, are not considered. These terms account for only a small fraction of the daily net radiation and can be considered negligible when compared with the other four components.
The latent heat flux (λET) representing the evapotranspiration fraction can be derived from the energy balance equation if all other components are known. Net radiation (Rn) and soil heat fluxes (G) can be measured or estimated from climatic parameters.

Measurements of the sensible heat (H) are however complex and cannot be easily obtained. H requires accurate measurement of temperature gradients above the surface.

Another method of estimating evapotranspiration is the mass transfer method. This approach considers the vertical movement of small parcels of air (eddies) above a large homogeneous surface. The eddies transport material (water vapour) and energy (heat, momentum) from and towards the evaporating surface. By assuming steady state conditions and that the eddy transfer coefficients for water vapour are proportional to those for heat and momentum, the evapotranspiration rate can be computed from the vertical gradients of air temperature and water vapor via the Bowen ratio. Other direct measurement methods use gradients of wind speed and water vapor. These methods and other methods such as eddy covariance, require accurate measurement of vapor pressure, and air temperature or wind speed at different levels above the surface. Therefore, their application is restricted to primarily research situations.

II.2.4.2. Soil water balance

Evapotranspiration can also be determined by measuring the various components of the soil water balance. The method consists of assessing the incoming and outgoing water flux into the crop root zone over some time period (Figure II-20). Irrigation (I) and rainfall (P) add water to the root zone. Part of I and P might be lost by surface runoff (RO) and by deep percolation (DP) that will eventually recharge the water table. Water might also be transported upward by capillary rise (CR) from a shallow water table towards the root zone or even transferred horizontally by subsurface flow in (SFin) or out of (SFout) the root zone. In many situations, however, except under condititions with large slopes, SFin and SFout are minor and can be ignored. Soil evaporation and crop transpiration deplete water from the root zone. If all fluxes other than evapotranspiration (ET) can be assessed, the evapotranspiration can be deduced from the change in soil water content (ΔSW) over the time period:

$$ET = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \qquad (2)$$

Some fluxes such as subsurface flow, deep percolation and capillary rise from a water table are difficult to assess and short time periods cannot be considered. The soil water balance method can usually only give ET estimates over long time periods of the order of week-long or ten-day periods.

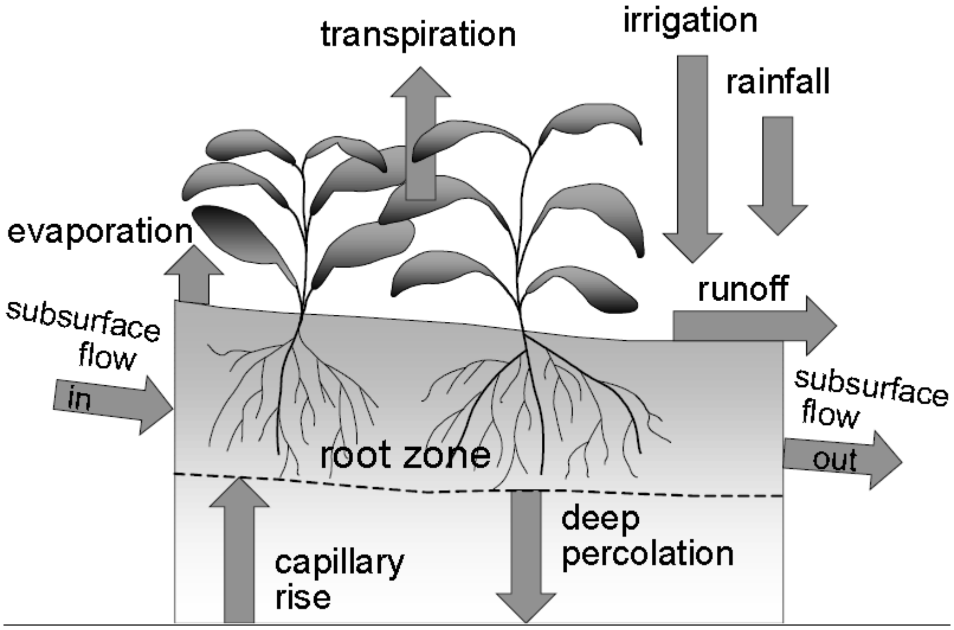

Figure II-20 Soil water balance of the root zone

ET computed from meteorological data

Owing to the difficulty of obtaining accurate field measurements, ET is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing crop or reference crop evapotranspiration from meteorological data.

Some of the methods are only valid under specific climatic and agronomic conditions and cannot be applied under conditions different from those under which they were originally developed.

Numerous researchers have analyzed the performance of the various calculation methods for different locations. As a result of an Expert Consultation held in May 1990, the FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration, ETo. The ET from crop surfaces under standard conditions is determined by crop coefficients (Kc) that relate ETc to ETo. The ET from crop surfaces under non-standard conditions is adjusted by a water stress coefficient (Ks) and/or by modifying the crop coefficient.

ET estimated from pan evaporation

Evaporation from an open water surface provides an index of the integrated effect of radiation, air temperature, air humidity and wind on evapotranspiration. However, differences in the water and cropped surface produce significant differences in the water loss from an open water surface and the crop. The pan has proved its practical value and has been used successfully to estimate reference evapotranspiration by observing the evaporation loss from a water surface and applying empirical coefficients to relate pan evaporation to ETo.

II.3.Types of pumps for irrigation and principles of operation

A pump is a machine which changes mechanical energy into useful water energy and needs diesel engine or an electric motor solar, wind or grid power to drive it. For surface irrigation the pump lifts water from a river or groundwater into a channel or pipe system. For sprinkler and trickle irrigation the pump provides the energy for the pressure and discharge needed to distribute water in the pipes to the sprinklers and emitters, in addition to the energy needed to lift water from the source.

Most irrigation pumps fall within the category of pumps that use kinetic principles, that is, centrifugal force or momentum in transferring energy. This category includes pumps such as centrifugal pumps, vertical turbine pumps, submersible pumps and jet pumps. Most of these pumps operate within a range of discharge and head where the discharge will vary as the head fluctuates (Allahwerdi, 1986).

The second category of pumps is that of positive displacement pumps, whereby the fluid is displaced by mechanical devices such as pistons, plungers and screws. Mono pumps, treadle pumps and most of the manual pumps fall into this category (Longenbaugh & Duke, 1980).

Allahwerdi (1986) calls the first category of pumps turbo pumps and depending on the type of discharge subdivides these pumps into:

- Radial flow pumps (centrifugal action)
- Axial flow pumps (propeller-type action)
- Mixed flow pumps (variation of both)

It should be noted that Allahwerdi's classification does not include positive displacement pumps.

Longenbaugh and Duke (1980) classify pumps into:

- Vertical turbine and centrifugal pumps
- Propeller or axial flow pumps
- Mixed flow pumps
- Positive displacement pumps

Figure II-21 shows this classification as a function of the total operating head and discharge. The schematic classification employed by the State Electricity Commission (SEC) is shown in Figure II-22 and the one employed by the Hydraulic Institute in FigureII-23

Positive displacement pumps are as a rule suitable for small discharges and high heads and the head is independent of the pump speed. Some types of these pumps should only be used with water free of sediments. The vertical turbine and the centrifugal pumps fit conditions of moderately small to high discharges and moderately low to high heads. These are the most commonly used pumps in irrigation. They can operate with reasonable amounts of sediments, but periodic replacement of impellers and volute casing should.

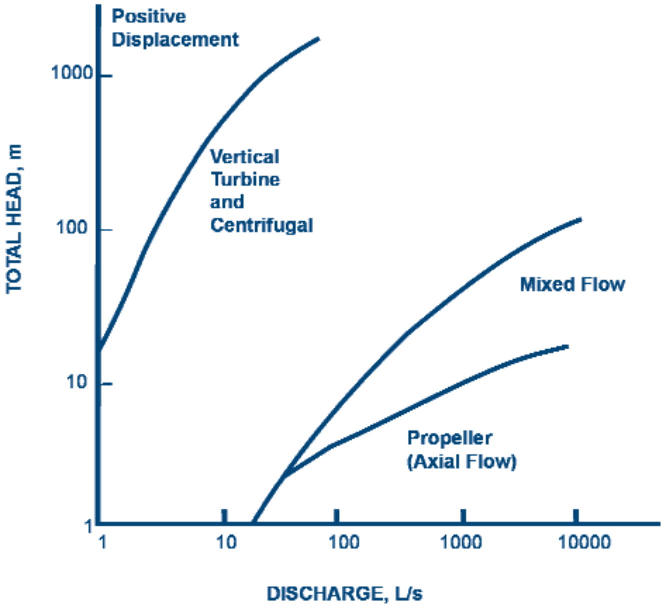

Figure II-21 Subclassification of pump types as a function of operating head and discharge (Adapted from (Longenbaugh & Duke, 1980))

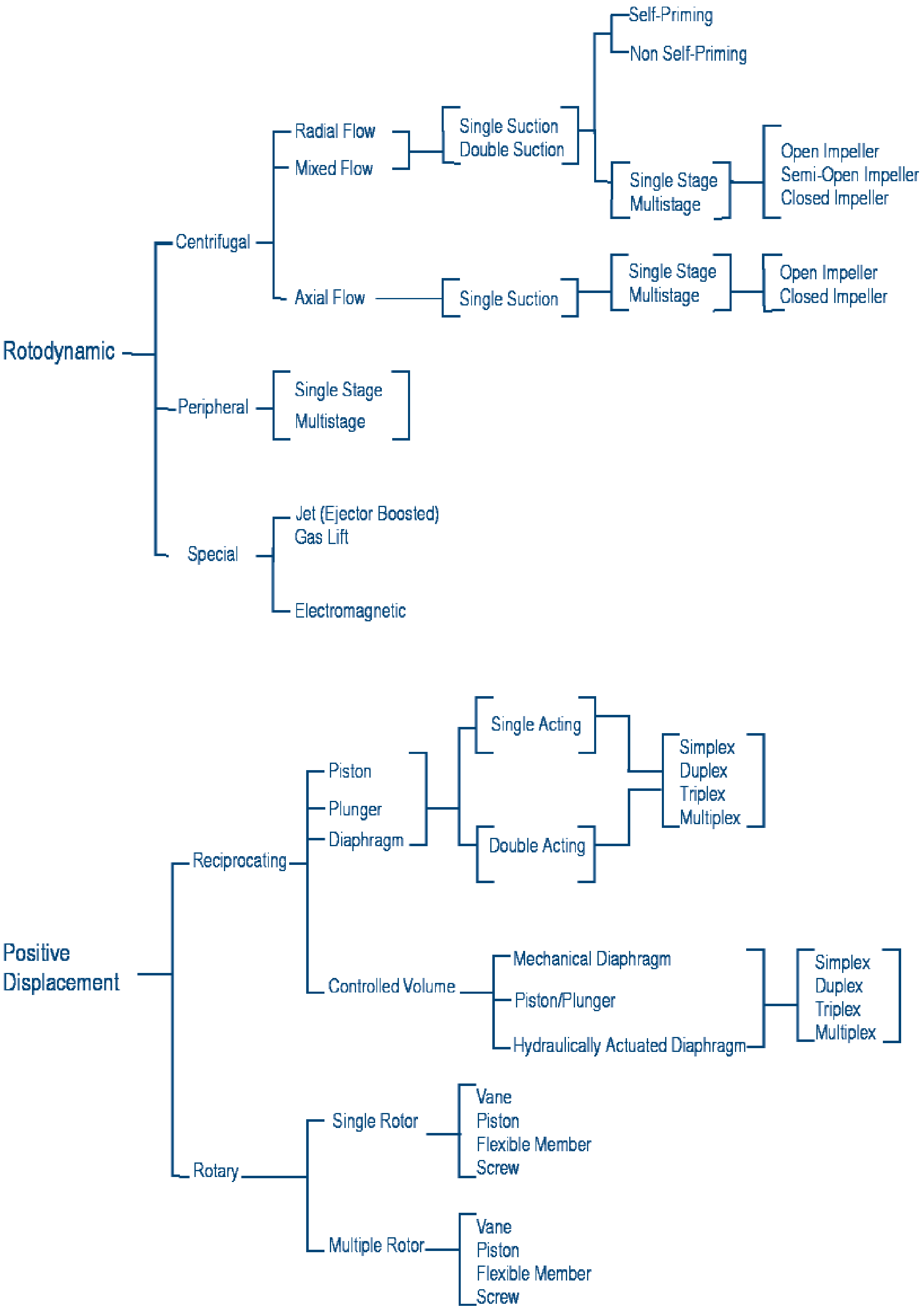

Figure II-22 Schematic classification of pump types by the State Electricity Commission in 1965 (Sawa & Fenken, 2001).

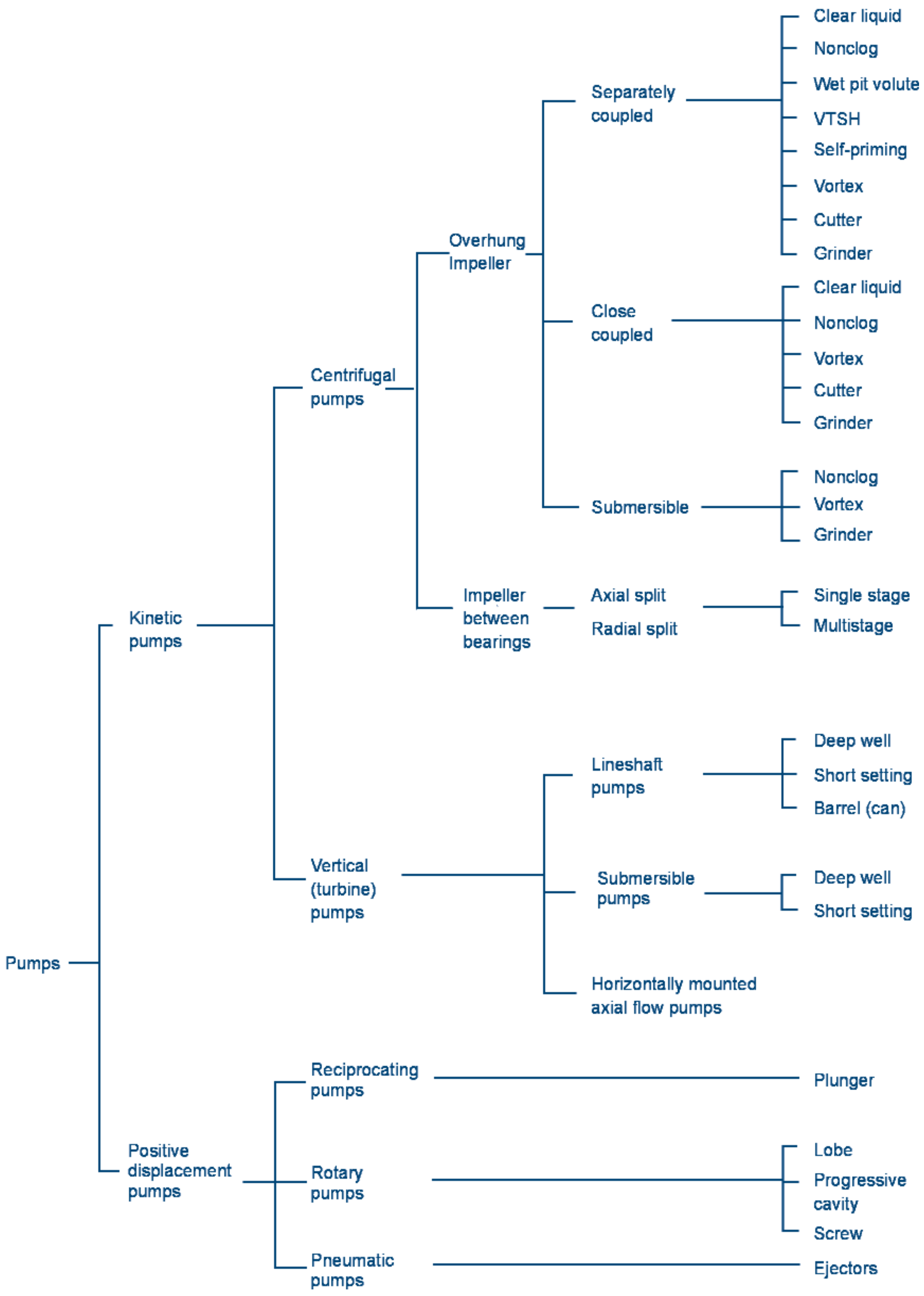

Figure II-23 Schematic classification of pump types by the Hydraulic Institute in 1983 (Sawa & Fenken, 2001)

II.3.1. Radial flow pumps

Radial flow pumps are based on the principles of centrifugal force and are subdivided into volute pumps and diffuser (turbine) pumps. Centrifugal pumps are the most common type of pump used on small schemes because they are much cheaper than axial pumps to buy and maintain. Small pump sets are often readily available in most developing countries. They are best suited to sprinkler and trickle irrigation, where a higher pressure is needed than for surface irrigation (Sawa & Fenken, 2001).

Volute pumps

The well-known horizontal centrifugal pump is a volute pump. The pump consists of two main parts, the propeller that rotates on a shaft and gives the water a spiral motion, and the pump casing that directs the water to the impeller through the volute and eventually to the outlet. The suction entrance of the casing is in such a position that the water enters the eye of the impeller. The water is then pushed outwards because of the centrifugal force caused by the rotating impeller. The centrifugal force, converted to velocity head and thus pressure, pushes the water to the outlet of the volute casing. Figure II-24 shows the components of a typical centrifugal pump. Figure II-25 shows the impeller inside the volute casing and the three types of impellers commonly used in centrifugal pumps. Closed impellers develop higher efficiencies in high-pressure pumps. The other two types are more able to pass solids that may be present in the water (Kay & Hatcho, 1992).

Volute pumps may be classified under three major categories (Figure II-26):

- Low head, where the impeller eye diameter is relatively large compared with the impeller rim diameter
- Medium head, where the impeller eye diameter is a small proportion of the impeller rim diameter
- High head, where the impeller rim diameter is relatively much larger than the impeller eye diameter

Diffuser or turbine pumps

The major difference between the volute centrifugal pumps and the turbine pumps is the device used to receive the water after it leaves the impeller. In the case of the turbine pumps, the receiving devices are diffuser vanes that surround the impeller and provide diverging passages to direct the water and change the velocity energy to pressure energy. Deep well turbine pumps and submersible pumps use this principle. (Sawa & Fenken, 2001)

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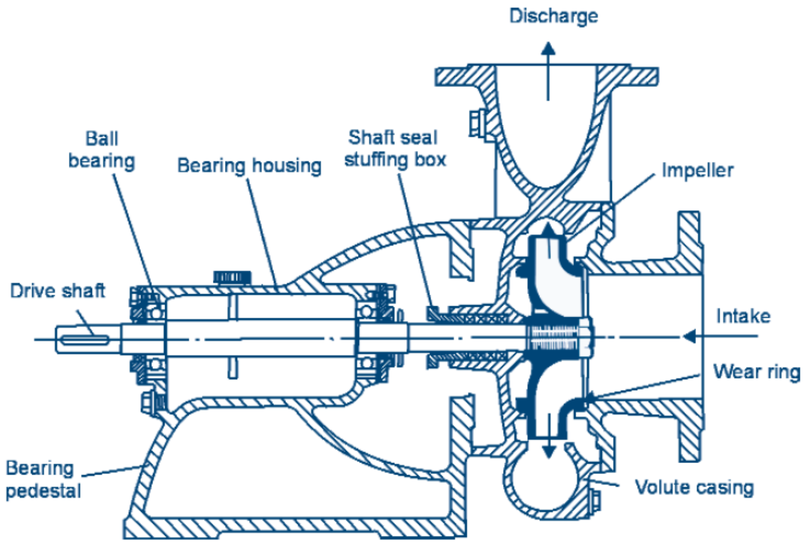


Figure II-24- Cross-section of a centrifugal pump (Sawa & Fenken, 2001)

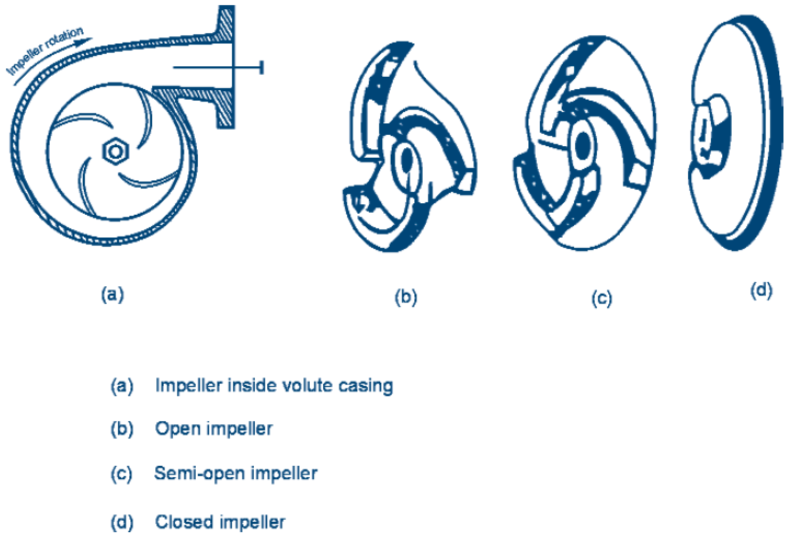


Figure II-25- Pump impellers and volute casing (Sawa & Fenken, 2001)

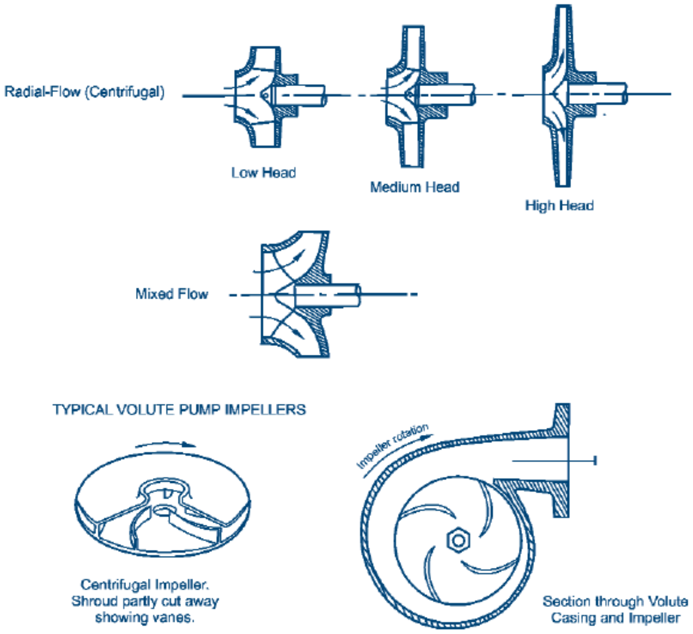


Figure II-26- Classification of volute pumps based on the impeller proportions

(Sawa & Fenken, 2001)

Figure II-27- Parts of bowl assembly (Sawa & Fenken, 2001)

Electric Motor Drive

The electric motor is a vertical flange mounted, totally enclosed fan-cooled squirrel-cage induction type manufactured in accordance with (IEC) international standards. Up to and including 30 kW (40 HP) the motors are fitted with special bearings to absorb the axial thrust. For 37 kW (50 HP) and larger motors a special intermediate housing with coupling and bearings is fitted between the pump head and the motor for the same purpose.

The GRUNDFOS deep well turbine pumps are available with electric motors up to 45 kW (60 HP) in standard design and motors up to 75 kW (100 HP) in special design.

Right Angle Gear Drive

The right angle gear drive is made from high specification materials to ensure a long and trouble free life.

The gear housing is made from rigid cast iron and constructed to ensure constant correct alignment of the gear wheels at maximum load. The hardened, ground, and paired gear wheels are kept in the correct position by angular contact bearings. In the construction of the gear wheels and the selection of the bearings, the aim has been to ensure long life with quiet operation.

The gear wheels and the bearings are oil lubricated by means of an oil pump positioned at the bottom of the gear housing. The largest gear types are water cooled as standard, and the smaller types are available with water cooling by request.

The vertical main shaft in the smaller types is of a solid construction, and the coupling between the main shaft and the column pipe shaft is positioned in the pump head. This means that the adjustment of the pump impellers can be made in the pump head without removing the gear dome.

In the larger types the main shaft is of a hollow construction, and the coupling between the main shaft and the column pipe shaft is positioned in the gear top, where the adjustment of the impellers is also made.

The right angle gears are available in four sizes from max. 22 kW (30 HP) to max. 92 kW (125 HP) nominal power at a ratio of 1:2 and a max. speed of 3500 r.p.m. For other ratios and pump speeds, the nominal power is reduced accordingly.

Pulley Drive

The pulley head and the bearings are made from high quality materials to obtain a long and trouble free life and smooth quiet operation.

The flat belt pulley drive is available for pumps up to 22 kW (30 HP) and for pump speed up to 3450 r.p.m.

The pulley head drive is also available in a design for V-belt drive for special purposes.

Figure II-28- Different drive configurations (Sawa & Fenken, 2001)

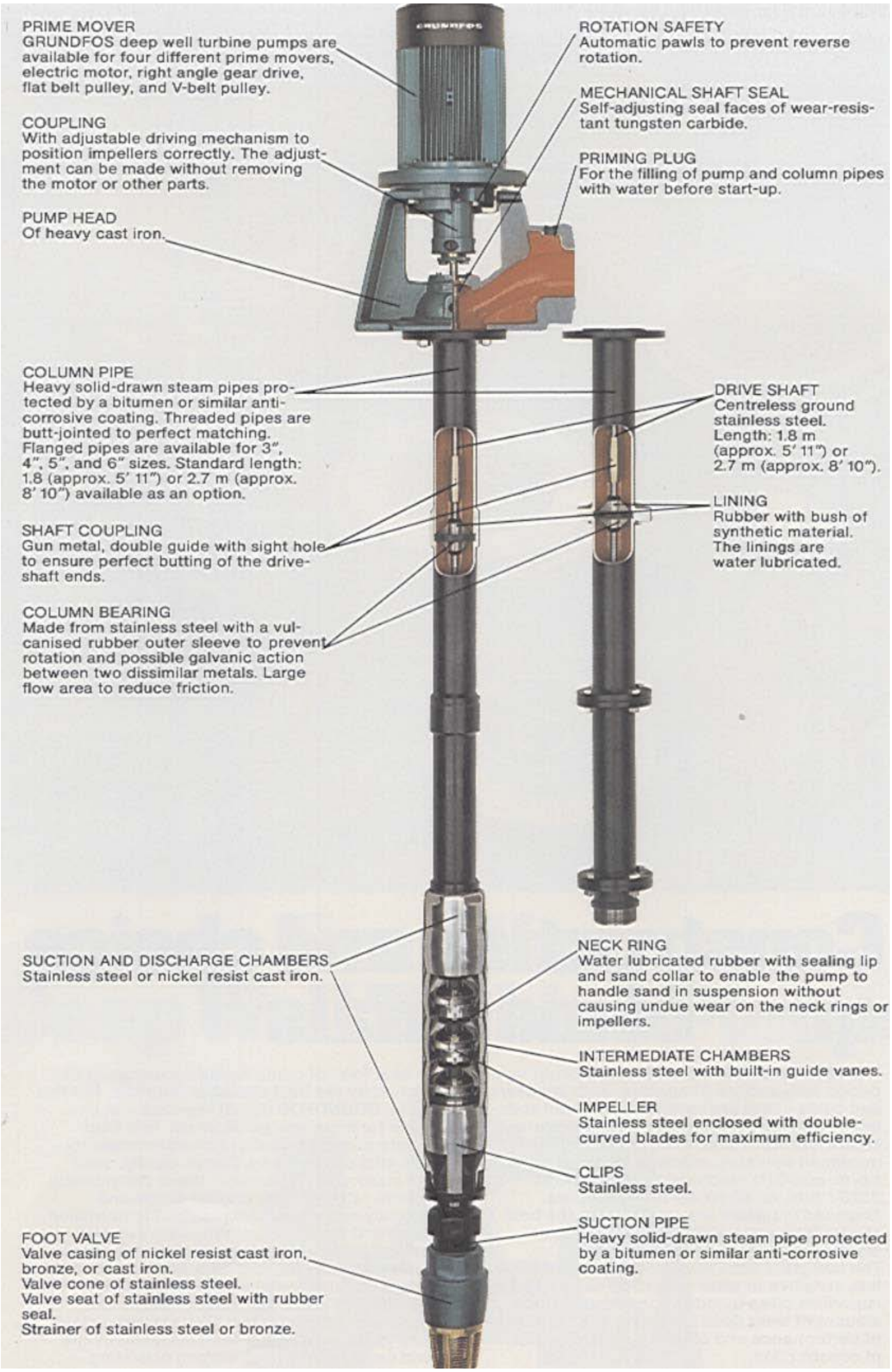
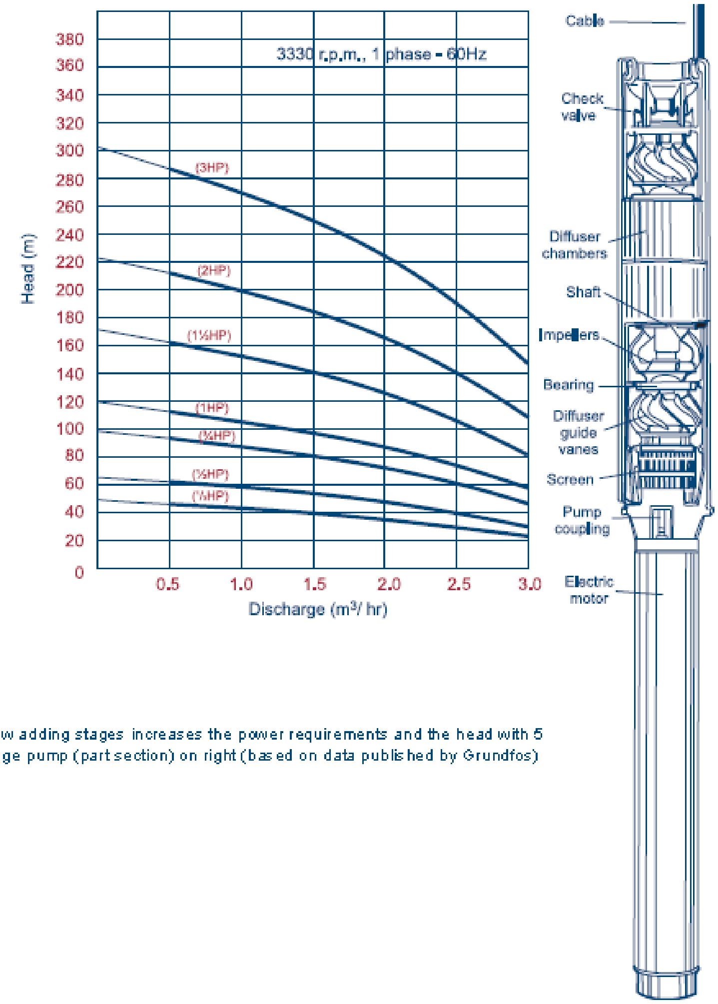


Figure II-29- Electrically driven turbine pump (Sawa & Fenken, 2001)

Depending on the required head, these pumps have a number of impellers, each of which is enclosed with its diffuser vanes in a bowl. Several bowls form the bowl assembly that must always be submerged in water. Figure II-27 shows parts of the bowl assembly. A vertical shaft rotates the impellers. In the case of turbine pumps the shaft is located in the center of the discharge pipe. At intervals of usually 2-3 m, the shaft is supported by rubber lined water lubricated bearings. Figure II-28 shows different drive configurations. Figure II-29 shows a complete electrically driven turbine pump. (Sawa & Fenken, 2001)

Electro-submersible pumps are turbine pumps with an electric motor attached in the suction part of the pump, providing the drive to the shaft that rotates the impellers. Therefore, there is no shaft in the discharge pipe. Both the motor and pump are submerged in the water. They are especially suitable for installation in deep boreholes. Submersible electrically driven pumps depend on cooling via the water being pumped, and a failure of the water supply can result in serious damage to the unit. For this reason submersible pumps are protected with water level cut-off switches. Figure II-30 shows a complete submersible pump. (Sawa & Fenken, 2001)



How adding stages increases the power requirements and the head with 5 stage pump (part section) on right (based on data published by Grundfos)

Figure II-30- Cross-section through a submersible pump and submersible motor (Sawa & Fenken, 2001)

II.3.2. Axial flow pumps

While the radial flow type of pump discharges the water at right angles to the axis of rotation, in the axial flow type water is propelled upwards and discharged nearly axially. The blades of the propeller are shaped somewhat like a ship's propeller. Axial flow type pumps are used for large discharges and low heads (see Figure II-21).

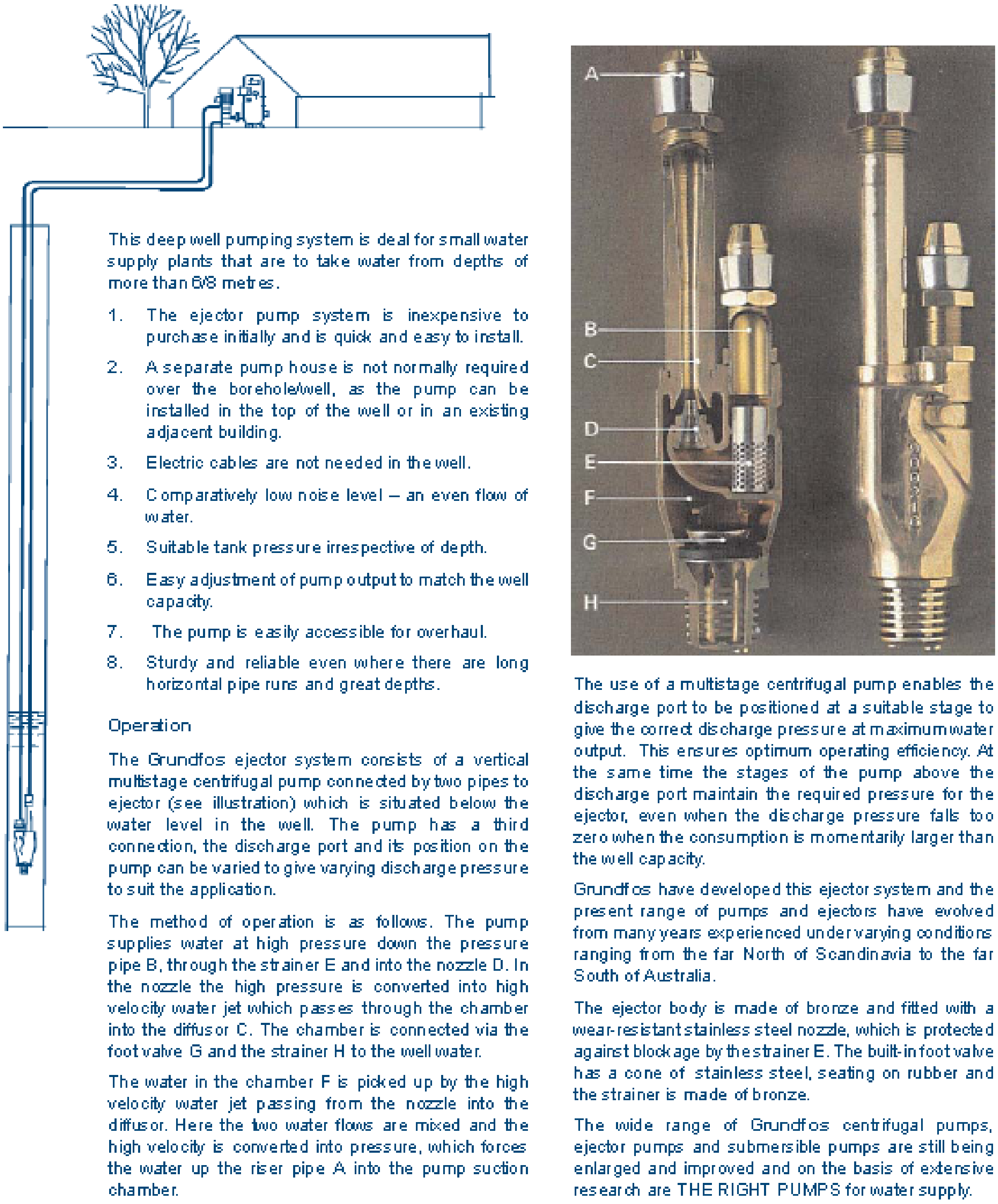
Mixed flow pumps

This category includes pumps whereby the pressure head is developed partially through the centrifugal force and partially through the lift of the vanes on the water. The flow is discharged both axially and radially. These pumps are suitable for large discharges and medium head. (Kay & Hatcho, 1992)

Jet pumps

This pump is a combination of a centrifugal pump and a nozzle converting high pressure into velocity (Figure II-31). As such it cannot fit into one of the above categories. A high pressure jet stream is ejected through a suitable nozzle to entrain a large volume of water at low pressure and force it to a higher level within the system. The pump has no moving parts in the well or beneath the water surface. It is composed of a multistage centrifugal pump installed above ground, an ejector installed below the water surface and connecting pipes. The disadvantage of these units is that when they are used in high head situations, the discharge and efficiency are greatly reduced (Sawa & Fenken, 2001). Basically such units are categorized as:

- Low head, large discharge – most efficient
- High head, low discharge – least efficient



This deep well pumping system is deal for small water supply plants that are to take water from depths of more than 6/8 metres.

1. The ejector pump system is inexpensive to purchase initially and is quick and easy to install.
2. A separate pump house is not normally required over the borehole/well, as the pump can be installed in the top of the well or in an existing adjacent building.
3. Electric cables are not needed in the well.
4. Comparatively low noise level – an even flow of water.
5. Suitable tank pressure irrespective of depth.
6. Easy adjustment of pump output to match the well capacity.
7. The pump is easily accessible for overhaul.
8. Sturdy and reliable even where there are long horizontal pipe runs and great depths.

Operation

The Grundfos ejector system consists of a vertical multistage centrifugal pump connected by two pipes to ejector (see illustration) which is situated below the water level in the well. The pump has a third connection, the discharge port and its position on the pump can be varied to give varying discharge pressure to suit the application.

The method of operation is as follows. The pump supplies water at high pressure down the pressure pipe B, through the strainer E and into the nozzle D. In the nozzle the high pressure is converted into high velocity water jet which passes through the chamber into the diffusor C. The chamber is connected via the foot valve G and the strainer H to the well water.

The water in the chamber F is picked up by the high velocity water jet passing from the nozzle into the diffusor. Here the two water flows are mixed and the high velocity is converted into pressure, which forces the water up the riser pipe A into the pump suction chamber.

The use of a multistage centrifugal pump enables the discharge port to be positioned at a suitable stage to give the correct discharge pressure at maximum water output. This ensures optimum operating efficiency. At the same time the stages of the pump above the discharge port maintain the required pressure for the ejector, even when the discharge pressure falls too zero when the consumption is momentarily larger than the well capacity.

Grundfos have developed this ejector system and the present range of pumps and ejectors have evolved from many years experienced under varying conditions ranging from the far North of Scandinavia to the far South of Australia.

The ejector body is made of bronze and fitted with a wear-resistant stainless steel nozzle, which is protected against blockage by the strainer E. The built-in foot valve has a cone of stainless steel, seating on rubber and the strainer is made of bronze.

The wide range of Grundfos centrifugal pumps, ejector pumps and submersible pumps are still being enlarged and improved and on the basis of extensive research are THE RIGHT PUMPS for water supply.

Figure II-31- Example of a Jet Pump (Sawa & Fenken, 2001)

II.3.3. Positive displacement pumps

Positive Displacement Pumps are any mechanism that seals water in a chamber, then forces it out by reducing the volume of the chamber such as: piston (including jack), diaphragm, rotary vane. Used for low volume and high lift. Contrast with Centrifugal (Kay & Hatcho, 1992).

II.3.4. Manual pumps

For all practical purposes, water is incompressible. Consequently, if a close-fitting piston is drawn through a pipe full of water it will displace water along the pipe (Figure II-32). Similarly, raising a piston in a submerged pipe will draw water up behind it to fill the vacuum that is created, and water is actually displaced by atmospheric pressure on its external surface. Two examples of manual pumps employing these principles are described below.

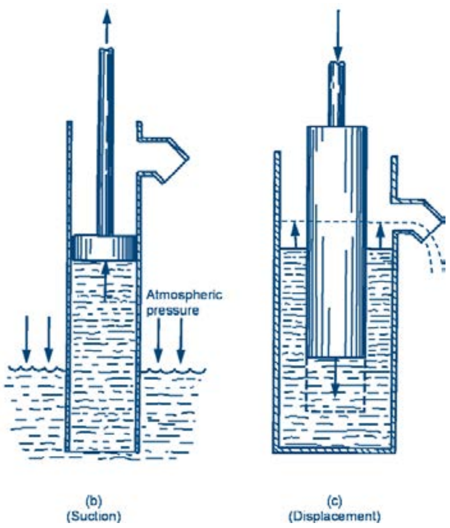


Figure II-32- Basic principles of positive displacement pumps

Piston or bucket pumps

The most common and well-known form of displacement pump is the piston pump, also known as the bucket, hand or bush pump. A common example is illustrated in Figure II-33. Water is sucked into the cylinder through an inlet check valve or non-return valve on the upstroke, which is opened by the vacuum created. This vacuum also keeps the piston valve closed. On the down stroke, the check valve is held closed by both its weight and the water pressure. As this happens the piston valve is forced open as the trapped water is displaced through the piston ready for the next upstroke.

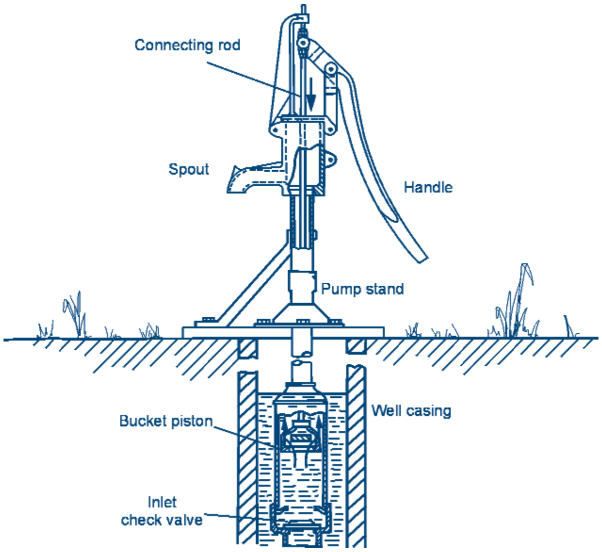


Figure II-33- Hand pump with single acting bucket and piston

The piston valve has two leather cup washer seals. The outer casing and fittings are normally cast iron. While this pump is widely used in Zimbabwe for domestic water supplies, it is also used to irrigate gardens, but to a limited extent. These pumps have wide operating head ranges of 2 to 100 m depending on construction of the pump. Discharges of 15 to 25 m3/hr or 4 to 7 l/s could be realized.

Treadle pumps

A treadle pump is another form of a positive displacement pump where the feet are used to treadle. Most treadle pumps are double acting, meaning that there is discharge on both the upstroke and downstroke. Figure II-34 shows a typical double acting pressure treadle pump. Tests carried out at the Zimbabwe Irrigation Technology Centre (ZITC) revealed that suction heads exceeding 3 m make the pump quite difficult to operate. In a similar argument, delivery heads in excess of 6 m are also not recommended. This shows that treadle pumps can only be used where there are shallow water tables. In semi arid regions, their use could be confined to vleis or dambos, where the water tables are shallow, or to draw water from dams or rivers. Table II-4 shows results of the tests carried out at ZITC on a pressure treadle pump.

Table II-IV- Pressure treadle pump test analysis

Total Dynamic Head (m) (= suction head + delivery head)	**Discharge (m3/hr)**
3.5	6.9
5.0	4.9
6.0	3.7

Other models of treadle pump, based on the same principles but delivering water without pressure, have been used extensively in the Indian Sub-continent, as typified by Figure II-35, and have recently been introduced in eastern and southern Africa. These types of treadle pump are also composed of two cylinders and two plungers. The pumped water, instead of being delivered at the lower part of the pump through a valve box, is delivered at the top through a small channel. Figure II-35 gives the details.

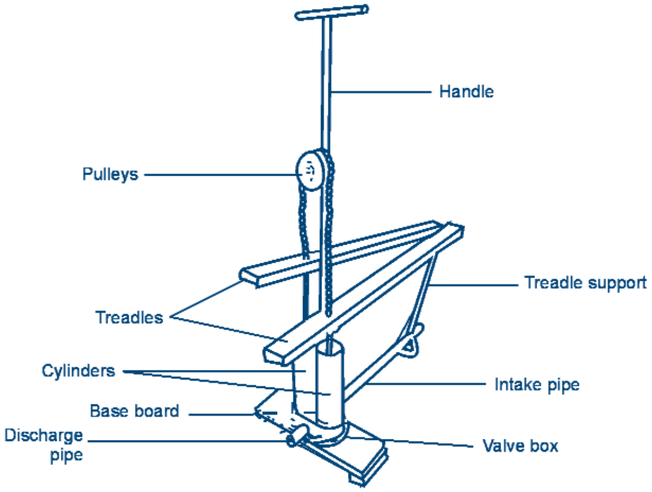


Figure II-34- Double acting pressure treadle pump

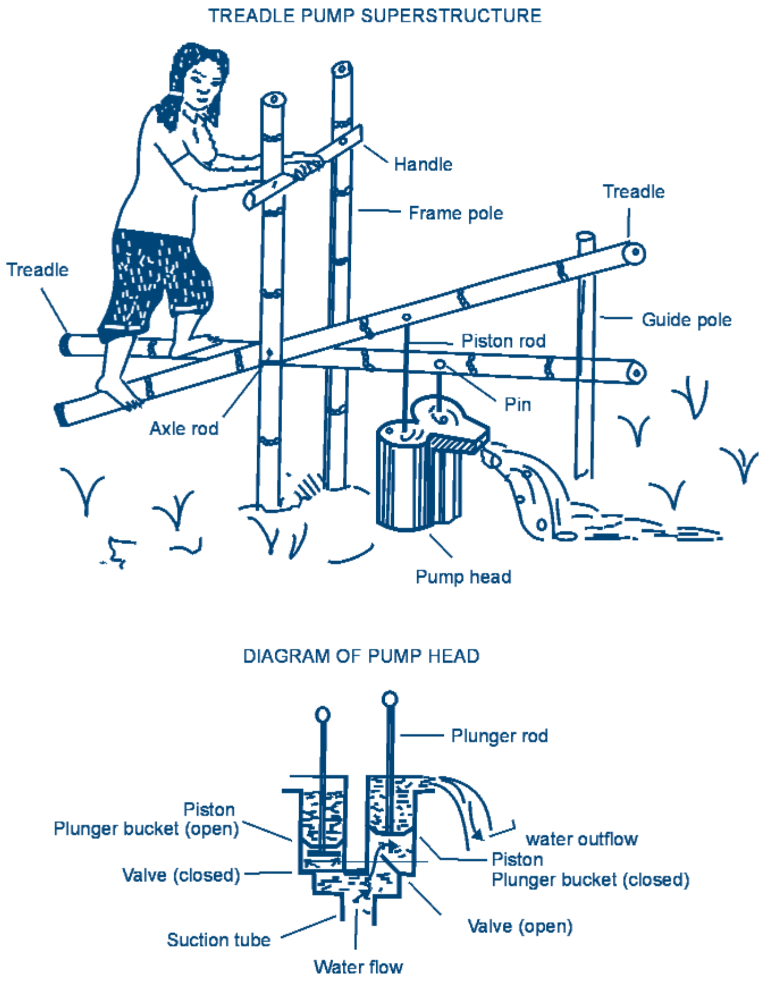


Figure II-35 Double acting non-pressure treadle pump

Rope pump

The Rope pump consists of a wheel and an endless rope with small pistons, made of polyethylene (or car tire in home made models) that are attached to the rope at intervals of 1 meter. The pistons fit, with a clearance of around 1 mm, in the PVC pipe called ‘rising main’. The rope and pistons move freely (and not in a pipe) down into the well. At the bottom, the rope is led by a guide box into the rising main. The wheel and handle are mounted on a support structure on top of the well (Figure II-36).

The rope and pistons are lifted by the wheel. The water is brought up by the pistons and discharged at the surface. When an additional wheel is added it can even be higher than ground level. Rope pumps can be used on open hand dug wells or boreholes with a diameter as small as a 3 inch (75 mm). (de Jongh & Rijs, 1999)

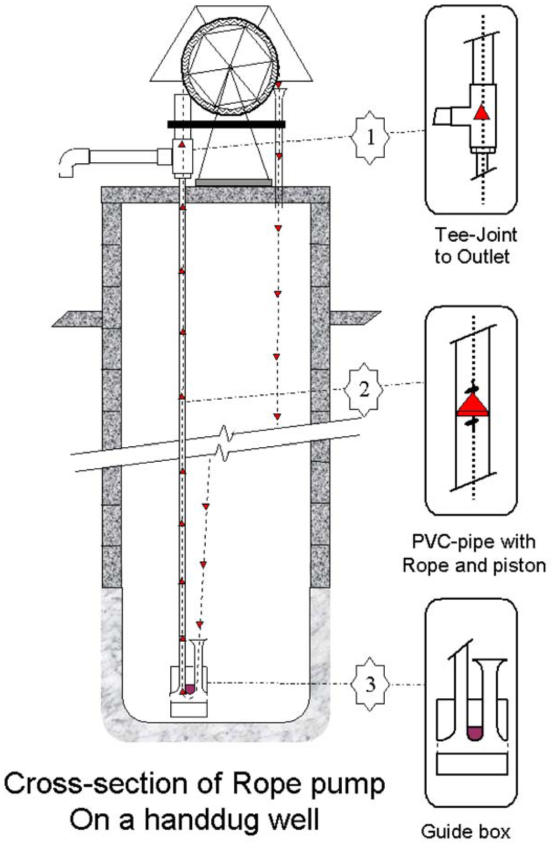


Figure II-36 Schematics of a typical rope pump (de Jongh & Rijs, 1999)

Table II-5 shows results of the tests carried out at Bomba de Mecate S.A. in Nicaragua on a pressure treadle pump.

Table II-V- Pumping Capacity of the rope pump according to depth (de Jongh & Rijs, 1999):

Depth(meters)	Adult(Liters per minute)	Child(Liters per minute)
5	70	39
10	41	19
15	27	13
20	20	10
25	16	8
30	14	6,5
35	12	5,5
40	10	4,8

The pumping capacity indicated in the table is based on operation under normal conditions. Even for children it is easy to fill a bucket thanks to the high efficiency of the pump. This is an important requirement to obtain the social acceptance of the rope pump (de Jongh & Rijs, 1999).

II.3.5. Motorized pumps

II.3.5.1. Diaphragm pumps

Diaphragm Pumps are a motorized positive displacement pump in which water is drawn in and forced out of one or more chambers, by a flexible diaphragm. Check valves let water into and out of each chamber. The diaphragm, pulled upwards by the movements of a piston or a handle causes a partial vacuum, opening the inlet port and closing the outlet, drawing in liquid (Figure II-37-a). Downward movement of the diaphragm pressurizes the liquid, closing the inlet valve and opening the outlet valve through which liquid is expelled by pressure (Figure II-37-b). (Jabsco, undated)

Figures II-38-a shows the components of a typical superficial diaphragm pump and Figure II-39-b shows a cross section of a typical submersible diaphragm pump.

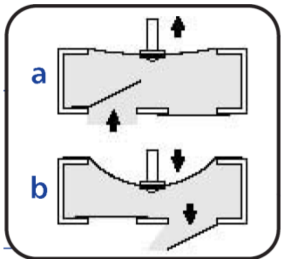


Figure II-37How a diaphragm pump works (Jabsco, undated)

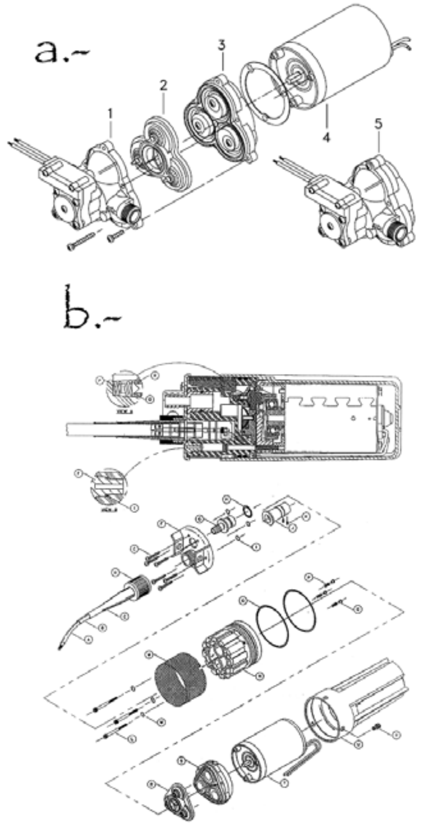


Figure II-38- Schematic diagram of a diaphragm superficial (a) and submersible (b) pump (Jabsco, undated)

II.3.5.2. Mono pumps (Helical)

Mono pumps are motorized positive displacement pumps. Water is displaced by means of a screw type rotor that moves through the stator. As mono pumps fall in the positive displacement category the head is independent to the speed. However, the flow is about proportional to the speed. Figure II-39 shows the individual components of a mono pump (helical).

Due to the material used there is an interference fit between rotor and stator. This close contact with the absence of valves or ports makes a very effective air exhauster as long as a lubricating film of water is present the pump will be able to self prime. Mono borehole pumps have a steady flow characteristic. Due to the line of seal which is a curve of constant shape moving through the stator at a constant axial velocity the rate of displacement is uniform and steady without any pulsation, churning or agitation and this makes this pump a very efficient mechanism. As the mono unity consists of a fixed stator with a single rotating element it is an extremely simple mechanism. Although the Mono Pump is constructed on very robust lines the simplicity of its pumping principle and the absence of valves or gears makes a very compact and light weight unit. These pumps are suitable to be electric motor or engine driven. (Sawa & Fenken, 2001)

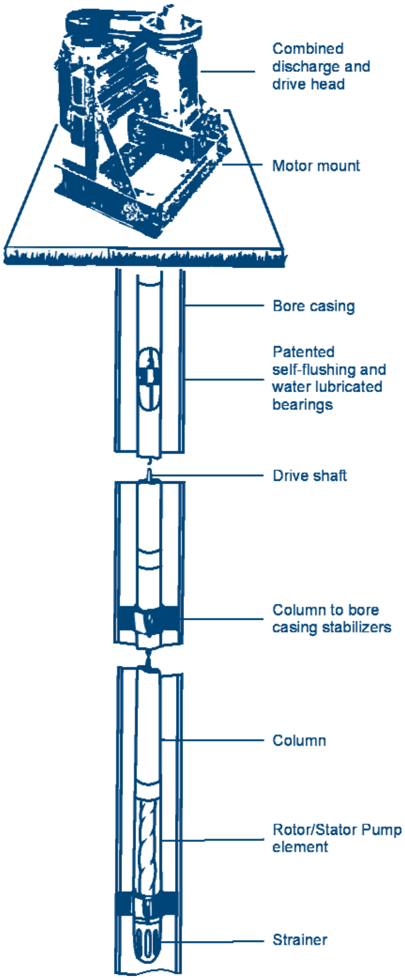


Figure II-39- Schematic diagram of a mono pump unit

II.4.Power units

Most irrigation pumps are powered either with electric motors or diesel engines. In some countries, natural gas, propane, butane and gasoline engines are also used to drive pumps. Wind and solar driven pumps are also used for pumping water, mostly for human and animal purposes.

For centrifugal pumps and turbine pumps up to 20 m deep it is not necessary to compute the energy required to overcome bearing losses in the pump. For turbine pumps that are more than 20 m deep, the manufacturer's literature should be consulted on line shaft bearing losses.

II.4.1. Electric motors

For most centrifugal pumps the motors are directly coupled to the pump. This results in the elimination of belt drives and energy loss due to belt slippage, and safety hazards. Most centrifugal pumps used in Eastern and Southern Africa are coupled to the motor shaft through a flexible coupling.

In the past it was common practice to overload motors by 10-15% above the rated output without encountering problems. However, because of the materials currently used, motors can no longer stand this overloading. Therefore, they should be sized to the needed and projected future output.

For sustained use of a motor at more than 1 100 m altitude or at temperatures above 37°C derating may be necessary. Manufacturer's literature should be consulted for the necessary derating.

Electric motors are very efficient in energy use (75 - 85%) and can be used to drive all sizes and types of pumps. The main drawback is the reliance on a power supply which is beyond the control of the farmer, and which in many places is unreliable. Inevitably electrical power supplies usually fail when they are most needed. Heavy demands occur when crops are needing most water and so a power failure over several days can have disastrous consequences for a crop. When using trickle irrigation on light sandy soils, serious crop losses may well occur after only a few days without power. It is here where solar and wind can be a good reliable alternative depending on these natural resources available for the farm.

II.4.2. Solar photovoltaic

While this chapter will deal solely with solar photovoltaic powered water pumps, it is also worth noting that solar thermal pumps, where the thermal properties of the sun's radiation are used to provide the pumping energy, have been considered to be an alternative to photovoltaics. Indeed, up until the late 1970s, it was expected that this type of pump would be the most likely to reach widespread commercial viability and use. Although substantial effort is still being placed into furthering solar thermal pumping, some of which is being carried out at the Durham Center for Renewable Energy (Short & Oldach, 2003), it is photovoltaic pumping that has become the norm, and it is on this that this chapter will focus.

Given that the need for potable water is often the greatest in areas of high sunlight,, it would seem inherently sensible to consider the use of solar radiation for water pumping. The problem faced by solar powered water pumps is how to convert energy available in the sun's radiation either to kinetic energy of a volume of water (for direct pumping systems) or, perhaps more likely, to gravitational potential energy of a volume of water (for reservoir/tank based systems). Of prime importance, however, is that this conversion should be done in a manner that is sustainable by the local community and is appropriate for the development of that community. Only then can such a technology truly be deemed to be Appropriate Technology.

II.4.2.1. The Effect of Varying Solar Radiation On Output

A major factor in sizing systems is the nature of solar radiation—it changes throughout the day is affected by the weather, and changes from season to season. This variation in input power does not greatly affect systems that are able to deliver water in proportion to the ambient solar intensity: they produce less water when the solar level is low and produce more when the solar level is high. This evens out over time. This variation does affect pumping systems where water output is nonlinear with solar intensity, e.g., the water output does not vary directly with the speed at which the pump operates. The implications for output are complex. In addition, they highlight the importance of properly defining the desired average daily water delivery in the purchase specifications, and requiring a well-defined acceptance test.

II.4.2.2. Solar Photovoltaic pumping (PV)

PV power is produced directly by sunlight shining on an array of PV modules, requires no moving parts, and is extremely simple and reliable. Many materials respond to visible light; the most common is silicon, a constituent of ordinary sand (Thomas, 1996) .

Generally, many individual cells are combined into modules sealed between layers of glass or transparent polymer to protect the electric circuit from the environment (Figure II-40). These modules are capable of producing tens of watts of power. Several modules are then connected in an array to provide enough power to run a motor-pump set in a pumping system. This array is usually mounted on a simple, inexpensive structure oriented toward the sun at an inclination angle close to the latitude of the site. This ensures that ample energy from the sun will shine on the array during all seasons of the year.

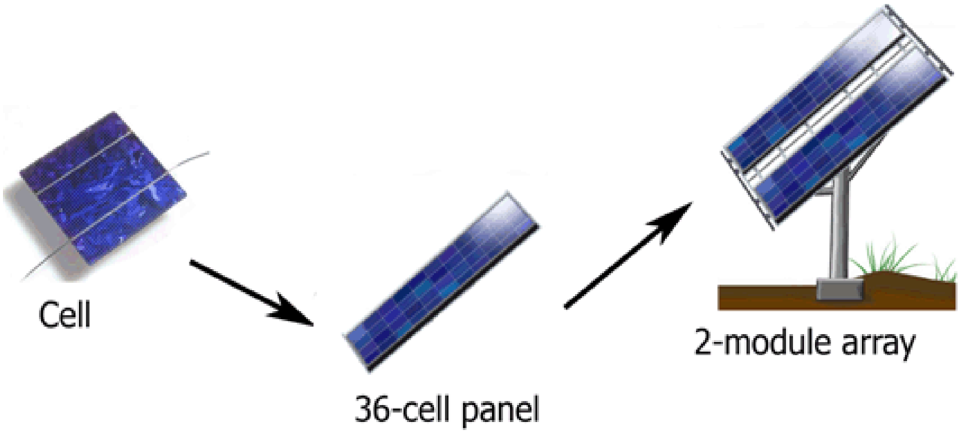


Figure II-40- PV DC electric generator (adapted from (Thomas, 1996))

A PV-powered water system is basically similar to any other water system (Figure II-41). All PV-powered pumping systems have, as a minimum, a PV array, a motor, and a pump. The array can be coupled directly to a direct current (DC) motor or, through an inverter, to an alternate current (AC) motor. For both ac and dc systems a battery bank can be used to store energy or the water can be stored. The motor is connected to any one of a variety of variable-speed pumps.

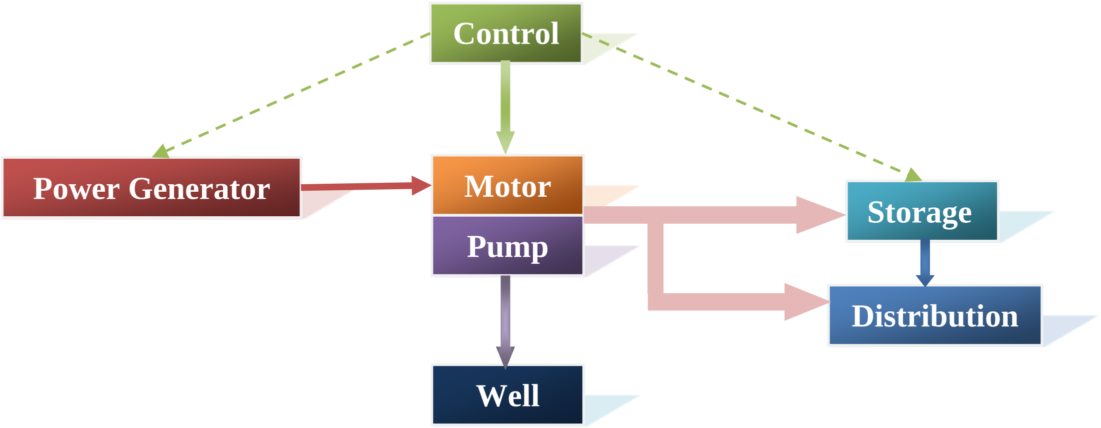


Figure II-41- Block diagram of a PV powered water pumping system (adapted from (Thomas, 1996))

AC vs. DC motors for photovoltaic pumping

The choice of the motor for a PV-powered system is dependent on the size requirement, need for the motor to be submersible or not, and availability of driving electronics. Three basic types are permanent magnet dc motors (brushed or brushless type), wound-field dc motors, and AC motors. The choice of a dc motor is attractive because PV arrays supply DC power. However, AC motors in conjunction with DC- AC inverters can be used for high-power applications. The criteria for choosing a motor are: efficiency, price, reliability and availability. Generally, the wattage determines the choice of the motor: permanent magnet DC motors under 2,250 watts (3 horsepower), wound-field DC motors for 2,250-7,500 watts (3-10 horsepower), and AC motors above 7,500 watts (10 horsepower). (Thomas, 1996)

Generally, AC motors are limited to high-power applications in PV-powered pumping systems because they require inverters, thereby introducing additional costs and some energy loss. Although AC systems are usually less efficient than DC motors, special improved-efficiency models are now available for PV systems. Since this thesis proposes a design for PV pumping for small farmers, a deeper analysis of PV pumping will be discussed on the methodology chapter.

II.4.3. Wind powered pumps (mechanical and electrical)

II.4.3.1. Mechanical windpumps

Windpumps are mechanical windmills that are used to drive a pump for lifting water. They can supply water for a variety of users, work in remote areas to provide water for livestock and in villages for community water supply. Smaller windpumps are used for low-lift irrigation, drainage and salt production. Large windpumps can supply water for irrigation of cash crops.

II.4.3.2. Characterization of Windpump Types

As seen in the previous section, the windpump family counts three different types of windpumps:

- first generation windpump (also called "American" type windmill)
- second generation windpump
- artisanal windpump

The characteristics of each of these windpump types and the differences between them are summarized in:

Table II-VI- <u>Characteristics of the three classes of windpumps: The"American" windmill, the second generation windpump and the artisanal windpump type</u>

Type	Characteristics	Strong points	Weak points	Cost
American windmill	multi-bladed slow running back-geared	long life highly reliable little maintenance	high weight complicated installation	high
second generation	less rotor blades fast running no gearbox	"easy" production light-weight cost-effective	technology not always proven	moderate
artisanal	simple design local, cheap materials	local production high user involvement low initial costs	short life-time much maintenance high unit water cost	investment: low maintenance: high

II.4.3.3. Wind rope pump

The rope and washer windpump or can be classified as a second-generation, low-cost wind pump. The existing models in Nicaragua indeed are rather “simple” structures compared to conventional wind pump designs. They have a steel rotor and tower and operate a rope pump comparable to the rope handpump described in section II-3.4 (see Figure II-36). The transmission between the rotor shaft and the rope pump consists of two pulleys and a rope. If there is no wind, the pump can be operated by hand.

The mechanics of the rope windpump is easy to understand. A rope pump, similar to a rope handpump but somewhat larger and sturdier, is connected to a wind rotor on top of a tower. The transmission consists of a large rope that turns in a loop over a top (rotor) pulley and a bottom pulley on the pump shaft. If the wind is blowing strong enough, the rotor starts turning and operates the pump (see Figure II-42).

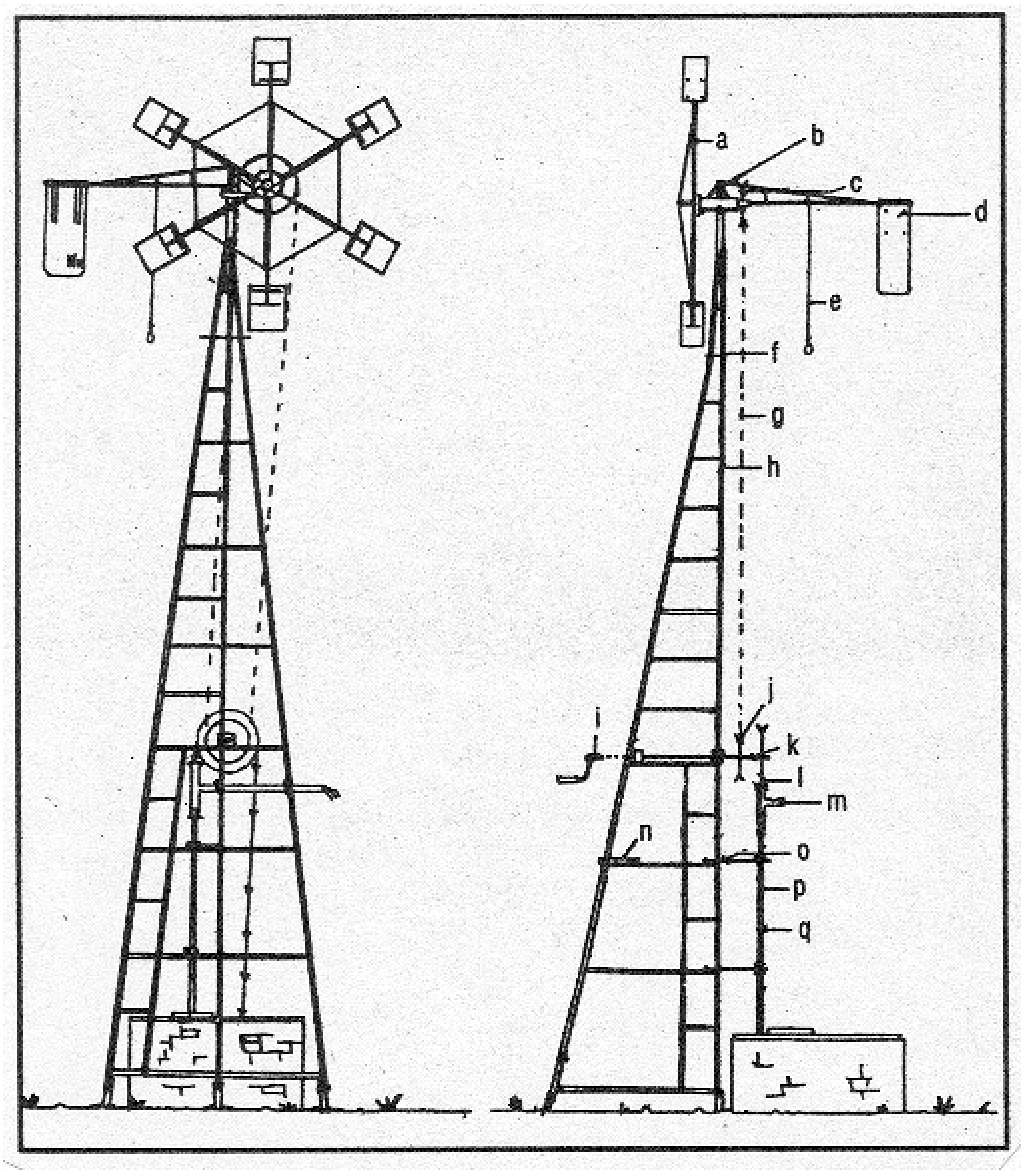


Figure II-42- Layout of the AMEC H-270 rope windpump, based on (de Jongh & Rijs, 1999). Indicated are the following components: the rotor (a); the head assembly and yaw bearing (b); the top pulley (c); the tail vane (d) the control rope (e); the tower (f); the transmission rope (g); the tower (h); the handle for manual pumping (i); the pump shaft transmission pulley (j); the main shaft (k); the pump pulley (l); the pump discharge tube (m)

Table II-7 gives an overview of the different windpump models that are currently produced with this model

Table II-VII- The different windpump models in production by the workshop Aerobombas de Mecateh in Managua (AMEC). The output figures are based upon the documentation provided by the manufacturer, for a wind speed of 5 m/s

DIFFERENT ROPE WINDPUMP MODEL PRODUCED					
	Model				
	H-8 (270)	H-8 (360)	H-10 (270)	H-10 (360)	H-12 (270)
rotor diameter	2.4 m	2.4 m	3 m	3 m	3.6 m
tower height	7 m -	-7m	7 - 10 m	7 - 10m	10 - 13m
maximum lifting height above ground level	2 m	2 m	3.7 m	3.7 m	3.7 m
maximum pumping depth	20 m	20 m	35 m	35 m	45 m
Output at 10 m head	25 l/min	25 l/min	40 l/min	40 l/min	50l/min
pump diameter	*3/4"*	*3/4"*	*1"*	*1"*	*1 1/2"*
Output at 20 m head	12 l/min	12 l/min	20 l/min	20 l/min	25l/min

pump diameter	*1/2"*	*1/2"*	*3/4"*	*3/4"*	*1"*
Output at 30 m head	-	-	12 l/min	12 l/min	16l/min
pump diameter	-	-	*1/2"*	*1/2"*	*3/4"*
Cost ex-factory	US$450	US$480	US$ 700	US$ 750	$780

Locally available, standard materials are used for the construction; assembly can be done by a workshop without the need for sophisticated tools. The design philosophy builds forth on the rope handpump technology and relies on maintenance and repair actions by the user.

In general, the following criteria were applied for the design and implementation of the rope windpump for developing countries:

- low investment cost
- easy maintenance, which is done by the user
- application of a simple but proven pump type
- the use of basic tools and materials available on the local market

II.4.3.4. Wind-electric pumping for farming

Wind turbine technology has been used to pump water since ancient history. Direct mechanically coupled wind turbines are the most common method for pumping water to croplands and livestock. Many more recent wind turbines are electrically coupled, with the water pump connected to the wind turbine via a motor-generator connection. With electrical coupling, the distance and location of the water pump is independent of the location of the wind turbine. Therefore, the wind turbine can be located at an optimal windenergy site while the water pump is close to the water well or water tank (Muljadi & Bergey, 1996). However, for low wind speed sites, the mechanical water pumper still offers more economic water pumping. (USDA, 2007)

In a study the USDA developed a study of wind electric systems for farming in the US, it was found that these systems were free of maintenance for over three years while supplying water from a 280 foot well for 75 beef cattle (USDA, 2007). The USDA considered the findings show that this new wind-electric water pumping system can be as reliable as utility powered systems. Several wind turbine manufacturers used the ARS control logic for their wind-powered water pumping systems.
This study developed a wind-water pumping system to operate in low wind regimes by using a helical positive-displacement type pump. This wind-helical system was able to meet the water demands by pumping water at a slower rate over longer periods of time. In the study it was also determined that wind power usage for irrigation did not match the periods of significant crop water use unless the producer was growing mostly winter wheat. Also a producer needed to be in a location that allowed for net energy billing of the electricity to receive a profitable return for the excess energy generated during the non-irrigation periods. This analysis led to searching for other rural energy users that better matched the available wind resources (USDA, 2007).

II.4.4. Internal combustion engines

Many small irrigation schemes do not have access to electricity and so rely on petrol (spark ignition) engines or diesel (compression ignition) engines to drive the pumps. These engines have a good weight: power output ratio, and are compact in size and relatively cheap due to mass production techniques.

Petrol vs. Diesel

Diesel engines tend to be heavier and more robust than petrol engines and are more expensive to buy. However, they are also more efficient to run and if operated and maintained properly they have a longer working life and are more reliable than petrol. In some countries petrol-driven pumps have needed replacing after only 3 years of operation. Diesel pumps operating in similar conditions could be expected to last at least 6 years. However, it must not be forgotten that engine life is not just measured in years, it is measured in hours of operation and its useful life depends on how well it is operated and serviced. There are cases in developing countries where diesel pumps have been in continual use for 30 years and more. A diesel-engined pump can be up to four times as heavy as a petrol-engined pump of equivalent power, and so if portability is important a petrol pump may be the answer. (Sawa & Fenken, 2001)

II.4.4.1. Diesel engines

As a rule, petrol engines drive very small pumps. For most irrigation conditions, the diesel engine has gained popularity. It is more robust, requires less maintenance and has lower overall operation and maintenance costs.

Most literature on engines uses English units of measurement. To convert kilowatts to horsepower a conversion factor of 1.34 can be applied. Horsepower versus speed curves (Figure II-43) illustrate how output power increases with engine speed. However, there is a particular speed at which the engine efficiency is highest. This is the point at which the selected engine should operate. The continuous rated curve indicates the safest continuous duty at which the engine can be operated. Care should be taken to use the continuous rated output curve and not the intermittent output curve.

Manufacturer's curves are calculated for operating conditions at sea level and below 30°C. It is therefore necessary to derate the engines for different altitudes and temperatures where the operating conditions are different. According to Pair et al. (1983), derating is approximately 1% per 100 m increase in altitude and 1% per 5.6°C increase in air temperature from the published maximum output horsepower curve. On the top of that, an additional 5-10% for reserve should be deducted. If the continuous output curves are used, only the 5-10% deduction is applied.

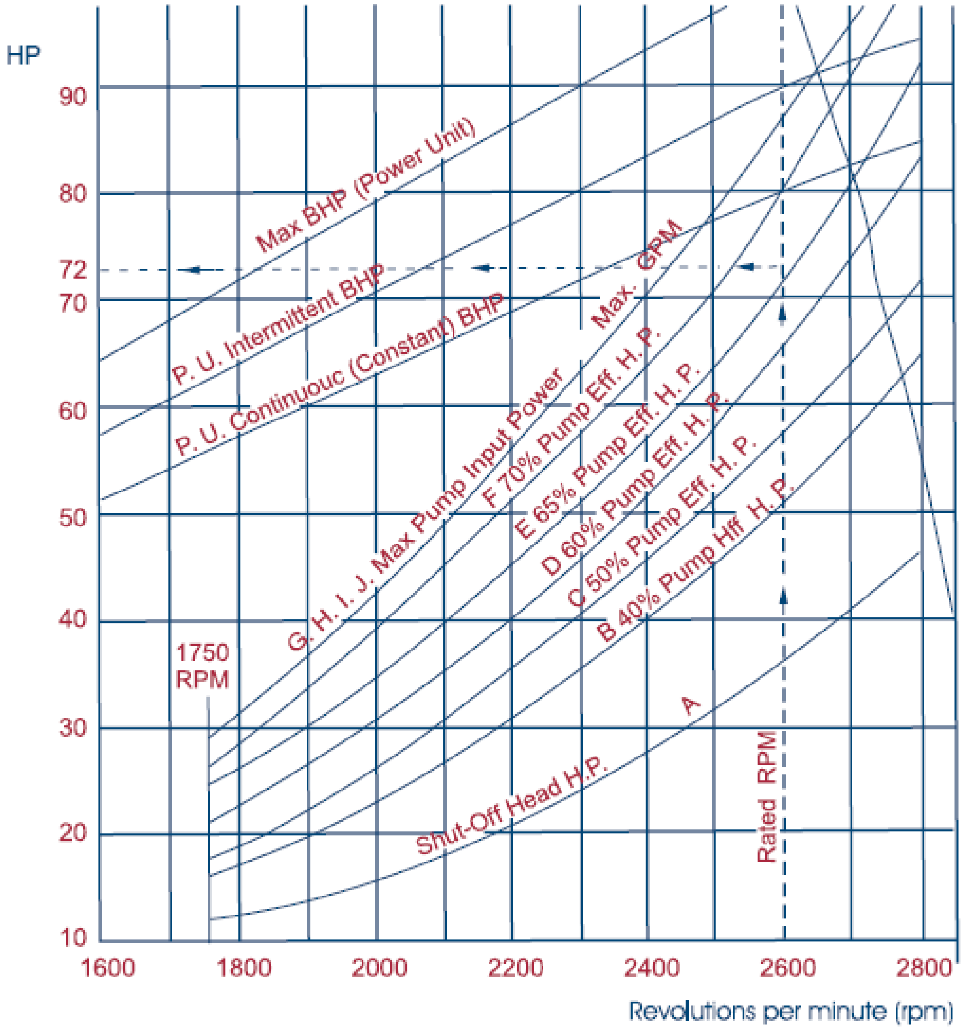


Figure II-43- Rating curves for engine (Sawa & Fenken, 2001)

Tractors can also be used to drive pumps. However, it may not be an economically sound approach to permanently attach a tractor to a pump in view of the high capital cost of a tractor.

III. THE SYSTEM DESIGN, INSTALLATION AND TESTING

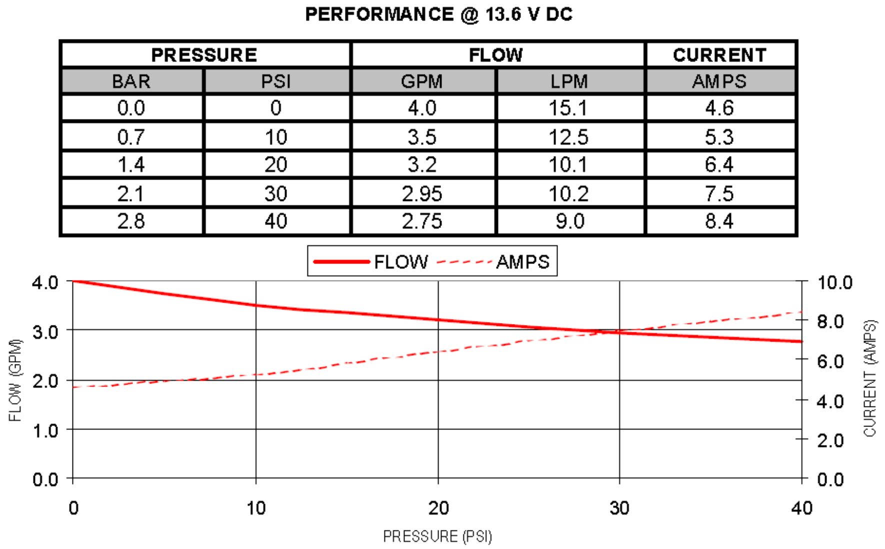
This chapter will describe the methodology used for the system's design, installation and testing. For the system's design the approach used to couple the photovoltaic water pumping with the water requirements of the plant was the FAO Penman- Monteith equation and the stand-alone system sizing procedure.

III.1. Pump selection

The criterion for the pump's selection of the system was low cost to assure affordability on the part of small farmers. Diaphragm pumps have been used in developing countries for water supply to communities, and UML has been using them for the last 4 years in the Culebras Valley, Peru where the prototype system was installed. Since these pumps are the cheapest in the market and are already known in the project's area, these were the two main considerations for diaphragm pump selection, since the users would assimilate easier the technology transfer.

Figure III-1 Shurflo ProBaitmaster 4901-6212

The pump selected was the Shurflo ProBaitmaster model 4901-6212. The disadvantage of these pumps, as discussed in the previous chapter is their durability since the manufacturer recommends replacing the diaphragms every two years (depending on the water quality). To ensure the continuous duty of this model for irrigation and domestic water supply applications, the operation time of the pump has been set to 20 minutes within an hour by means of a timer selected to control the pump's on and off cycle. The pumps are otherwise reliable in our own experience in the Culebras Valley and are used in other parts of the world (personal communication and other references: See section VI.1)



PERFORMANCE @ 13.6 V DC

PRESSURE		FLOW		CURRENT
BAR	PSI	GPM	LPM	AMPS
0.0	0	4.0	15.1	4.6
0.7	10	3.5	12.5	5.3
1.4	20	3.2	10.1	6.4
2.1	30	2.95	10.2	7.5
2.8	40	2.75	9.0	8.4

Figure 2. Shurflo pump performance chart and curves[4]

The irrigation area was designed to match with the daily volume delivered by the pump depending on the solar radiation and operating pressure and flow.

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[4] www.shurflo.com

III.2. FAO Penman-Monteith method

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This so-called combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors (Allen & Pereira, 1998).

The resistance nomenclature distinguishes between aerodynamic resistance and surface resistance factors (Figure III-2). The surface resistance parameters are often combined into one parameter, the ‘bulk’ surface resistance parameter which operates in series with the aerodynamic resistance. The surface resistance, rs, describes the resistance of vapor flow through stomata openings, total leaf area and soil surface. The aerodynamic resistance, ra, describes the resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces. Although the exchange process in a vegetation layer is too complex to be fully described by the two resistance factors, good correlations can be obtained between measured and calculated evapotranspiration rates, especially for a uniform grass reference surface.

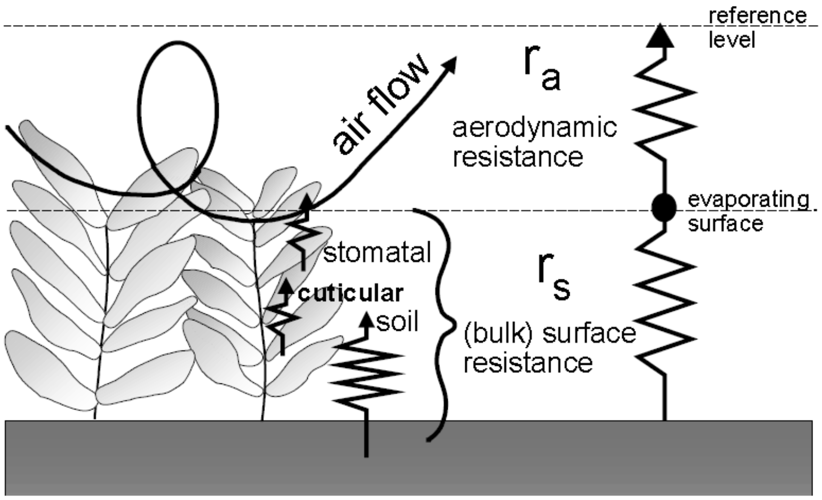


Figure III-3 Simplified representation of the (bulk) surface and aerodynamic resistances for water vapor flow (Allen & Pereira, 1998).

The Penman-Monteith form of the combination equation is (Allen & Pereira, 1998):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad (3)$$

where Rn is the net radiation, G is the soil heat flux, (e_s - e_a) represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.

The Penman-Monteith approach as formulated above includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters are measured or can be readily calculated from weather data. The equation can be utilized for the direct calculation of any crop evapotranspiration as the surface and aerodynamic resistances are crop specific (Allen & Pereira, 1998).

The FAO Expert Consultation on Revision of FAO Methodologies for Crop Water

Requirements accepted the following unambiguous definition for the reference surface (Allen & Pereira, 1998):

"A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m-1 and an albedo of 0.23."

The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The requirements that the grass surface should be extensive and uniform result from the assumption that all fluxes are one-dimensional upwards.

The FAO Penman-Monteith method is selected as the method by which the evapotranspiration of this reference surface (ETo) can be unambiguously determined, and as the method which provides consistent ETo values in all regions and climates.

A consultation of experts and researchers was organized by FAO in May 1990, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO methodologies on crop water requirements and to advise on the revision and update of procedures.

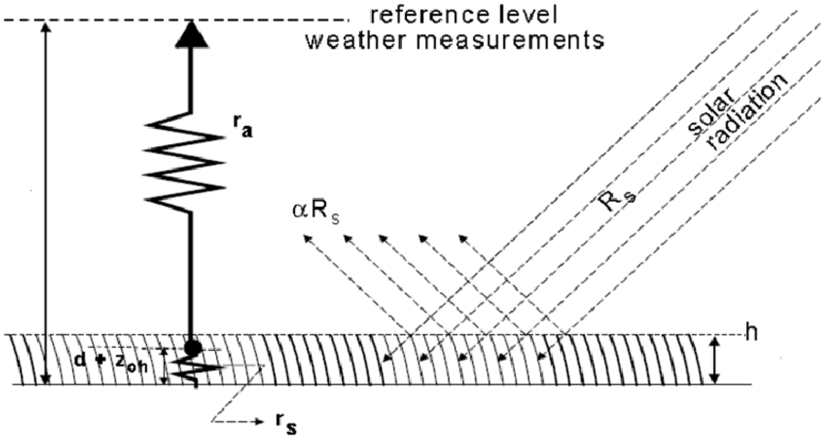


Figure III-4 Characteristics of the hypothetical reference crop

The panel of experts (Allen & Pereira, 1998) recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration and advised on procedures for calculation of the various parameters. By defining the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m-1 and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, the FAO Penman-Monteith method was developed. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide.

The reference evapotranspiration, ETo, provides a standard to which:

- evapotranspiration at different periods of the year or in other regions can be compared;
- evapotranspiration of other crops can be related.

No weather-based evapotranspiration equation can be expected to predict evapotranspiration perfectly under every climatic situation due to simplification in formulation and errors in data measurement. It is probable that precision instruments under excellent environmental and biological management conditions will show the FAO Penman-Monteith equation to deviate at times from true measurements of grass ETo. However, the expert consultation agreed to use the hypothetical reference definition of the FAO Penman-Monteith equation as the definition for grass ETo when deriving and expressing crop coefficients (Allen & Pereira, 1998).

The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. By using the FAO Penman- Monteith definition for ETo, one may calculate crop coefficients at research sites by relating the measured crop evapotranspiration (ETc) with the calculated ETo, i.e., Kc = ETc/ETo. In the crop coefficient approach, differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are accounted for within the crop coefficient. The Kc factor serves as an aggregation of the physical and physiological differences between crops and the reference definition.

III.3. Data

The irradiation data for the design of this project was taken from the UML data acquisition system installed in the community of Raypa, which was the closest weather data available to the project site: Turripampa. Wind data from the data base of RETscreen program for the city of Huarmey was used to have an approximation for the project site. Altitude above sea level (m) and latitude (degrees north or south) of the location should be specified. These data are needed to adjust some weather parameters for the local average value of atmospheric pressure (a function of the site elevation above mean sea level) and to compute extraterrestrial radiation (Ra) and, daylight hours (N). The (average) daily maximum and minimum air temperatures in degrees Celsius (°C) are measured as well at the UML Raypa weather station. The (average) daily actual vapour pressure, ea, in kilopascals (kPa) is required. The actual vapor pressure, was not available for our case; however, it was derived from maximum and minimum relative humidity (%), psychrometric data (dry and wet bulb temperatures in °C). The relative humidity was also derived from empirical equations using the minimum and maximum temperatures.

III.3.1. Radiation, Wind and Temperature

The (average) daily net radiation expressed in megajoules per square meter per day (MJ m^{-2} day^{-1}) is required. These data is derived from the (average) solar (shortwave) radiation measured with a pyranometer. Three years of hourly average global solar radiation data on a horizontal surface (collected with an Apogee Pyr-R pyranometer and stored in a Campbell Scientific CR10 data logger) was treated with the following the procedure from chapter 2.3 of the solar engineering course (22.527).

$$R_n = B_c + \left(\frac{1+\cos\beta}{2}\right) D_h + \rho_g \left(\frac{1-\cos\beta}{2}\right) H_h \qquad (4)$$

Where Rn is the monthly average radiation, Bc is the beam radiation on a tilted surface, β is the slope angle (-9 for PV sizing), Dh is the diffuse irradiation, ρ_g is the (green grass) ground reflectance and Hh is the monthly average global horizontal irradiation.

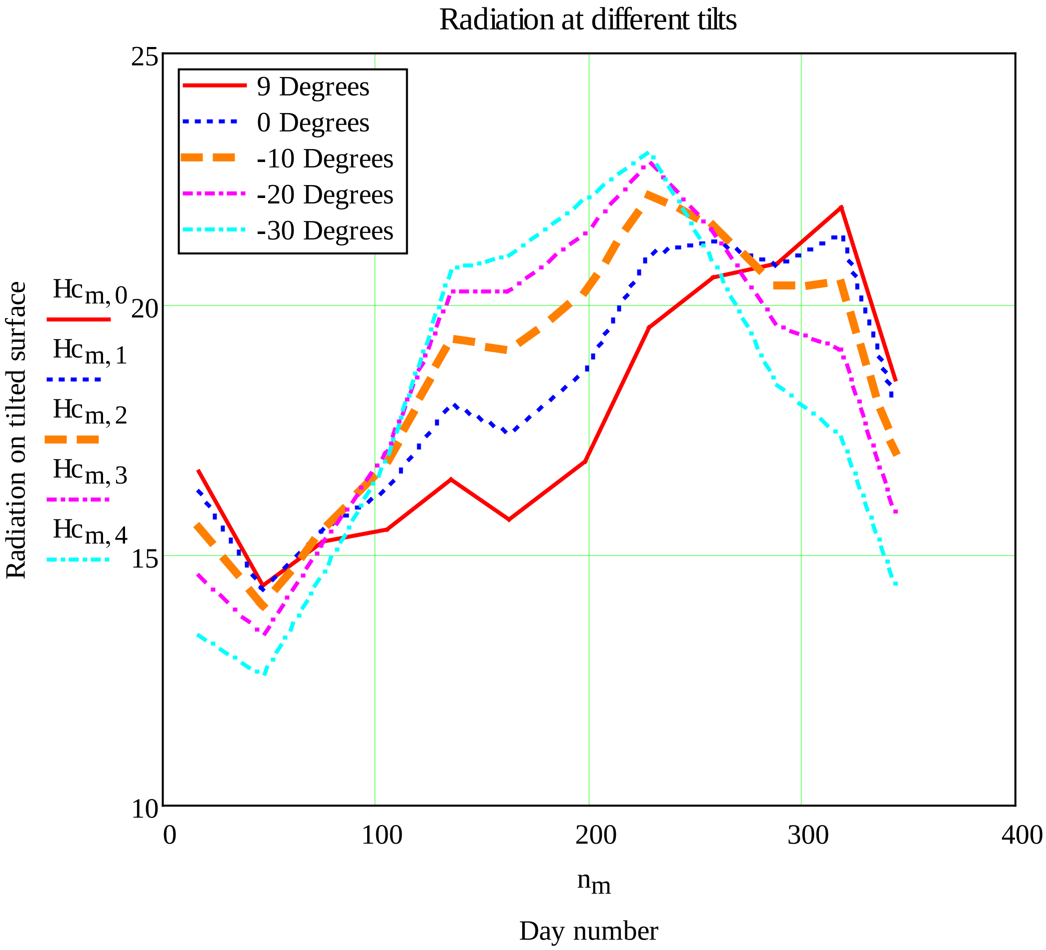


Figure III-5 Average solar radiation with different slopes

Different slopes were used to find the optimal tilt at which the photovoltaic array could be installed. The slope that was considered to be the most optimal regarding the average solar radiation for the PV array was -10 degrees or 10 degrees facing the equator, or north. The monthly average radiation with the slope equals zero degrees was used for the reference crop and crop under adjusted evapotranspiration conditions.

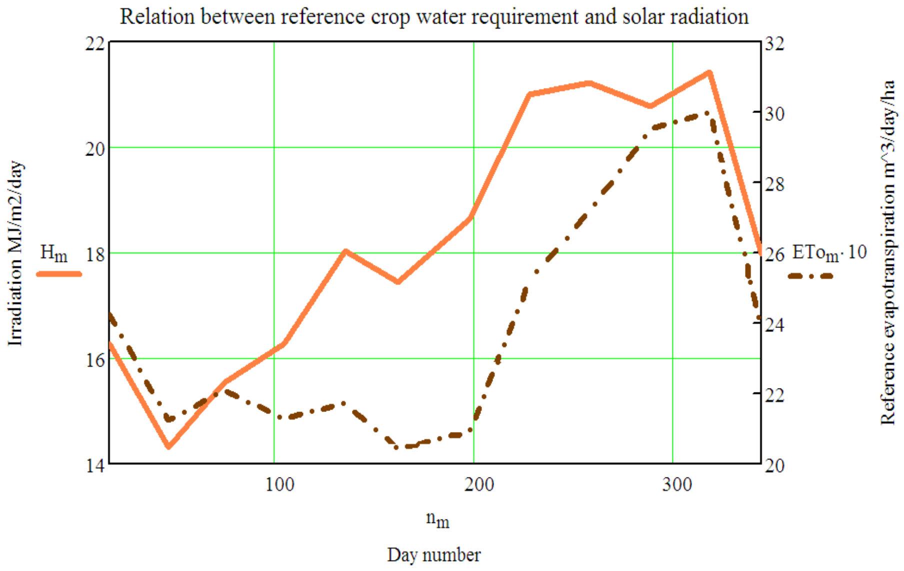


Figure III-6 Relation between water requirements and solar radiation

This graphic shows how the solar radiation is the main parameter governing the Penman-Monteith (equation (3)) and how it affects the water requirements of the plant. Since the photovoltaic technology is proportional to the solar radiation as well, this shows how PV water pumping can be nicely coupled to the irrigation fields.

III.4. Stand alone photovoltaic pumping

The size of the photovoltaic array is determined by considering the available solar radiation, the slope angle and the orientation of the array and the characteristics of the photovoltaic modules being considered. The array is sized to meet the average daily load requirement for the month or season of the year with the lowest ratio of daily radiation to the daily load.

The available radiation affecting a photovoltaic array varies throughout the year and is a function of the slope angle and azimuth orientation of the array. If the load is constant, the designer must consider the time of the year with the minimum amount of sunlight. With the radiation available (at slope) and the power output required, the array can be sized using module specifications supplied by manufacturers.

Since both the plants and the pumping system depend on the radiation for their water consumption and generation respectively, the radiation data is treated the same in both cases. The minimum solar radiation on a tilted surface was selected to size the PV system. The PV pumping was sized using the following formula.

$$Number\ of\ PV\ Modules = \frac{\frac{V_{pump} * I_{pump} * N_{cyc} * T_{cyc}}{\eta_c * \eta_b}}{Rn_{min} * V_{nom} * I_{max}} \qquad (5)$$

Where Vpump and Ipump are the rated voltage and current of the pump respectively at the respective operating pressure, Ncyc and Tcyc are the number and duration of the pump on and off cycles in hours. η_c and η_b are the charge controller and battery efficiencies respectively. Rnmin is the lowest monthly solar radiation. Vnom and Imax are the operating voltage and current of the PV system when connected to the charge controller and battery (Figure III-6).

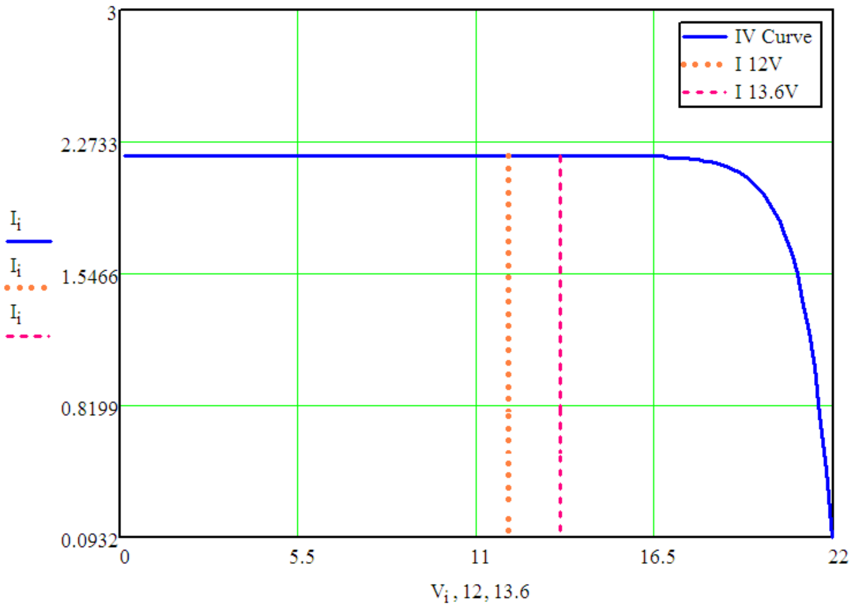


Figure III-7 IV curve for a 12 V of a 50W Panel

In Figure III-7, the graphic shows how the photovoltaic technology as an alternative to water pumping for irrigation could nicely meet the water requirements of the plants since the behavior of the water demand and production is governed by a common factor that is radiation. Note the different units for both reference crop evapotranspiration (mm/day) and photovoltaic power production (Wh/day). This relation is important for decisions that were taken for the system component’s design discussed in the conclusion chapter. Even though not discussed in this thesis it would be important to analyze how the changes in tilt of the PV array will positively affect the water generation related to the crop water requirements. Note the PV module production at different tilts and how they closely relate to the water consumption.

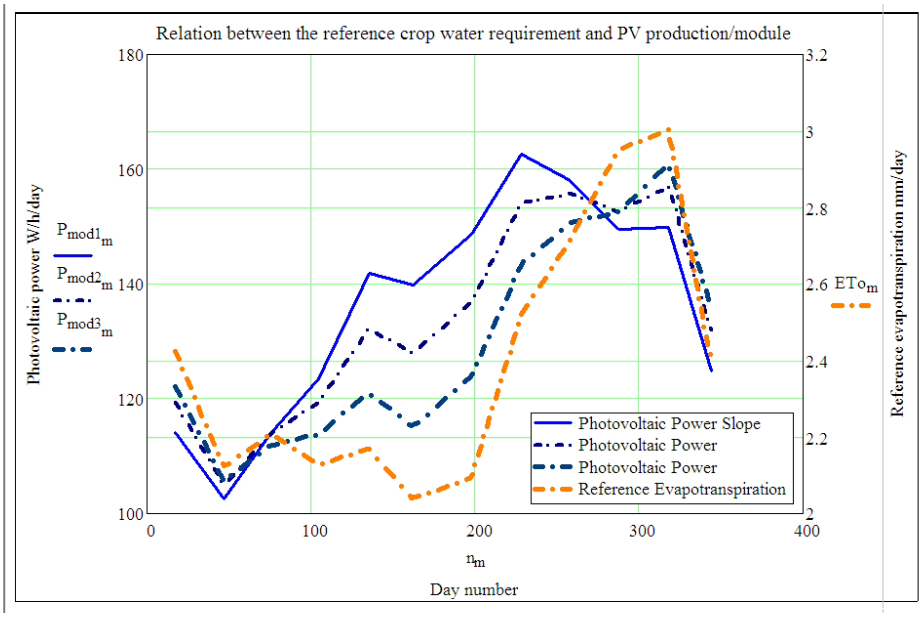


Figure III-8 Relation between PV module production at different slopes and reverence crop water requirement

As a result of equation 5 the system array size is 150 Watts for 12 cycles of 20 minutes each. However, this methodology is designed for a non-variable load. Since both the load (crop water requirement) and generation (PV modules) will increase proportionally to the solar radiation throughout the year; therefore, the numbers of cycles of the pump were increased to reach the highest volume of water that can be pumped in a characteristic day of the month.

III.5. Asparagus evapotranspiration matched with solar drip irrigation

The crop evapotranspiration differs distinctly from the reference evapotranspiration (ETo) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (Kc). In the crop coefficient approach, crop evapotranspiration is calculated by multiplying ETo by Kc.

III.5.1. Crop coefficient approach

In the crop coefficient approach the crop evapotranspiration, ETc, is calculated by multiplying
the reference crop evapotranspiration, ETo, by a crop coefficient, Kc:

$$ET_c = K_c \, ET_o \qquad (6)$$

Where ETc crop evapotranspiration [mm d^{-1}],
Kc crop coefficient [dimensionless],
ETo reference crop evapotranspiration [mm d^{-1}].

Most of the effects of the various weather conditions are incorporated into the ETo estimate. Therefore, as ETo represents an index of climatic demand, Kc varies predominately with the specific crop characteristics and only to a limited extent with climate. This enables the transfer of standard values for Kc between locations and between climates. This has been a primary reason for the global acceptance and usefulness of the crop coefficient approach and the Kc factors developed in past studies. The method recommended by FAO and reviewed by the American Society of Civil Engineers (ASCE) for sprinkler and flooding irrigation is (Allen & Pereira, 1998):

$$ET_c = \frac{K_c\, ET_o}{Ea} \qquad (7)$$

Where Ea is the irrigation water efficiency or the water application efficiency, which is generally 75% for sprinkler and 40% for furrow. Higher efficiencies have been claimed for furrow irrigation, up to 80%; however, for small farmers in developing countries is usually 40% because of the lack of use and knowledge of engineering techniques that could be used to improve the water application.

Drip irrigation is a more controlled watering method with an application efficiency of 85%, and the kadj or adjusted factor can be brought in to the formula as the following :

$$ET_c = \frac{K_c * Kadj * ET_o}{Ea} \qquad (8)$$

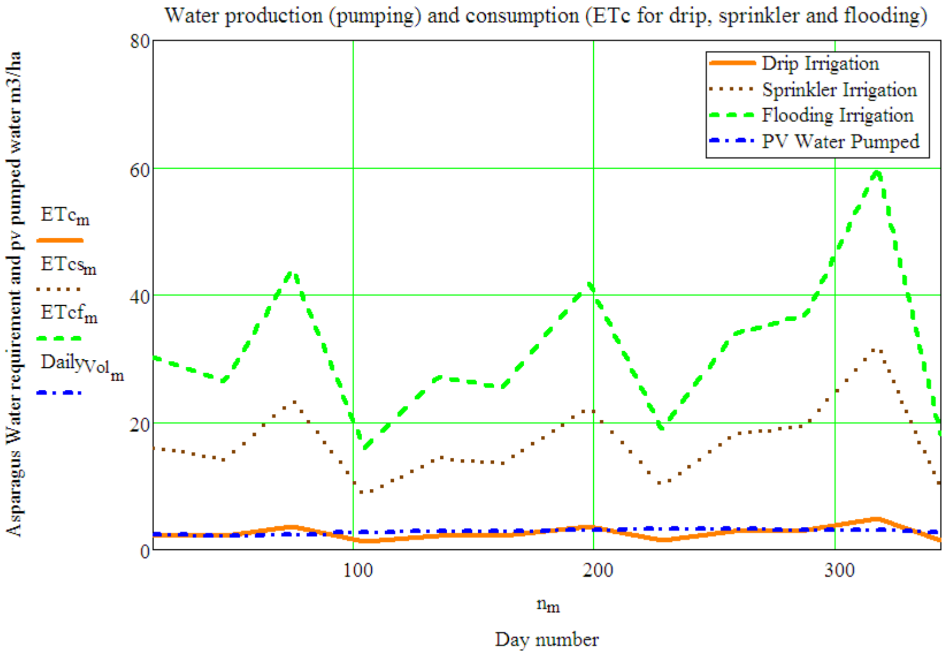


Figure III-9 Water requirements for different irrigation methods .

This figure shows the comparison between the asparagus' water requirement using different drip, furrow, and sprinkler irrigation methods in cubic meters per hectare (note that the FAO Penman Monteith method standardized the water requirement per hectare). Clearly, drip irrigation is the system that could be better matched with the PV pump's daily flow capacity since more plants can be watered per unit area with this method. For this reason drip irrigation was the method selected for the system's installation. The results of the pump capacity per unit area using the different watering methods are summarized in the following table.

Table III-I Watering methods and diaphragm pump capacity

Irrigation method	**PV pump area capacity**
Drip	65,000 m^2
Sprinkler	1,000 m^2
Furrow	526 m^2

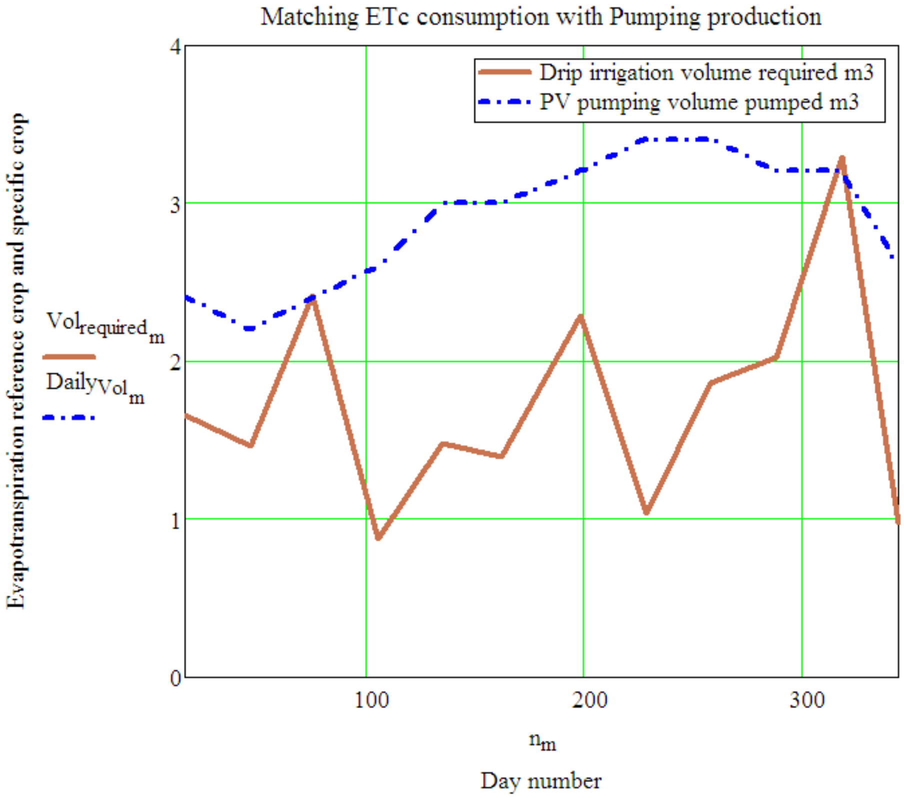


Figure III-10 Matching Asparagus consumption with PV pumping

The asparagus peaks the water requirement during the floration period, and dips the lowest one month right before harvesting. Between those peaks there is a water surplus that could be lowered by reducing the amount of cycles per day of the pump. The benefit of doing this could be to extend the life expectancy of the pump which is 4 years, or the diaphragm parts, which are 2 years. Figure III-10 shows how the water needs can be matched by reducing the pump cycles per day.

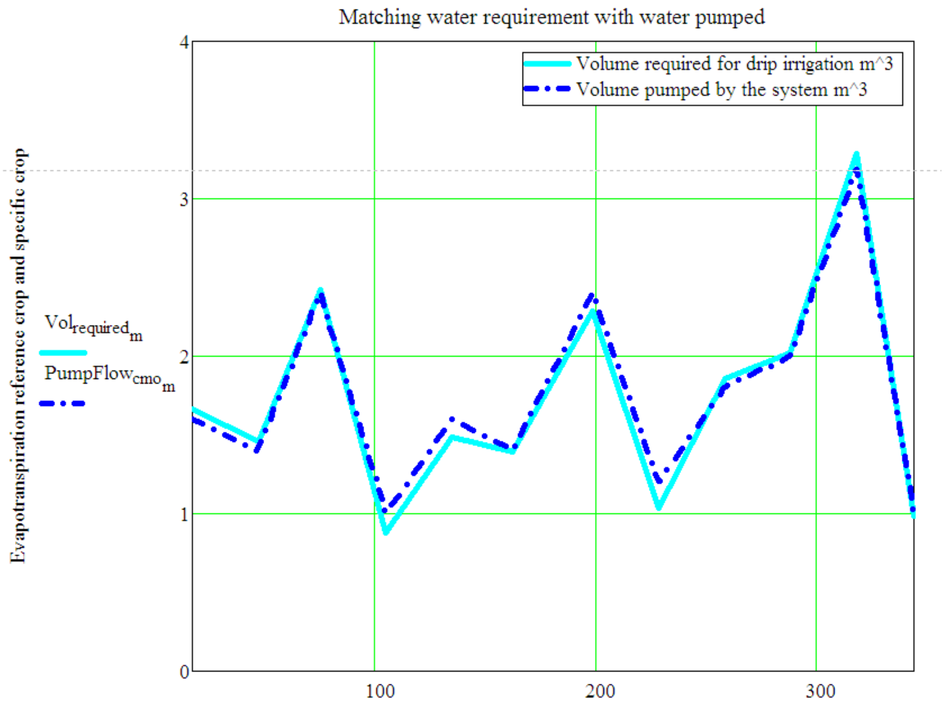


Figure III-11 Reducing the pump's usage according to the water needs

III.6. Water and energy storage

PVXTOOL

PVXtool is an expert system based software that was developed by J. J. Duffy and S. L. Frye (N., 2007). It is a user friendly software designed to size PV water pump systems to meet a constant or variable load demand for a minimum cost and to meet a given loss of load probability (LOLP). Like most software, PVXtool use among other data, total solar energy in kWh/m^2 obtained from monthly average data, load and the time of its occurrence to compute the size PV array required to meet that load with a given LOLP. Should there be nightly load requirement, the program compute the size of the battery required in addition to required PV array size for a minimum cost. The key is that the objective is to minimize the cost of PV system subject to the fulfillment of load, acceptable loss of load and the environment where the load is used. Upon execution of the program, the size of PV array and water storage capacity, the cost of the different components of the system and their minimum costs are obtained and are showed in table III-2.

Table III-II PVXTOOL results

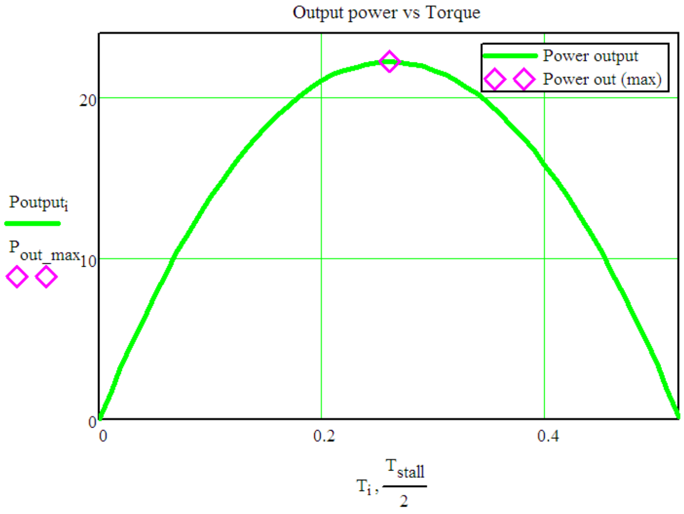
WATER STORAGE OPTION:	
RATED OUTPUT OF PHOTOVOLTAIC ARRAY (Wp):	149
COST OF PHOTOVOLTAIC ARRAY ($):	1198.48
TOTAL STORAGE CAPACITY (m3):	6.7
COST OF STORAGE ($):	670
MINIMIZED COST: PV, STORAGE & WELL ($):	1968.48
ELECTRICAL STORAGE OPTION	
RATED OUTPUT OF PHOTOVOLTAIC ARRAY (Wp):	100
COST OF PHOTOVOLTAIC ARRAY ($):	806.97
ROUND-TRIP STORAGE EFFICIENCY (decimal):	.75
DEPTH OF DISCHARGE (decimal):	.8
TOTAL STORAGE CAPACITY (kW hr):	2.96
COST OF STORAGE ($):	296.52
MINIMIZED COST: PV, STORAGE & WELL ($):	1203.49

The LOLP used was a non critical one (0.05), since the water requirement of the plants are going to be reduced along with lower solar radiation. In other words, the load in this case and the available solar irradiation are very highly correlated, leading to a lower PV system size than would be the case for uncorrelated load and irradiation. The extension of the LOLP method to the case of correlated load and irradiation was begun by (Lee, 1999) and is recommended as for future work in this study.

The selected option was the water storage option with a resulting capacity of $4m^3$, since the costs for electrical and water are not too different. However, the system will still count with 1 battery with 1 day of autonomy of the system. The cost of storage is US$100/m^3. This decision was made taking into account that during the moths the crop water needs are not peaking, this water can be stored to irrigate more area even for another short period (100 days) crop (see Figure III-9) such as beans, tomatoes,etc.

III.7. Mathematical model of the pump

For the modeling of the pump several factors had to be assumed. After contacting the manufacturer Shurflo and asking for the required data for the modeling, the information request was denied. Therefore, we proceeded to assume many of the parameters used. The angular velocity of the motor was taken from the website http://www.kansaswindpower.net/pumps.htm where they show a diaphragm pump similar to the one to be modeled with 1200 rpm. The input power required for the pump was 49.3 W and the peak output power 22.3 W with an efficiency of 45%. The mathematical model used was taken from the Solar Systems Course notes.



III.8. The system’s components and installation

This section will describe the components and criteria for the selected for the system. Except for the pump which was been explained in the section III.1, also refer to section II.3.5.1. for more detailed description of the diaphragm pumps.

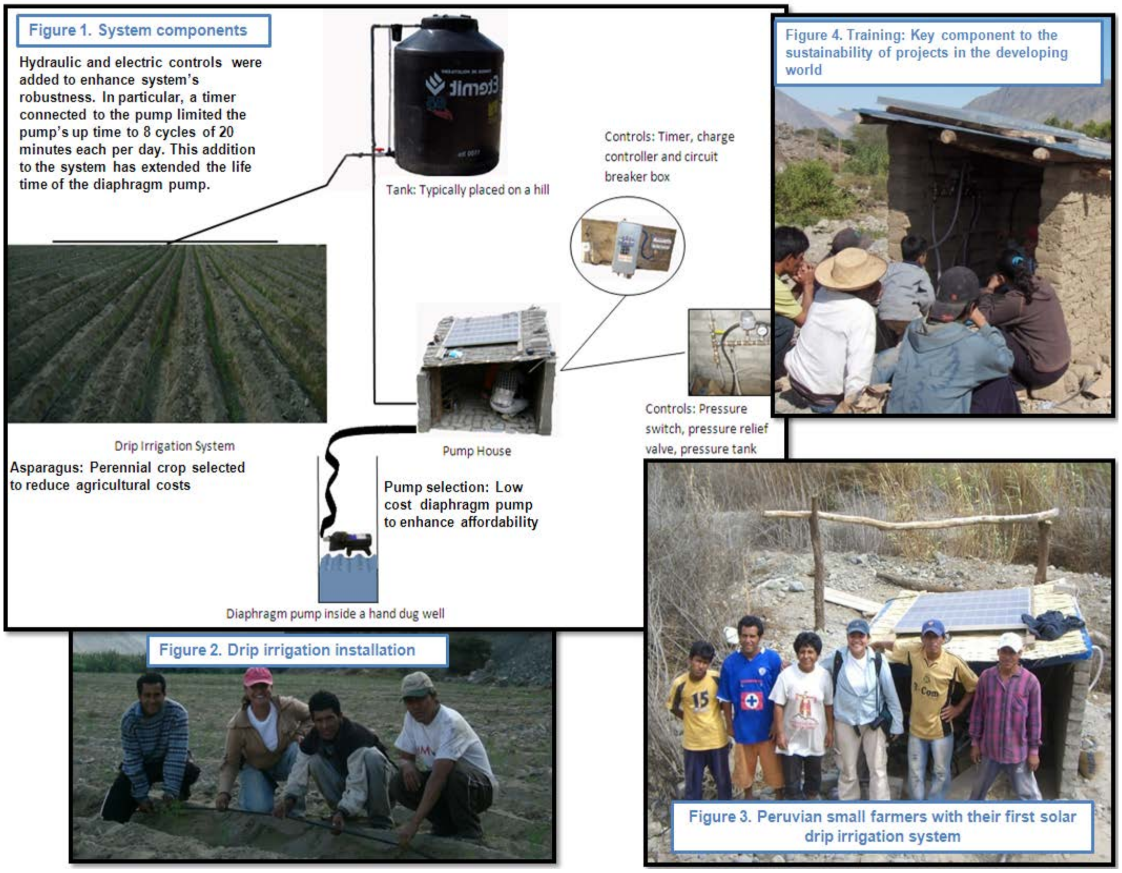


Figure III-12 System’s components in installation

III.8.1. System Controls

Even though most of the literature recommends to store energy in “form of water” (tank storage) rather than with batteries, for the pump selected this was not possible. Below two recommendations quoted from the installation manual of the pump :

“DUTY CYCLE

> - The pump is rated for “continuous duty” (no ON/OFF cycling), when operated at open flow (less than 10 psi. [7 bar] backpressure).
> - Operating the pump for a “intermittent duty” for more than twenty minutes, within an hour, is not recommended. Rapid cycling (ON/OFF within 2 sec.) should be minimized to ensure long life.**”** [5]

This means that in order to meet these recommendations to prolong the life of the pump it is necessary to use a battery and a timer to ensure the 20 minutes within an hour of use for an intermittent duty because it would be operated at a pressure higher than 10 psi. For this reason the non battery system was not taken into account.

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[5] www.shurflo.com

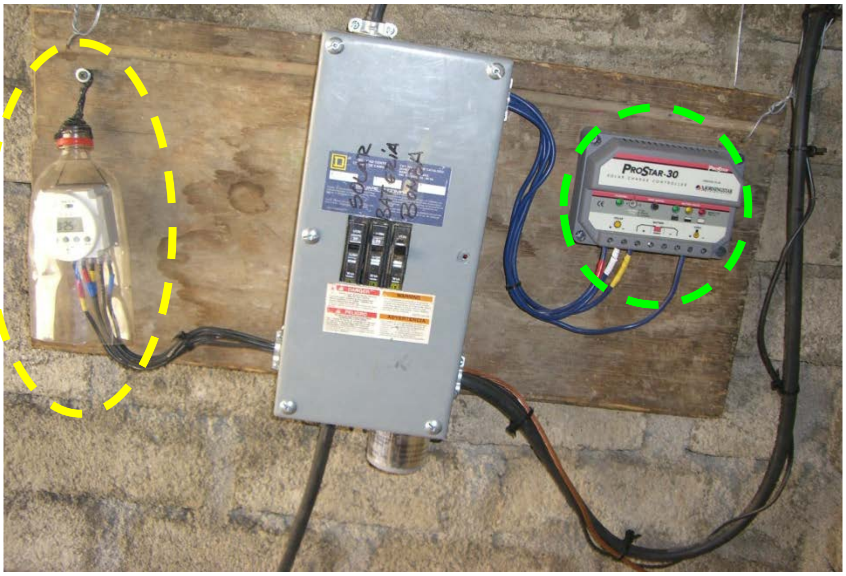


Figure III-13 Timer selected for the system (yellow), Charge controller (green)

III.8.2. Timer (Diehl Control) Series 884

The timer is a digital time switch which provides precise timing with the flexibility of daily and/or weekly programming. This device will allow us to operate the pump 20 minutes each hour for a total of from 5 to 16 hours a day depending on the water requirement.

Table III-III Timer specifications

Number of channels	2
Operating voltage	12V DC
Minimum time setting	1 minute
Number of operations	8 daily on/off (each channel)
Display	24 hr (military or AM/PM)
Rated power	3.5 VA
Switching	SPST - SPDT
Connections	6.3 x 0.8mm tab terminals (complies with DIN 46244)
Switch rating	16 Amps @ 45°C - 10 Amps @ 55°C
Operating temperature range	14°F (-10°C) to 131°F (55°C)

III.8.3. Charge controller

A charge controller is the device in the system that regulates the amount of energy that will charge or discharge the battery avoiding overcharge, deep discharge, and overvoltage in the system . Because of lack of data a 30 amps charger was selected for safety issues. Even though in the calculation the maximum current was 11 A, it was considered some of the experiences from the past in Peru were a charge controller of 15 A was presumably burned by the start up of the motor. There were no 20 A charge controller; therefore, the Pro Star 30 A was selected. See Figure III-13

III.8.4. Pressure switch

A pressure switch was added to the system in addition to the one built in the pump. From previous experiences with this pumps, the Village Empowerment group has found that the built in pressure switches would fail very often, and when this happens the pump can run at pressures higher that their specifications. As a consequence of the pressure switch failure some motors only last a few months. For this reason a separate pressure switch was installed with the pump. The turn on pressure of the switch at 21 PSI and the turn off was set up at 40 PSI, 5 PSI lower than the pump's maximum pressure capacity.

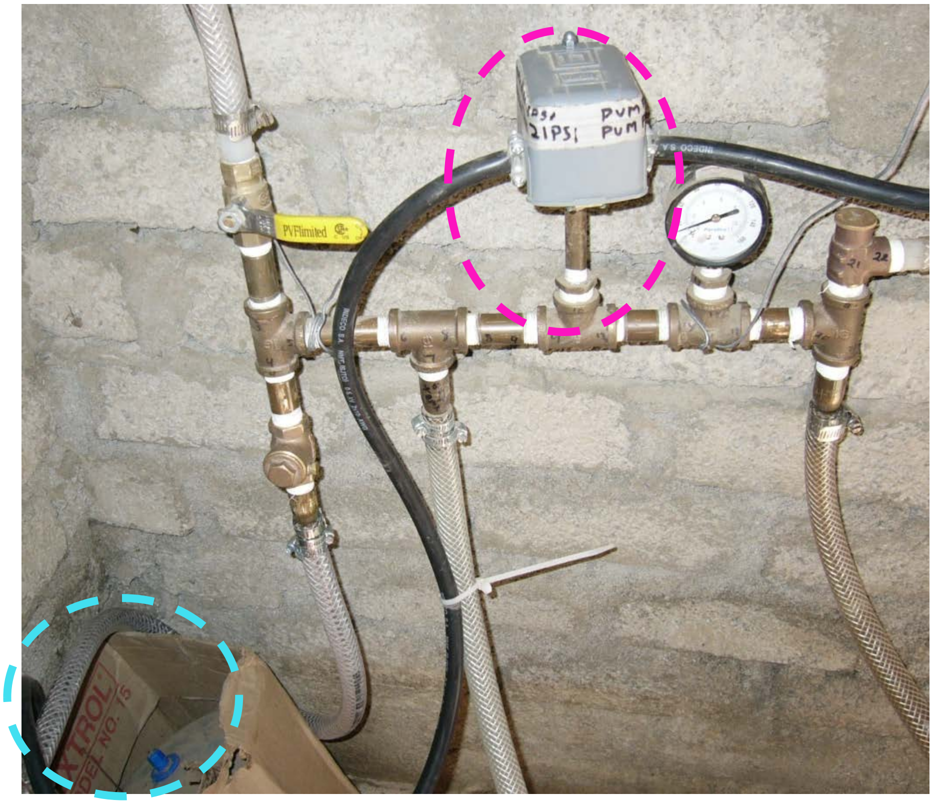


Figure III-14 Pressure switch (pink) and pressure tank (blue)

III.8.5. Pressure tank

A pressure tank was also added to the system as a control component to avoid the early start of the motor when the float valve located at the tank starts to come down when the tank is getting empty. It was observed in previous systems that the pump would start running when the tank would lower a few litters. The pump then would go on and off without a real water demand need, and this quick on an off cycle would lower the life of the motor .The pressure tank was set with 18 PSI.

Figure III-15 Tank float valve

III.8.6. Tank float valve

Another component that will control the system will be the tank's float valve which will close when the tank is full and the closing of the valve will increase pressure on the system which through the pressure switch will turn the pump off.

III.8.7. Number of modules needed

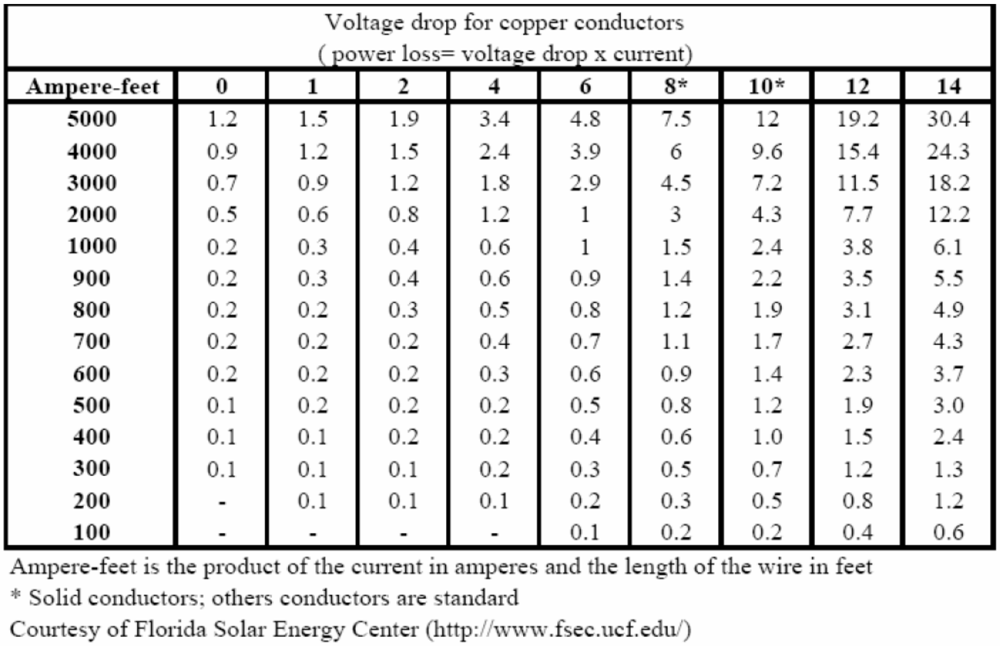
The modules selected, Arco Solar 53-50-47, were donated to the Village Empowerment Inc. among other brands, such as Evergreen Solar. The Arco solar modules' size is very convenient for traveling purposes from both: the US to Peru and Lima to the villages, where the transportation system could only be by foot or donkey. These panels are at least 10 years old, and this is reason to reduce the project economic analysis from 25 to 15 years.

Figure III-16 PV installation in Turripampa

III.8.8. Wiring considerations

For a 30 feet wire length, 15 amps peak, 12 V voltage system and 5% of power loss in the wires, the voltage drop is 0.6 V for 180 ampere feet. Then table III-5 for Voltage drop for cooper conductors is used to get a gauge wire #10. Below the table to size the wiring is a sketch of the wiring diagram of the system, which specifies the color codes.

Table III-IV Voltage drop for copper conductors



Voltage drop for copper conductors
(power loss= voltage drop x current)

Ampere-feet	0	1	2	4	6	8*	10*	12	14
5000	1.2	1.5	1.9	3.4	4.8	7.5	12	19.2	30.4
4000	0.9	1.2	1.5	2.4	3.9	6	9.6	15.4	24.3
3000	0.7	0.9	1.2	1.8	2.9	4.5	7.2	11.5	18.2
2000	0.5	0.6	0.8	1.2	1	3	4.3	7.7	12.2
1000	0.2	0.3	0.4	0.6	1	1.5	2.4	3.8	6.1
900	0.2	0.3	0.4	0.6	0.9	1.4	2.2	3.5	5.5
800	0.2	0.2	0.3	0.5	0.8	1.2	1.9	3.1	4.9
700	0.2	0.2	0.2	0.4	0.7	1.1	1.7	2.7	4.3
600	0.2	0.2	0.2	0.3	0.6	0.9	1.4	2.3	3.7
500	0.1	0.2	0.2	0.2	0.5	0.8	1.2	1.9	3.0
400	0.1	0.1	0.2	0.2	0.4	0.6	1.0	1.5	2.4
300	0.1	0.1	0.1	0.2	0.3	0.5	0.7	1.2	1.3
200	-	0.1	0.1	0.1	0.2	0.3	0.5	0.8	1.2
100	-	-	-	-	0.1	0.2	0.2	0.4	0.6

Ampere-feet is the product of the current in amperes and the length of the wire in feet

* Solid conductors; others conductors are standard

Courtesy of Florida Solar Energy Center (http://www.fsec.ucf.edu/)

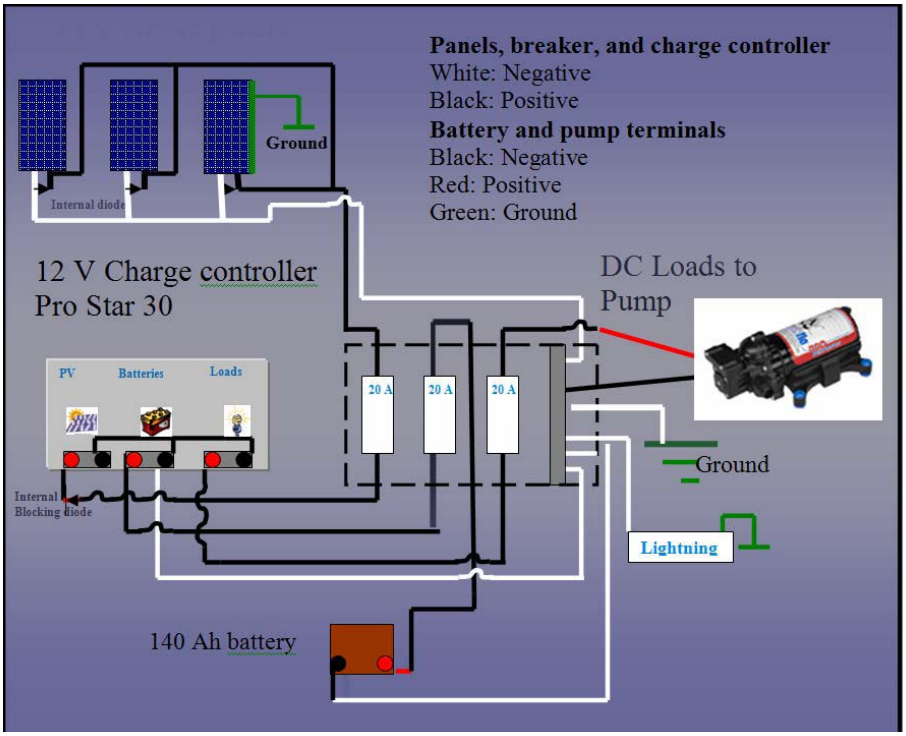


Figure III-17 Sketch of wire diagram

A long wire was left to leave space for the pump to float when the water of the well fluctuates. The well was being dug while the system was being installed (see picture below) and at the present is finalized with cement rings. On June 2008 (last visit to the site) the water level of the well was at the same as the pump house because of a flooding the area suffered from during the rainy season.

Figure III-18 Float pump (Jan 2008)

Figure III-19 Pump house

Figure III-20 Tank installed at 16m of height

III.8.9. Irrigation tape (pipes)

The irrigation system selected was drip irrigation since it was the system that can take a better advantage of the solar water pumping (Figures above). The drip tape found in the Peruvian market was Ro-Drip from John Deere. The only two flow rates for drip irrigation tapes available in Peru where 1 lph and 0.67 lph built in emitters. The recommended distance between emitters for a percentage wet area of 60% (dry climate) is 0.4 cm. However, the only drip irrigation tape available was 0.3cm of spacement within emitters, and this is the one that was selected.

Figure III-21 Ro-Drip irrigation tape

The minimum, maximum and flushing operating pressures of the system are given on the table below from the manufacturer. The system was desing to have the emiters at an operating presure of 10 meters of pressure in order to deliver the designed flow rate 0.67lph, taking in to account the friction losses of the drip irrigation pipes using the christiansen method for the multiple outlets pipes, and the losses due to accessories and connections such as the filter, valves, elbows, etc.

Table III-V Recommended operating pressures

Grade (thinkness)/ Pressure	**5 mil**	**8mil**	**15mil**
Minimum	6 PSI	6 PSI	6 PSI
Maximum	10 PSI	12 PSI	15 PSI
Flushing pressure	12 PSI	15 PSI	25 PSI

Under certain circumstances increased pressure of short duration may help as a flushing method. Increased pressure flushes are to be used infrequently and are not a substitute for regular maintenance.

The figure below show the method to connect the polyethylene drip irrigation tapes to a PVC pipe (sub-mainline).

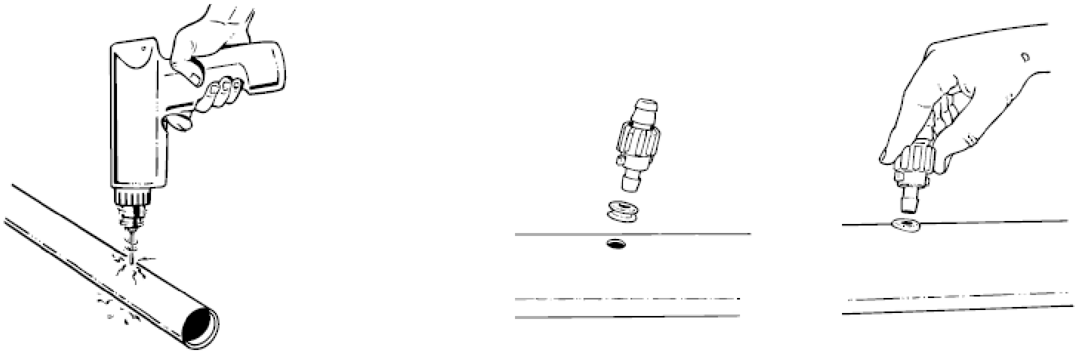


Figure III-22 PE to PVC connectors and seals have to be used to avoid leaks.[6]

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[6] www.johndeere.com

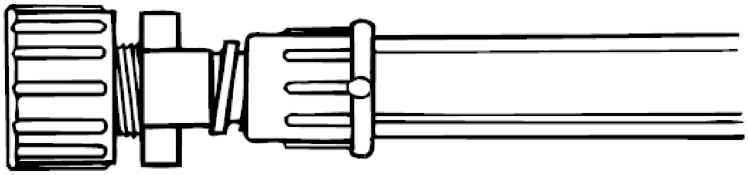

Figure III-23 Tape attached to the PE to PVC connectors

For the design all the considerations were taken for a sandy type of soil which does not have a good water storage capacity. The actual system is using mulching which will reduce the water percolation losses, and depending on the mulching techniques the irrigation frequency (which is 1 day) can be lower than that and the system could be irrigated every 2 to 3 days. This would allow for an incremental increase of the irrigated area.

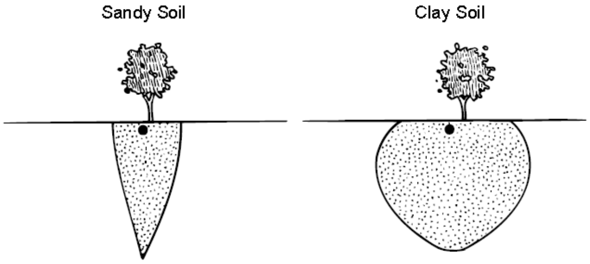

Figure III-24 Water behaviour according to soil type.

IV. ECONOMIC ANALYSIS

The present thesis seeks to propose a productive use of photovoltaic systems where small farmers of developing countries can generate income for their families and to pay back the system.

The feasibility of the solar drip irrigation investment was analyzed by calculating the net present value, internal rate of return and the payback of the system. In addition, three other scenarios of the common practices of small farmers in developing countries were compared to the proposed system.

IV.1. Constraints in small farming financing

Since the prototype system was developed in Peru, research was done on the financial mechanisms for small farmers loans in that country. However, Peru reflects the same constraints that other small farmers in developing countries face. The following is a list of pre-requisites that small farmers have to present in order to have a loan approved from the bank:

- Caja Municipal Paita S.A.: 51.11% (Effective interest anual rate)
    - Property title (original) and topographic drawings

  - Agricultural experience 1 year or 1harvest
  - Proof of being a farmer and have as a minimum 1.5 hectares
  - Watering plan for the harvest

- Caja Sur Créditos y Ahorros: 55%. Most of the requisites same as above except for
  - Water bill
  - Electricity bill

Both the prerequisites and the high interests rates are very difficult to meet by small farmers. With additional searching, there were found a few banks with lower interest rates; however, there was no information on the requisites. Below is explanation of some of the constraints to the proposed requisites for the loan.

IV.1.1. The property of land

It is difficult for small farmers in the Culebras Valley area to come up with this pre-requisites for a loan, given that most of them do not own the land they cultivate. After a land agricultural reform in the 90´s, the law states that farmers that do not live in their land will lose it and thus those farms became government owned. Now these government owned lands are the lands that many of the small farmers in the Culebras Valley are using.

IV.1.2. Water, Electricity and other bills

Peruvian small farmers as other poor farmers in developing countries lack of access to electricity, and even when there is access most of them cannot afford to pay the electricity bill. This has been observed in some of the projects of the Village Empowerment Program where water pumping projects for small communities had been installed and a few years later the towns were interconnected to the grid. Even though theses villagers had grid access they prefer to use the solar pumping systems because cash flows are very small in the area. Access to potable water is a mirror image to the lack of access to electricity. Therefore it is very difficult for farmers to present proof of bills such as water and electricity, and so get approved for their loan request.

IV.1.3. Lack of technological assessment

Unfortunately, most of the small farmers rely on seasonal water for their harvests, and therefore lack of a watering plan that will reduce the yield losses risk because of their exposure to weather fluctuations. This is another requisite that makes them less attractive for investment. Small farmers need technical assessment to improve their yields. With very simple and sustainable practices that wouldn´t require large investment their economical situation would be improved, and this is showed in the economical analysis results.

IV.2. Solar Drip irrigation system payback, IRR, NPV and B/C

Besides the solar drip irrigation cost analysis, three other base scenarios of the common irrigation practices in Peru were analyzed to compare with the proposed system.

The following formulas describe the methodology used:

Cash in: Yearly harvest

Cash out:

$$Mortg = (I\%) * C * \frac{i}{(1 - (1 + i)^{-n}}$$

$Mortg = Mortgage\ payments$ (\$/yr)

$I\% = \ Percentage\ of\ Initial\ Investment$ as the loan

C = total cost of the system (\$)

$i = financed\ interest\ rate$ per year

$n = \ years\ to\ pay\ back\ the\ loan$

Assuming a percentage increase of the maintenance of the system (j)

$$Maint = \frac{Yearly\ maintenance\ cost}{(1 + j)^n}$$

Where j is the inflation rate and n is the year number of the maintenance cost.

With the cash in and cash out was calculated the cumulative costs and incomes to later find the system’s payback.

The solar irrigation income of the system is:

$$Yearly\ solar\ income = Yearly\ harvest - Maintenance - Mortgage$$

Then this result was used to calculate the present worth value of the solar irrigation system to add it or subtract it to the initial investment.

$$PW = \frac{yearly\ solar\ income}{(1 + i_i)^{n_i}}$$

Where $i_i$is the market discount rate and n_i is the number of the year in the project from 1 to 15. With PW was later calculated the NPV, IRR and the cost benefit of the system.

Considerations and assumptions:

The financing interest rate used was 23.5%, which was an average from different banks that would loan US$6,000 for 5 years. This data was taken from the Peruvian Superintendence of Banks website. The interest rate paid for individual savings deposits to the bank is 1%, which was assumed to be the market discount rate. Both the energy costs and agricultural costs and income were taken into account for the system cash flow analysis for the diesel irrigation system for comparison.

IV.2.1. Solar drip irrigation scenario

For the solar drip irrigation design it was considered the cost of the PV modules as their cost in the Peruvian market which is US$8/Wp (without including installation cost). Note that Wp denotes peak Watts which is the power output of the PV module at a solar irradiation incident of 1000 W/m2 (typical of a bright noon day sun) and is the parameter commonly used for cost comparison and energy calculation purposes. For the prototype system that was installed, the price given to the farmers where US$3/Wp since the panels had at least a ten year use, and this system was a student prototype. However, for the results to be more realistic, they should reflect the cost of the PV modules in the developing world. Therefore, the $8/Wp cost was used in this analysis.

IV.2.2. Diesel drip irrigation scenario

For this system the energy consumption of the diesel pump was calculated the following way:

$$Energy\ required = \frac{\left(\left(\Sigma\left(ETC_{Drip}\right)*n_{days}\right)*head\ required\right)}{367*Pump_{efficiency}}\text{ , in kWh}$$

Where the head required is in meters, the evapotranspiration times number of days summation is in cubic meters per hectare and 367 is a conversion factor to kWh.

The energy cost of the diesel system was calculated as follows:

$$Energy\ cost = Energy\ required * fuel\ consumption * fuel\ cost$$

Where the fuel consumption is in liters per kilowatt hour and the amount assumed is 0.5 l/kWh (Kay & Hatcho, 1992). The fuel cost of the diesel was assumed 1.5 dollars per litter which was taken in to account the transportation cost to the rural areas. The actual cost of diesel in Lima is 0.93dollars per liter. This system takes into consideration a pump replacement in year 10.

IV.2.3. Diesel furrow irrigation scenario

The energy requirement for this scenario was similar to the “diesel drip irrigation” scenario with the difference that the water requirements for furrow are higher; therefore the evapotranspiration or ETC of furrow irrigation is used instead. As in the scenario before, the pump will be replaced in year 10. This system was considered since it is the most common used when the user owns a diesel motor. Some assumptions were taken in to account such as that the user will buy a new pump when usually they will buy used refurbished pumps. Another assumption made is that the farmer will buy a 1HP pump which is enough for more than one hectare. However, in reality the farmers will buy 2 to 4 HP pumps since the difference between them is around US$300. Using a over dimensioned pump will reduce the efficiency of the system.

IV.2.4. Gravity fed system

This scenario is based on the assumption that there is a seasonal source supplying the irrigation system. Since the source is seasonal, only one harvest a year is taken into consideration in the income, given that it is required to have water year round for more than one harvest a year.

IV.3. Results of the economic analysis

The following table summarizes the calculations described in this chapter.

Table IV-I Economical analysis

Type of system	Initial investment	NPV	IRR	Payback period (yr)
Solar Drip Irrigation	$5,373.76	$59,151.32	61%	2.5
Diesel Drip Irrigation	$6,108.76	$49,082.55	48%	2.8
Diesel Furrow Irrigation	$5,073.00	$25,867.64	29%	3
Gravity Fed Furrow Irrigation	$2,406.00	$7,531.85	11%	7.5

The system with the highest net present value, IRR and smallest payback period is the solar drip irrigation since the system reduces both operational costs in both labor and fuel and increases yield.

Operational costs are reduced by the drip irrigation system given that fertilization can be made through the drip tape. This will reduce personal to apply fertilizer. Drip irrigation also reduces bad weed grow that could compete for nutrients with the asparagus. The solar drip irrigation system analysis is taking into consideration the replacement of the pump, irrigation tapes and asparagus plants every four years and also the pump's head every 2 years.

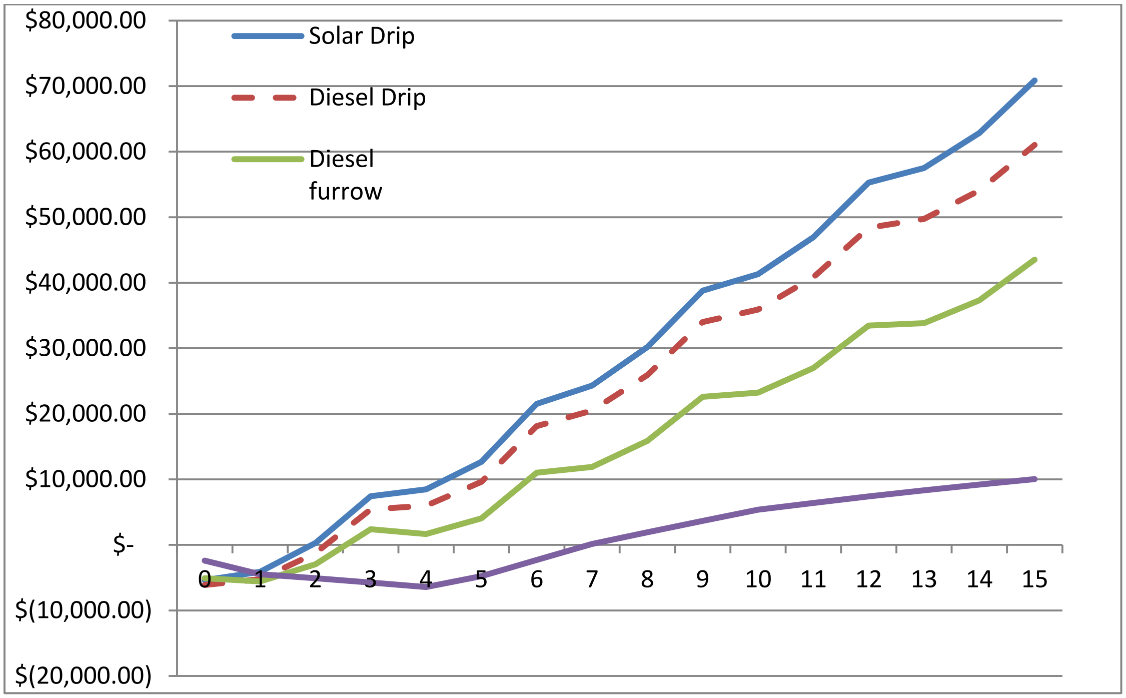

Figure IV-1 Payback analysis with diesel price at 1$/liter and asparagus 0.7$/kg (Cumulative cash flow vs. years)

It is important to notice how the diesel performance increases with an efficient watering delivery. Most of the farmers that already own diesel pumps could increase their yields and reduce their expenses only by changing to a more efficient watering method such as drip irrigation. Even if drip irrigation is not used, by conveying the water in pipes would increase the efficiency. Especially for the asparagus the efficiency of conveyance and delivery is very low since the asparagus needs sandy soil to develop well, and the losses in infiltration and percolation in sandy soils are very high when using furrow irrigation.

It is important to mention that all the systems are being analyzed with the same irrigated area except for the gravity fed system, which is taking in to account that since there is water available one hectare could be watered. Also the there is no replanting asparagus every 4 years because when the plant is being harvested once a year it could last 15 years. Even then, with the lowest punctual reinvestments, and lowest initial investment the gravity fed system has the lower capital recovery since only one harvest can be yielded.

IV.3.1. Oil prices fluctuations

On the following graph the only systems analyzed are the diesel powered systems. The purpose of the graph is to prove how vulnerable the farmers is to oil price fluctuations when using furrow irrigation and how little drip irrigation is affected by it. When the price of diesel reaches 4 $/l the diesel furrow irrigation stops being feasible, both the NPV and IRR are negative.

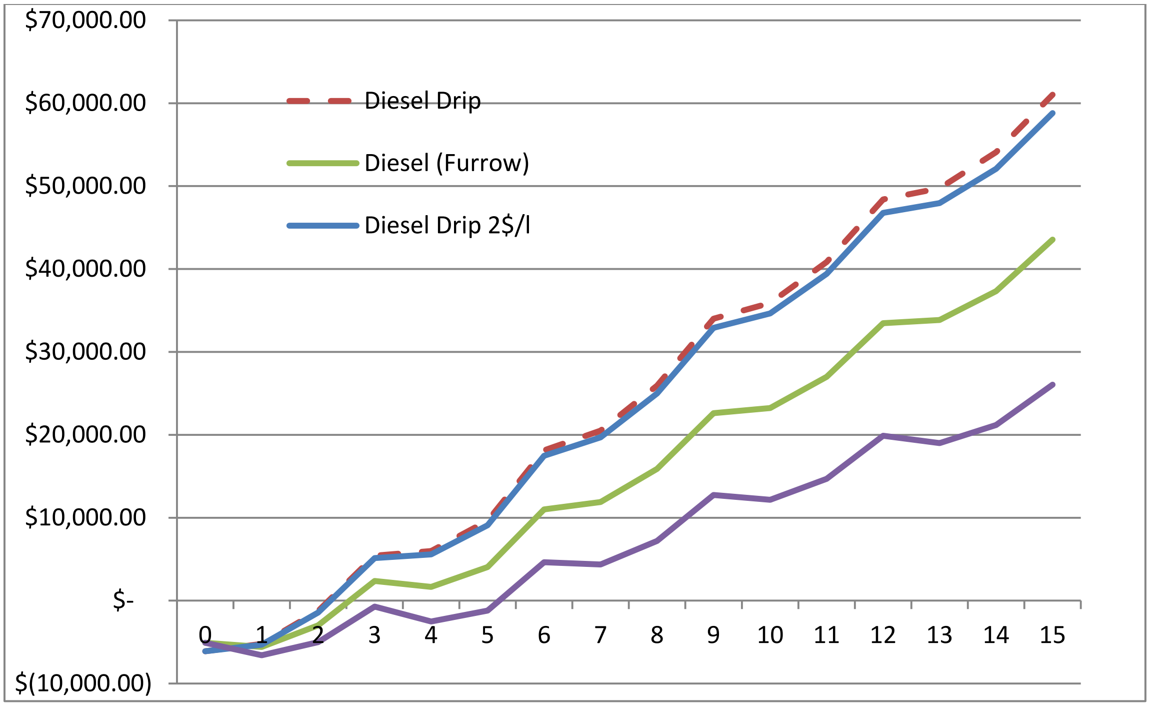

Figure IV-2 Payback analysis with diesel price at 2$/liter and asparagus 0.3$/kg (Cumulative cash flow vs. years)

Another important assumption that has been made is that the wells being used for furrow and drip have the capacity to be exploited for irrigation. However, it is important to notice that the peak water requirement of drip is 3.5m^3/day and for furrow (in sandy soil) is70m^3/day. Most of the wells used by small farmers are hand dug wells and some of them are even seasonal.

IV.3.2. Crop prices fluctuations

This is another graph that shows the weakness of the diesel-furrow irrigation method and how the gravity fed system with only one harvest a year starts to become more feasible.

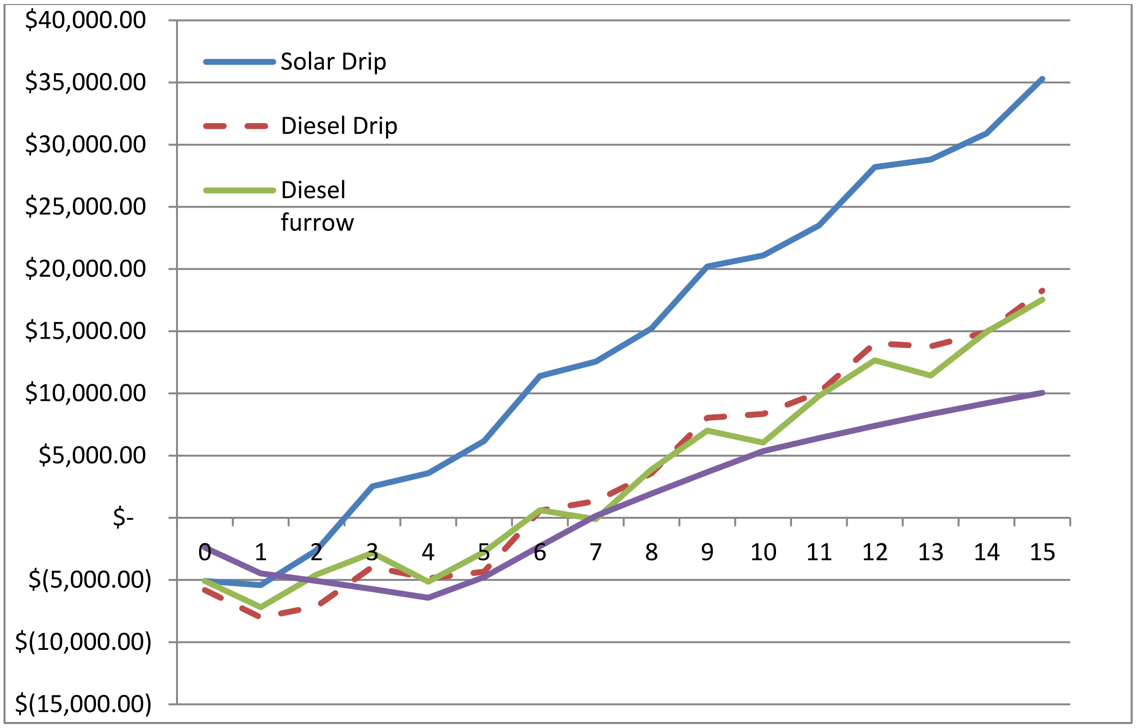

Figure IV-3 Crop price fluctuations asparagus 0.3$/kg and diesel 1$/l (Cumulative cash flow vs. years)

Taking in to consideration the fluctuations of the crop price is important to analyze when at what price the system stops being feasible. The prices of asparagus have been fluctuating since the system was first installed in January, 2008 when the price was a 1$/kg. The lowest recorded was 0.3$/kg in June 2008, with the average between January 2008 to December 2008 0.7$/kg {personal communication}.

IV.4. Turripampa system

Since this system is a prototype, the beneficiaries are not being charged with interest to the Village Empowerment Inc. The purpose of the system is to promote among small farmers in the area a sustainable use of water and energy. The system is already fulfilling its purposes and small farmers in the area, governmental and non-profit agencies are visiting the small plot to see how it works. There are now two formal requests from small farmers of the Culebras valley and one from the Huarmey Valley to install other systems.

Table IV-II. Economical analysis summary for the solar drip irrigation option

Type of system	Initial investment	NPV	IRR	B/C	Payback period (yr)
Solar Drip Irrigation	$5,073.76	$28,851.09	39%	5.6863	2

Village empowerment Inc. financed only 30% of the initial investment of the system, and the 3 siblings working in the plot came up with the rest of the investment.

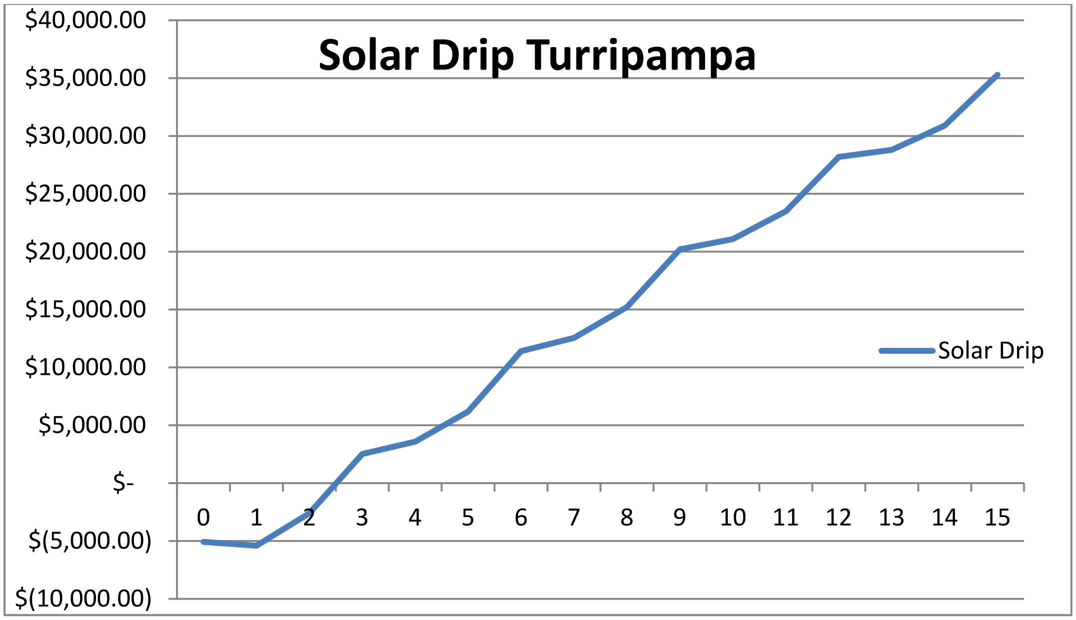

Figure IV-4 Price of Asparagus December, 2008: 0.4$/kg (Cumulative cash flow vs. years)

More data will be collected on this system to compare with these projections with the farmers costs. The actual system lacks of the required water storage capacity; therefore the system is working a third of what it could. The figure above shows the payback period of the particular system of Turripampa, which includes the purchase of more storage capacity to $3m^3$ / day.

V. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

The irrigation system that can take a better advantage of solar water pumping is drip irrigation. The sizing of the system has to take into account the highest water demand of the crop. Water draught resistant crops are a good match with small diaphragm solar water pumping given that the pump’s flow is low and the system that uses less water to get more crop per unit area. The sizing methodology used for small diaphragm pumps in this system is:

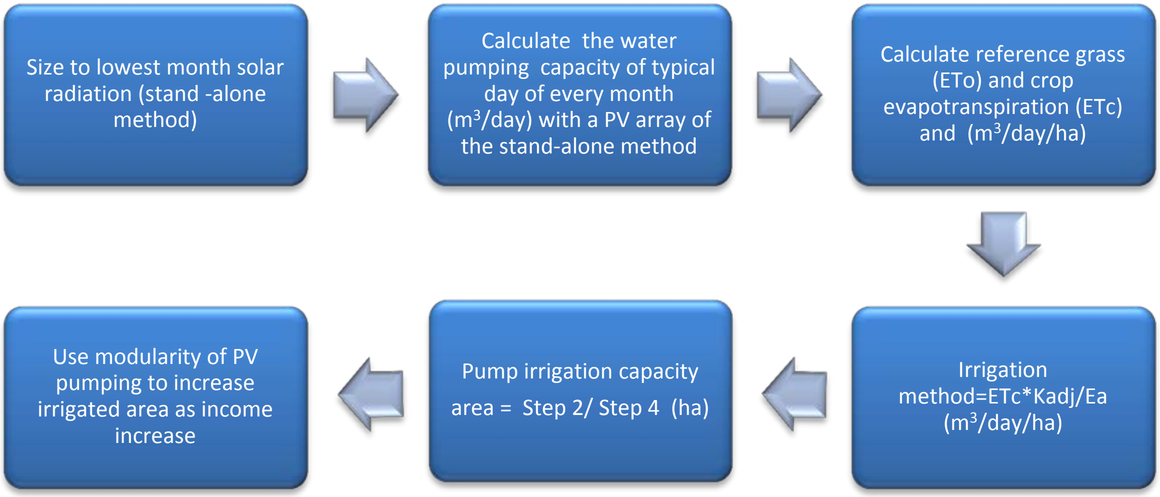

Figure V-1 Proposed sizing methodology used for small solar diaphragm pumps

In the prototype system the irrigated area for the Shurflo diaphragm pump watering the asparagus crop was 5,000m^2, using drip irrigation with a 250W solar array. The system can generate up to three harvests per year of the perennial crop. However, the life time of the plant is reduced from 15 years to 3. The production costs of the replanting every 4 years, is worthwhile, given that the yearly yield/area is higher. Part of the economic analysis that still needs to be made is to include the cost of the system expansion by connecting 2 pumps alternating their 20 minutes cycle to get 40 minutes pumping an hour. Connecting the pumps in parallel would increase cost; nevertheless, having them share the same controls would reduce costs.

Perennial crops reduce the agricultural maintenance of the system since the replanting does not have to be every year. These costs reductions make the solar system more affordable to small farmers.

For the asparagus, there is a water surplus in the pumping production when the plant's Kc is very low at a vegetative state that lasts almost 100 days. This is a period that can be used to either store the surplus which will be around 190 cubic meters, or it can be used for a 100 days non perennial crop.

Also, other good agricultural practices such as organic composting and mulching could also reduce the evapotranspiration and therefore increase the irrigated area. This can be done because by mixing the top soil with organic matter the drip irrigation wet bulb shape (watering pattern in the soil) gets wider. The soil increases its storage capacity and by doing this the irrigation frequency can be reduced for daily to every two to three days. This lower irrigation frequency can increase the irrigated area from two to three times depending on the soil storage capacity.

V.1. Risks and sustainability strategies

The main constraint that this approach has is the lack of access to credit on behalf of small farmers, and when they have access the interest rates could be as high as 79% annually. Of course, this constraint is not unique to solar drip irrigation but affects many means of production of food and goods that require loans. Obviously, lower interest rates on loans in developing countries is critical. The beneficiaries or the system were trained to install and maintain the system, and their skills were tested when a flooding forced them to uninstall and then reinstall the pumping system for village water supply installed by the Village Empowerment Program.

There are requests for new systems, and there is a critical need of technical assistance to small farmers to train them in how to implement more sustainable practices in their irrigation methods. The ultimate goal would be to have farmers training farmers when installing the new systems. Manuel Minaya, one of the farmers trained, has already volunteered to help install a new system that will be set up in January 2008.

To ensure the beneficiary system's ownership, it was requested from them to invest in the tanks and pipes of the system. The perception that the system was a donation had to be avoided, especially since it is generating an income. This is a perception easily made since Village Empowerment is a US based non-profit. This made the project more difficult; however, there was a need to secure the farmers commitment to the project. It technically affected the project by not having, for instance, adequate storage capacity; however, this is a necessary technical loss that can be replaced with future incomes. On the other hand, a completely “foreign” system to the farmer could have had repercussions in the technology transfer of it. The sense of ownership of the system is important to the long term sustainability of the project.

In final conclusion, using solar energy to power irrigation is a very good match since typically more solar irradiation means higher evapotranspiration and lower solar means lower ET. Drip irrigation is a very efficient water delivery system, particularly coupled with mulching. Yields can be tripled with drip irrigation in some cases. Financial rates of return are very favorable with a two-year payback for the prototype system designed and installed as part of this study, even taking into account very high interest rates. Lack of capital with reasonable interest rates and lack of technical information are potential barriers to the wide spread use of this approach.

Future technical research should include development of models which in the design process take into account the high correlation between solar irradiation and evapotranspiration. Planned future research and development includes the installation of a second improved prototype system and the monitoring and analysis of the existing system along with the second one.

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VII. APPENDIX

MathCad Calculations

Solar Drip Irrigation Pumping Design

Turripampa, Huarmey. Anchash, Peru

$\text{Altitude} := 1400$ Raypa is the closest UML data to Turripampa (the actual site)

$\text{Long} := 77.9170$ W

$L := -9.6500$ latitude in Raypa

Monthly average irradiation

H is horizontal irradiation in MJ/m2

$$H := \begin{pmatrix} 16.2695 \\ 14.317 \\ 15.5175 \\ 16.2885 \\ 18.0195 \\ 17.438 \\ 18.65265 \\ 20.9915 \\ 21.236 \\ 20.7905 \\ 21.408 \\ 17.96 \end{pmatrix} \qquad n := \begin{pmatrix} 17 \\ 47 \\ 75 \\ 105 \\ 135 \\ 162 \\ 198 \\ 228 \\ 258 \\ 288 \\ 318 \\ 344 \end{pmatrix}$$

n is the day number representative of each month.

Tmax: Maximum temperature

$$T_{max} := \begin{pmatrix} 30.03 \\ 30.27 \\ 31.4 \\ 30.82 \\ 30.54 \\ 31.64 \\ 31.99 \\ 32.62 \\ 30.91 \\ 30.13 \\ 29.04 \\ 28.23 \end{pmatrix}$$

Tmin: Minimum temperature

$$T_{min} := \begin{pmatrix} 13.53 \\ 8 \\ 13.64 \\ 11.73 \\ 11.67 \\ 10.82 \\ 9.7 \\ 10.36 \\ 10.24 \\ 12.21 \\ 11.26 \\ 12.26 \end{pmatrix}$$

$$T := \begin{pmatrix} 19.1297 \\ 18.2653 \\ 19.1675 \\ 18.8902 \\ 19.7406 \\ 19.2705 \\ 19.3456 \\ 19.2673 \\ 19.0334 \\ 19.0418 \\ 18.2447 \\ 18.2000 \end{pmatrix}$$

T is the Monthly average temperature

Latitude Turripampa

$$L := -9.983 \cdot \frac{\pi}{180}$$

Assumed ground reflectance (albedo) for the green grass reference crop

$$\rho := 0.23$$

$$m := 0 .. 11$$

Declination angle

$$\delta_m := 23.45 \cdot \frac{\pi}{180} \cdot \sin\left(\frac{\pi}{180} \cdot 360 \cdot \frac{284 + n_m}{365}\right)$$

$\delta_m =$

-0.365
-0.226
-0.042
0.164
0.328
0.403
0.37
0.235
0.039
-0.168
-0.33
-0.402

sunset hour

$$hs_m := \mathrm{acos}\left(-\sin(L)\cdot\frac{\sin(\delta_m)}{\cos(L)\cdot\cos(\delta_m)}\right)$$

$hs_m =$

1.638
1.611
1.578
1.542
1.511
1.496
1.503
1.529
1.564
1.601
1.631
1.646

Cos of average solar zenith angle:

$$\mathrm{cosz}_m := \left(\cos(L)\cdot\cos\left(\delta_m\right)\cdot\sin\left(\mathrm{hs}_m\right) + \mathrm{hs}_m\cdot\sin(L)\cdot\sin\left(\delta_m\right)\right)$$

$\mathrm{cosz}_m =$

1.019
1.022
0.995
0.927
0.846
0.802
0.822
0.895
0.974
1.017
1.022
1.015

Extraterrestrial irradiation on horizontal surface:

$$\mathrm{Ho}_m := 24\cdot\frac{1.377\cdot 3.6}{\pi}\cdot\left(1 + 0.033\cdot\cos\left(\frac{360\cdot n_m}{365}\cdot\frac{\pi}{180}\right)\right)\cdot\mathrm{cosz}_m$$

$\mathrm{Ho}_m =$

39.819
39.57
38.043
34.851
31.327
29.423
30.14
33.113
36.545
38.819
39.571
39.64

Clearness index:

$$KT_m := \frac{H_m}{Ho_m}$$

KT =

	0
0	0.409
1	0.362
2	0.408
3	0.467
4	0.575
5	0.593
6	0.619
7	0.634
8	0.581
9	0.536
10	0.541
11	0.453

Slopes:

$$\beta := \begin{pmatrix} 9 \\ 0 \\ -10 \\ -20 \\ -30 \end{pmatrix} \cdot \frac{\pi}{180}$$

$$j := 0 .. 4$$

$$W_{m,j} := \operatorname{acos}\left(-\tan\left(L - \beta_j\right) \cdot \tan\left(\delta_m\right)\right)$$

$W_{m,j} =$

1.703
1.65
1.585
1.514
1.453
1.424
1.437
1.488
1.557
1.629
1.689
1.718
1.638
1.611
1.578
...

Sunset hour on the collector

$$hsp_{m,j} := \mathrm{if}\left(hs_m < W_{m,j}, hs_m, W_{m,j}\right)$$

$$DhHratio_m := 0.775 + 0.00606\cdot\left(hs_m\cdot\frac{180}{\pi} - 90\right) \ldots$$
$$+ (-1)\cdot\left[\left[0.505 + 0.00455\cdot\left(hs_m\cdot\frac{180}{\pi} - 90\right)\right]\cdot\cos\left[\left(115\cdot KT_m - 103\right)\cdot\frac{\pi}{180}\right]\right]$$

$DhHratio_m$
0.506
0.542
0.495
0.44
0.363
0.351
0.337
0.333
0.366
0.401
0.402
0.47

Diffuse component of horizontal irradiation

$$Dh_m := H_m \cdot DhHratio_m$$

$Dh_m =$

8.237
7.763
7.678
7.17
6.534
6.113
6.293
6.989
7.781
8.332
8.599
8.445

beam component of horizontal irradiation

$$Bh_m := H_m - Dh_m$$

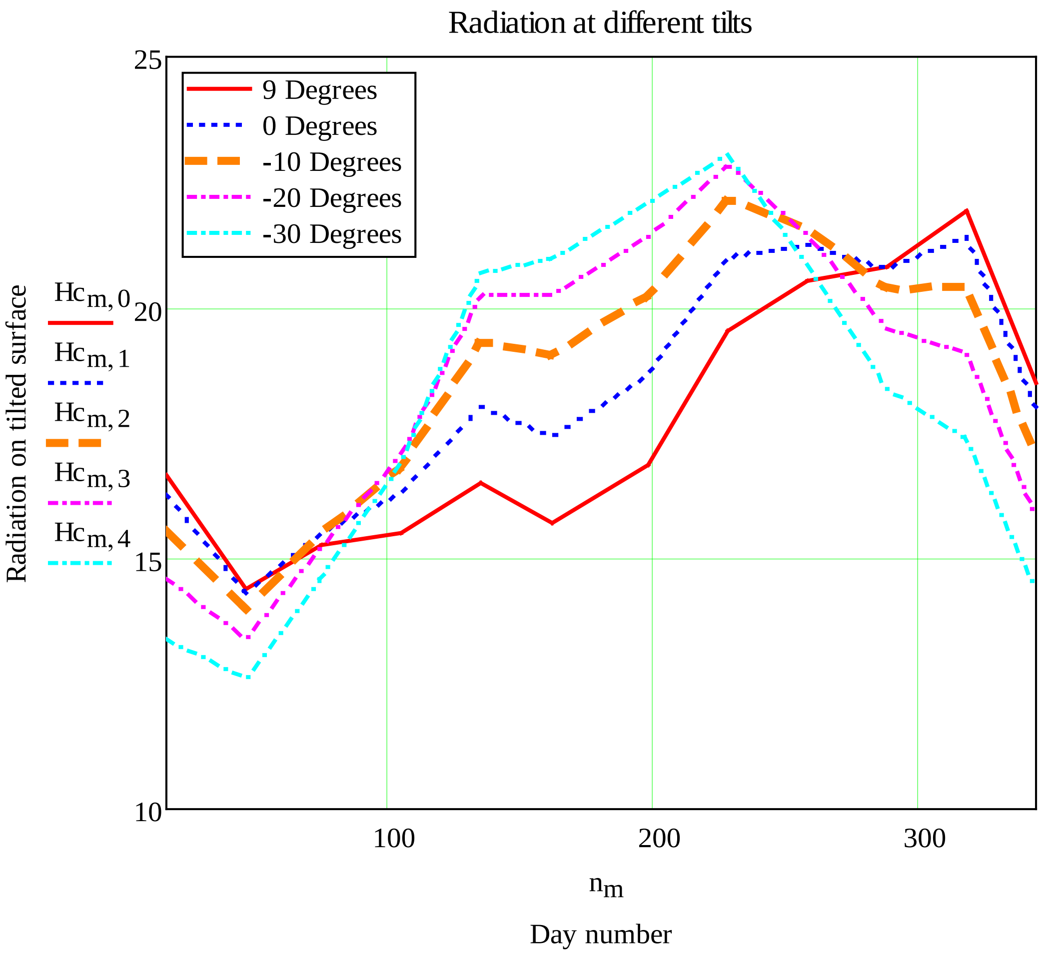
MJ/m2-day

$Bh_m =$

8.033
6.554
7.84
9.118
11.486
11.325
12.36
14.002
13.455
12.458
12.809
9.515

$$Rb_{m,j} := \frac{\cos\left(L - \beta_j\right)\cdot\cos\left(\delta_m\right)\cdot\sin\left(hsp_{m,j}\right) + hsp_{m,j}\cdot\sin\left(L - \beta_j\right)\cdot\sin\left(\delta_m\right)}{cosz_m}$$

$$Hc_{m,j} := Rb_{m,j}\cdot Bh_m + \left(\frac{1 + \cos\left(\beta_j\right)}{2}\cdot Dh_m\right) + \left(\frac{1 - \cos\left(\beta_j\right)}{2}\right)\cdot\rho\cdot H_m$$



$Hc_{m,2} =$ MJ/m2

15.563
13.98
15.515
16.84
19.343
19.057
20.267
22.171
21.568
20.384
20.43
17.033

$$Hc_{min} := 13.98 \cdot \frac{1000}{3.6}$$

$$Hc_{min} = 3.883 \times 10^{3} \quad \frac{wh}{m^{2}day}$$

Calculation of Eto: FAO Penman Monteith method

Aerodynamic resistance for a grass reference surface ra

$h := 0.12$ m crop height

$d := \frac{2}{3} \cdot h$ m zero plane displacement height

$z_{om} := 0.123 \cdot h$ m roughness length govering the momentum transfer

$z_{oh} := 0.1 \cdot z_{om}$ m roughness length governing transfer of heat and vapour

$z_m := 10$ m height of wind measurements

$z_h := z_m$ m height of humidity measurements

$k := -0.41$ von Karman's constant

wind speed

Wind speed at 2 m above ground surface

$\frac{m}{s}$ $u_{2_m} := u_{z_m} \cdot \left(\frac{4.87}{\ln\left(67.8 \cdot z_m - 5.42\right)} \right)$

$$u_z := \begin{pmatrix} 3.4 \\ 3.2 \\ 3.2 \\ 3.4 \\ 3.8 \\ 4.4 \\ 4.4 \\ 4.4 \\ 4.3 \\ 3.9 \\ 3.8 \\ 3.6 \end{pmatrix}$$

Assuming a constant height of 0.12 m and a standarized height for wind speeed, temperature and humidity at 10m (zm=zh=10m), the aerodynamic resistance ra [s m-1] for the grass reference surface becomes (Eq.   ):

$$r_{a_m} := \frac{\left[\ln\left[\frac{(z_m - d)}{z_{om}}\right]\cdot\ln\left[\frac{(z_h - d)}{z_{oh}}\right]\right]}{k^2\cdot u_{2_m}}$$

$r_a =$

	0
0	134.218
1	142.606
2	142.606
3	134.218
4	120.089
5	103.714
6	103.714
7	103.714
8	106.126
9	117.01
10	120.089
11	126.761

$\frac{s}{m}$

Bulk surface resistance [s/m] rs

$LAI := 24\cdot h$ Leaf area index

$LAI_{active} := 0.5\cdot LAI$ Active leaf area index

$r_1 := 100\frac{s}{m}$ Bulk stomatal resistance of the well illuminated leaf

$r_s := \frac{r_1}{LAI_{active}}$ $r_s = 69.444\ \frac{s}{m}$

Atmospheric Pressure (P)

$z := 40\ m$ elevation above sea level [m]

$P := 101.3\cdot\left[\frac{(293 - 0.0065\cdot z)}{293}\right]^{5.26}$ $P = 100.828\ kPa$

Latent heat of vaporization @ an air temperature of 20 C

$\lambda := 2.45\ MJ\cdot kg^{-1}$

Specific heat at constant pressure

$C_p := 1.013\cdot 10^{-3}\ \frac{MJ}{\frac{kg}{C}}$

Ratio molecular weight of water vapour/dry air

$\varepsilon := 0.662$

Psychrometirc constant (γ)

$\gamma := \frac{(C_p\cdot P)}{\varepsilon\cdot\lambda}$ $\gamma = 0.063\frac{kPa}{C}$

Mean saturation vapour pressure (es)

$$e_{max_m} := 0.6108 \cdot e^{\frac{17.27 \cdot T_{max_m}}{T_{max_m} + 237.3}}$$

$$e_{min_m} := 0.6108 \cdot e^{\frac{17.27 \cdot T_{min_m}}{T_{min_m} + 237.3}}$$

Mean saturation vapour for the day

$$e_{s_m} := \frac{\left(e_{max_m} + e_{min_m}\right)}{2} \qquad \mathrm{kPa}$$

Slope of saturation vapour pressure curve (Δ) $\frac{\mathrm{kPa}}{\mathrm{DegreesC}}$

$$\Delta_m := \frac{\left[4098 \cdot \left[0.6108 \cdot e^{\frac{(17.27 \cdot T_m)}{T_m + 237.3}}\right]\right]}{\left(T_m + 237.3\right)^2} \qquad \frac{\mathrm{kPa}}{\mathrm{DegreesC}}$$

Actual vapour pressure (ea) estimating missing humidity data

$$e_{a_m} := 0.611 \cdot e^{\left[\frac{\left[17.27 \cdot \left(T_{min_m} - 3\right)\right]}{\left(T_{min_m} - 3\right) + 237.3}\right]} \qquad \mathrm{kPa}$$

Mean air density at constant pressure ρa

$$\rho_{a_m} := \frac{P}{1.01 \cdot \left(T_m + 273\right)} \qquad \frac{\mathrm{kg}}{\mathrm{m}^3}$$

$$c_s := 2.1 \quad \frac{\mathrm{Mj}}{\frac{\mathrm{m}^3}{\mathrm{C}}}$$ soil heat capacity

Soil heat flux

$G_1 := 0.7\cdot(T_1 - T_{11})$

$G_1 = 0.046$

$G_2 := 0.7\cdot(T_2 - T_0)$

$G_2 = 0.026$

$G_3 := 0.7\cdot(T_3 - T_1)$

$G_3 = 0.437$

$G_4 := 0.7\cdot(T_4 - T_2)$

$G_4 = 0.401$

$G_5 := 0.7\cdot(T_5 - T_3)$

$G_5 = 0.266$

$G_6 := 0.7\cdot(T_6 - T_4)$

$G_6 = -0.276$

$G_7 := 0.7\cdot(T_7 - T_5)$

$G_7 = -2.24 \times 10^{-3}$

$G_8 := 0.7\cdot(T_8 - T_6)$

$G_8 = -0.219$

$G_9 := 0.7\cdot(T_9 - T_7)$

$G_9 = -0.158$

$G_{10} := 0.7\cdot(T_{10} - T_8)$

$G_{10} = -0.552$

$G_{11} := 0.7\cdot(T_{11} - T_9)$

$G_{11} = -0.589$

$G_{12} := 0.7\cdot(T_0 - T_{10})$

$G_{12} = 0.619$

MJ/m^2/day

Net solar radiation in the fields

Clear sky solar radiation Rso

$$Rso_m := \left[0.75 + \left(2\cdot Altitude\cdot 10^{-5}\right)\right]\cdot Ho_m$$

MJ/m^2/day

Net solar or net shortwave radiation Rns

$$Rns_m := (1 - \rho)\cdot H_m$$

MJ/m^2/day

$$\sigma := 4.903\cdot 10^{-9}$$

MJ/m^2/day

$$Rnl_m := \sigma\cdot\left[\frac{\left[\left(Tmax_m + 273.16\right)^4 + \left(Tmin_m + 273.16\right)^4\right]}{2}\right]\cdot\left(0.34 - 0.14\sqrt{e_{a_m}}\right)\cdot\left[1.35\cdot\left(\frac{H_m}{Rso_m}\right) - 0.35\right]$$

Net longwave radiation

Net radiation

$$Rn_m := Rns_m - Rnl_m$$

MJ/m^2/day

$Rn_m =$

10.091
8.926
9.502
9.272
9.281
8.497
8.979
10.625
11.542
11.959
12.323
10.826

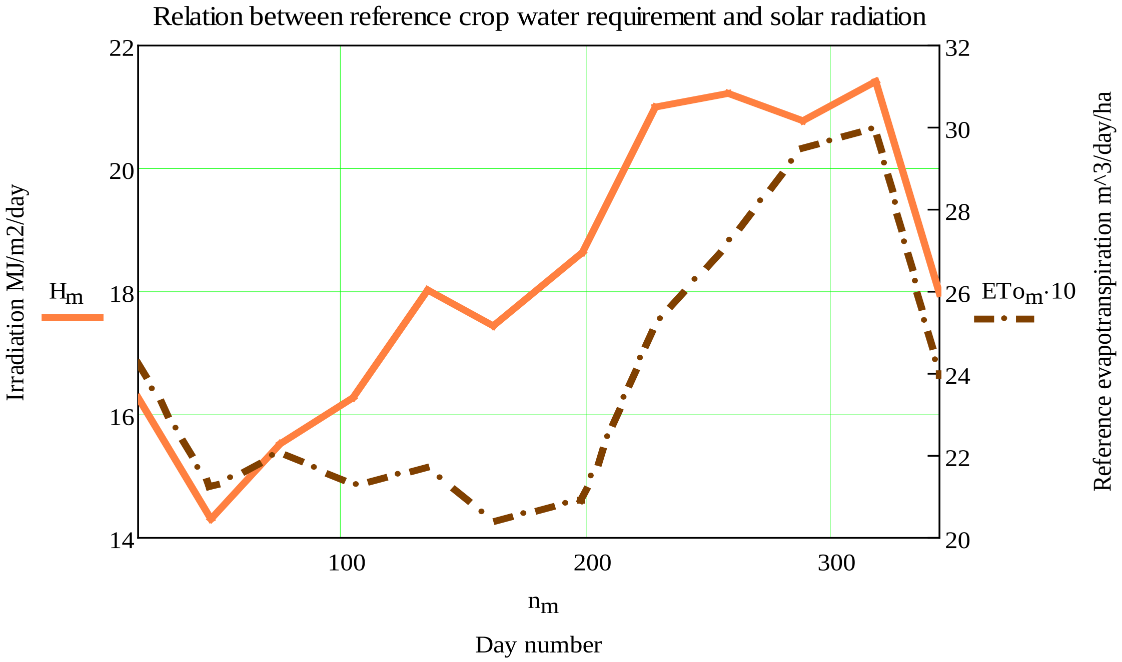
Formulation of the Penman-Montheith Equation

Reference Evapotranspiration (ETo) mm/day

$$ETo_m := \frac{\dfrac{\Delta_m \cdot \left(Rn_m - G_{month_m}\right) + \rho_{a_m} \cdot C_p \cdot \dfrac{\left(e_{s_m} - e_{a_m}\right)}{r_{a_m}}}{\Delta_m + \gamma \cdot \left(1 + \dfrac{r_s}{r_{a_m}}\right)}}{\lambda}$$

$ETo_m =$

2.423
2.123
2.206
2.128
2.169
2.04
2.092
2.521
2.715
2.951
3.002
2.39



Water Photovoltaic Pumping Design

Loads

Voltage from battery to pump

$Vload := 12$

Current of pump at 20 m head (approx. 30 PSI)

$Ip := 7.5$

Pump wattage requirement

$DC_{pump} := Vload \cdot Ip$ watts

$N_{cyc} := 12$

$T_{cyc} := 20\ min$

$\text{Load} := \frac{DC_{load}}{\eta_c \cdot \eta_b}$ $\text{Load} = 494.845$ Wh

$$DC_{load} := DC_{pump} \cdot N_{cyc} \cdot \frac{T_{cyc}}{60}$$

$DC_{load} = 360$ Wh

$\eta_b := .75$ $\eta_c := .97$

Daily module power output

Arco Solar Modules Model No M53

$I_{max} := 2.2$ A

$V_{oc} := 18.8$ V

Required Amperage

$$Req_{amp} := \frac{DC_{pump}}{0.97 \cdot 12}$$

$Req_{amp} = 7.732$ A

A Pro Star 30 charge controller was
selected for security reasons of initial
motor current

$Pump_{flowi} := 10$

$Daily_{voli} := Pump_{flowi} \cdot T_{cyc} \cdot \frac{N_{cyc}}{1000}$ $Daily_{voli} = 2.4$ m^3

Number of modules needed

$P_{mod} := \left[\left(\frac{Hc_{min}}{1000}\right)\cdot V_{nom}\cdot I_{max}\right]$ $P_{mod} = 102.52$ $\frac{Wh}{day}$

$N_{mod} := \frac{Load}{P_{mod}}$ $N_{mod} = 4.827$ Five modules in parallel

Battery Storage Calculations

$DOD := 0.8$ $N_{day} := 1$

$Storage := Load\cdot\frac{N_{day}}{DOD}$ $Storage = 618.557$ Wh

Battery capacity

$Bat_{cap} := \frac{Storage}{12}$ $Bat_{cap} = 51.546$ Ah

Lead acid batteries used in Peru 140 Ah

$Peru_{bat} := 140$ Ah

Number of batteries needed

$NoBat := \frac{Bat_{cap}}{Peru_{bat}}$ $NoBat = 0.368$ 1 battery is needed

Wiring

$Length := 30$ ft

$I_{peak} := 15$ A Assumed

$V := 12\,V$

$AF := Length\cdot I_{peak}$ $AF = 450$ Ampere Feet

$Power_{total} := I_{peak}\cdot V$ $Power_{total} = 180$ W

$P_{loss} := Power_{total}\cdot 0.05$ $P_{loss} = 9$ W

$V_{drop} := \frac{P_{loss}}{I_{peak}}$ $V_{drop} = 0.6$ V

From chart number 4 in chapter 2.5 of the Solar Energy Engineering course notes we can choose wire gage #8

$$P_{mod1_m} := \left(\frac{Hc_{m,2}}{3.6}\right)\cdot V_{nom}\cdot I_{max}$$

$$P_{mod2_m} := \left(\frac{Hc_{m,1}}{3.6}\right)\cdot V_{nom}\cdot I_{max}$$

$$P_{mod3_m} := \left(\frac{Hc_{m,0}}{3.6}\right)\cdot V_{nom}\cdot I_{max}$$

$P_{mod1} =$

	0
0	114.128
1	102.523
2	113.774
3	123.492
4	141.845
5	139.75
6	148.623
7	162.589
8	158.167
9	149.482
10	149.82
11	124.91

$$\frac{Wh}{\frac{day}{module}}$$

Number of mudules

$$N_{mod1_m} := \frac{Load}{P_{mod1_m}}$$

$$N_{mod2_m} := \frac{Load}{P_{mod2_m}}$$

$$N_{mod3_m} := \frac{Load}{P_{mod3_m}}$$

Optimization of the use of the PV modules in terms of the number of cycles of the timer

$Ncycjan := 12$
$Ncycfeb := 11$
$Ncycmar := 12$
$Ncycabr := 13$
$Ncycmay := 15$
$Ncycjun := 15$

$Ncycjul := 16$
$Ncycaug := 17$
$Ncycsep := 17$
$Ncycoct := 16$
$Ncycnov := 16$
$Ncycdec := 13$

$$Ncyc_{opt} := \begin{pmatrix} Ncycjan \\ Ncycfeb \\ Ncycmar \\ Ncycabr \\ Ncycmay \\ Ncycjun \\ Ncycjul \\ Ncycaug \\ Ncycsep \\ Ncycoct \\ Ncycnov \\ Ncycdec \end{pmatrix}$$

$$N_{Min} := 20$$

$$P_{flow} := 10\,lpm$$

$$\mathrm{Daily}_{\mathrm{Vol}_m} := \frac{\left(P_{\mathrm{flow}} \cdot \mathrm{Ncyc}_{\mathrm{opt}_m} \cdot N_{\mathrm{Min}}\right)}{1000} \quad \mathrm{m}^3\mathrm{pd}$$

$$\mathrm{DC}_{\mathrm{loady}_m} := 13.6 \cdot 9 \cdot \mathrm{Ncyc}_{\mathrm{opt}_m} \cdot \frac{T_{\mathrm{cyc}}}{60}$$

$$\mathrm{Load}_{y_m} := \frac{\mathrm{DC}_{\mathrm{loady}_m}}{\eta_c \cdot \eta_b}$$

$\mathrm{Load}_{y_m} =$ Wh

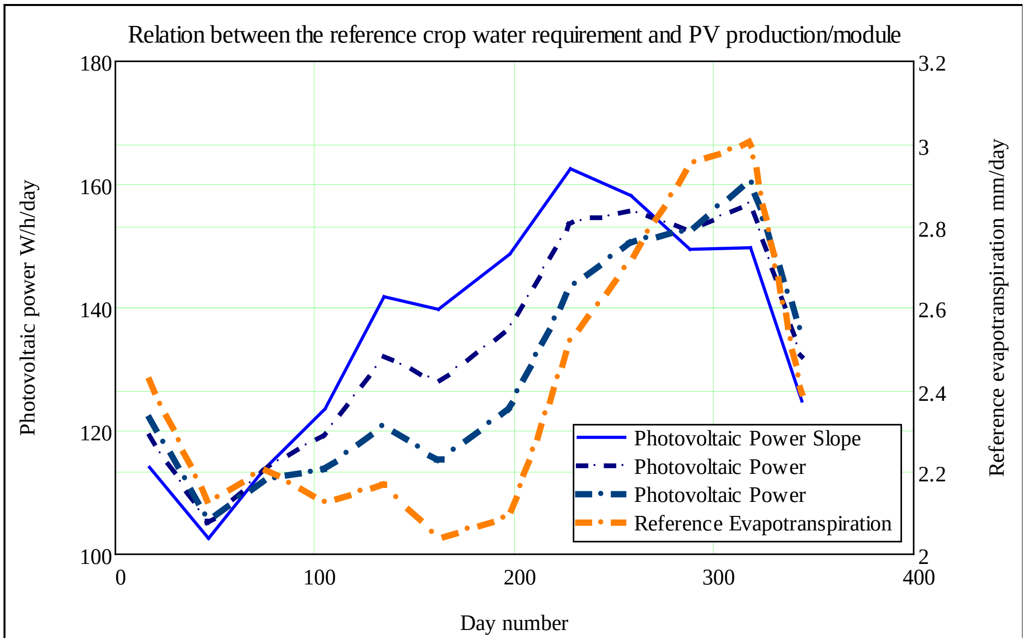
672.99
616.907
672.99
729.072
841.237
841.237
897.32
953.402
953.402
897.32
897.32
729.072

$$n_{\mathrm{days}} := \begin{pmatrix} 31 \\ 28 \\ 31 \\ 30 \\ 31 \\ 30 \\ 31 \\ 31 \\ 30 \\ 31 \\ 30 \\ 31 \end{pmatrix}$$

$\mathrm{Daily}_{\mathrm{Vol}} =$

	0
0	2.4
1	2.2
2	2.4
3	2.6
4	3
5	3
6	3.2
7	3.4
8	3.4
9	3.2
10	3.2
11	2.6

m^3



To convert the reference evapotranspiration from mm to m^3

$$ETo_{cm_m} := ETo_m \cdot 10 \qquad m^3$$

ETc Calculation of crop evapotranspiration under standard conditions for a single crop coeffieicnt Kc (Furrow and Sprinkler) and doble coefficient for Drip

Single crop coeficients for the Asparagus

$Kc_{ini} := 0.5$ Vegetative

$Kc_{med} := 0.95$ Floration

$Kc_{fin} := 0.3$ harvest

$Kr := .20$ For drip irrigation

$Ea := 85\%$

$$ETc_{Jan} := \frac{\left(Kr \cdot Kc_{ini} \cdot ETo_{cm_0}\right)}{Ea} \qquad ETc_{Jul} := \frac{\left(Kr \cdot Kc_{med} \cdot ETo_{cm_6}\right)}{Ea}$$

$$ETc_{Feb} := \frac{\left(Kr \cdot Kc_{ini} \cdot ETo_{cm_1}\right)}{Ea} \qquad ETc_{Aug} := \frac{\left(Kr \cdot Kc_{fin} \cdot ETo_{cm_7}\right)}{Ea}$$

$$ETc_{Mar} := \frac{\left(Kr \cdot Kc_{med} \cdot ETo_{cm_2}\right)}{Ea} \qquad ETc_{Sept} := \frac{\left(Kr \cdot Kc_{ini} \cdot ETo_{cm_8}\right)}{Ea}$$

$$ETc_{Abr} := \frac{\left(Kr \cdot Kc_{fin} \cdot ETo_{cm_3}\right)}{Ea} \qquad ETc_{Oct} := \frac{\left(Kr \cdot Kc_{ini} \cdot ETo_{cm_9}\right)}{Ea}$$

$$ETc_{May} := \frac{\left(Kr \cdot Kc_{ini} \cdot ETo_{cm_4}\right)}{Ea} \qquad ETc_{Nov} := \frac{\left(Kr \cdot Kc_{med} \cdot ETo_{cm_{10}}\right)}{Ea}$$

$$ETc_{Jun} := \frac{\left(Kr \cdot Kc_{ini} \cdot ETo_{cm_5}\right)}{Ea} \qquad ETc_{Dic} := \frac{\left(Kr \cdot Kc_{fin} \cdot ETo_{cm_{11}}\right)}{Ea}$$

For Sprinkler irrigation $E_{as} := 75\%$

$$ETc_{Jans} := \frac{\left(Kc_{ini} \cdot ETo_{cm_0}\right)}{E_{as}}$$

$$ETc_{Febs} := \frac{\left(Kc_{ini} \cdot ETo_{cm_1}\right)}{E_{as}}$$

$$ETc_{Mars} := \frac{\left(Kc_{med} \cdot ETo_{cm_2}\right)}{E_{as}}$$

$$ETc_{Abrs} := \frac{\left(Kc_{fin} \cdot ETo_{cm_3}\right)}{E_{as}}$$

$$ETc_{Mays} := \frac{\left(Kc_{ini} \cdot ETo_{cm_4}\right)}{E_{as}}$$

$$ETc_{Juns} := \frac{\left(Kc_{ini} \cdot ETo_{cm_5}\right)}{E_{as}}$$

$$ETc_{Juls} := \frac{\left(Kc_{med} \cdot ETo_{cm_6}\right)}{E_{as}}$$

$$ETc_{Augs} := \frac{Kc_{fin} \cdot ETo_{cm_7}}{E_{as}}$$

$$ETc_{Septs} := \frac{\left(Kc_{ini} \cdot ETo_{cm_8}\right)}{E_{as}}$$

$$ETc_{Octs} := \frac{\left(Kc_{ini} \cdot ETo_{cm_9}\right)}{E_{as}}$$

$$ETc_{Novs} := \frac{\left(Kc_{med} \cdot ETo_{cm_{10}}\right)}{E_{as}}$$

$$ETc_{Dics} := \frac{\left(Kc_{fin} \cdot ETo_{cm_{11}}\right)}{E_{as}}$$

For Flooding irrigation $E_{af} := 40\%$

$$ETc_{Janf} := \frac{\left(Kc_{ini} \cdot ETo_{cm_0}\right)}{40\%}$$

$$ETc_{Febf} := \frac{\left(Kc_{ini} \cdot ETo_{cm_1}\right)}{40\%}$$

$$ETc_{Marf} := \frac{\left(Kc_{med} \cdot ETo_{cm_2}\right)}{40\%}$$

$$ETc_{Abrf} := \frac{\left(Kc_{fin} \cdot ETo_{cm_3}\right)}{40\%}$$

$$ETc_{Mayf} := \frac{\left(Kc_{ini} \cdot ETo_{cm_4}\right)}{40\%}$$

$$ETc_{Junf} := \frac{\left(Kc_{ini} \cdot ETo_{cm_5}\right)}{40\%}$$

$$ETc_{Julf} := \frac{\left(Kc_{med} \cdot ETo_{cm_6}\right)}{40\%}$$

$$ETc_{Augf} := \frac{Kc_{fin} \cdot ETo_{cm_7}}{40\%}$$

$$ETc_{Septf} := \frac{\left(Kc_{ini} \cdot ETo_{cm_8}\right)}{40\%}$$

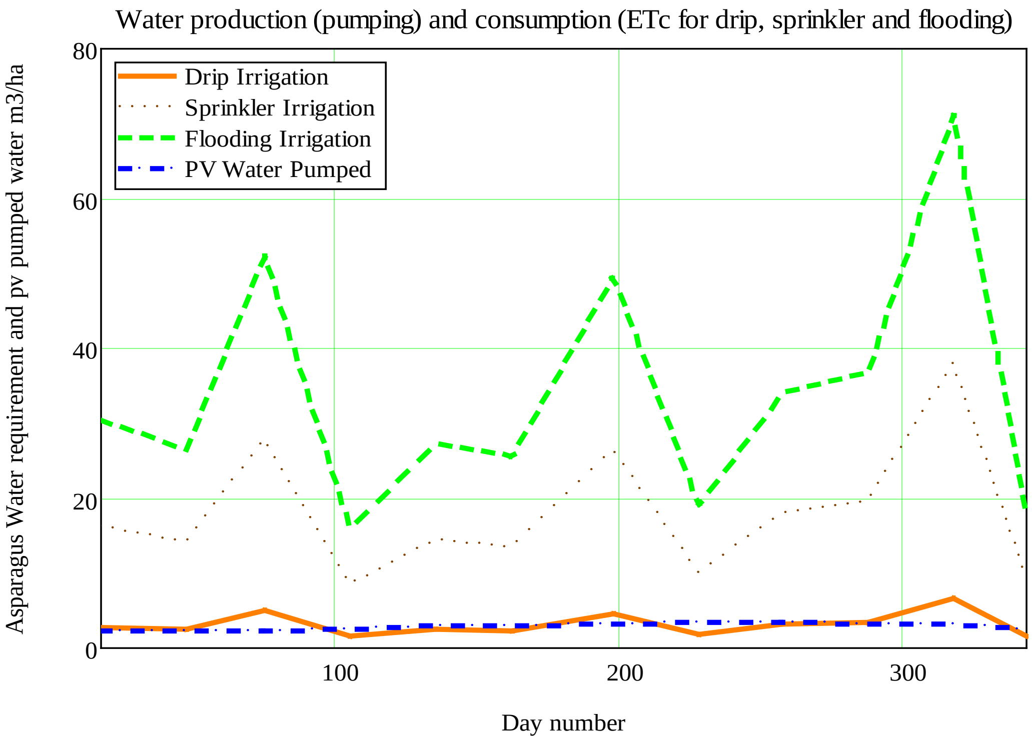
$$ETc_{Octf} := \frac{\left(Kc_{ini} \cdot ETo_{cm_9}\right)}{40\%}$$

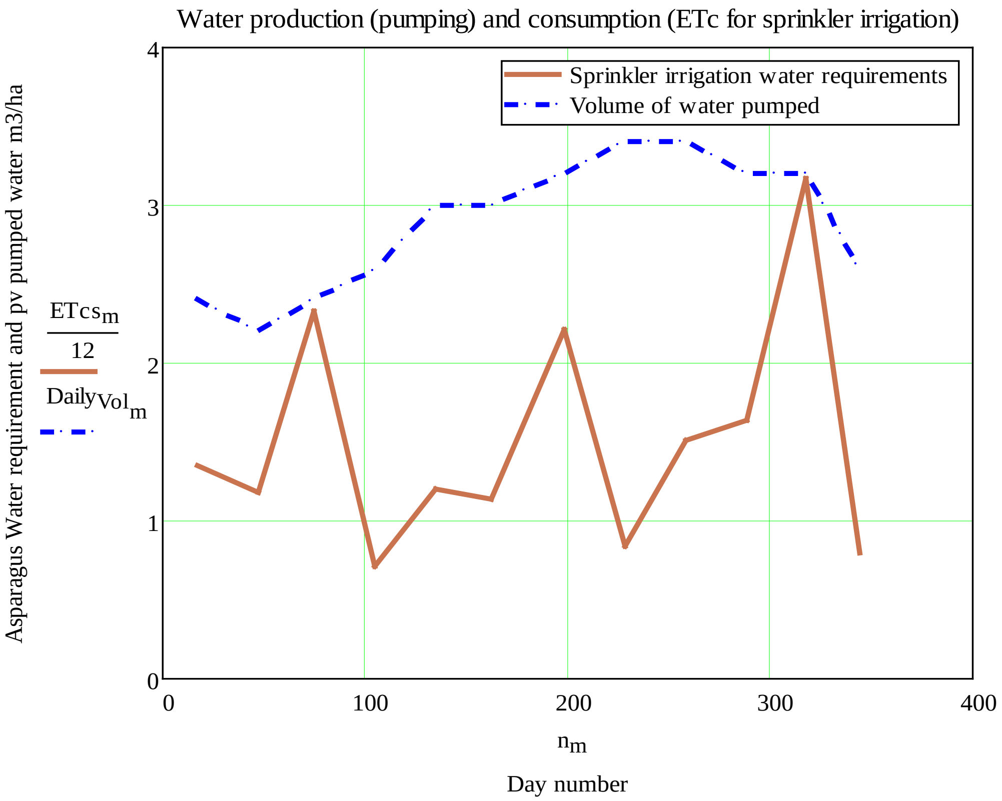
$$ETc_{Novf} := \frac{\left(Kc_{med} \cdot ETo_{cm_{10}}\right)}{40\%}$$

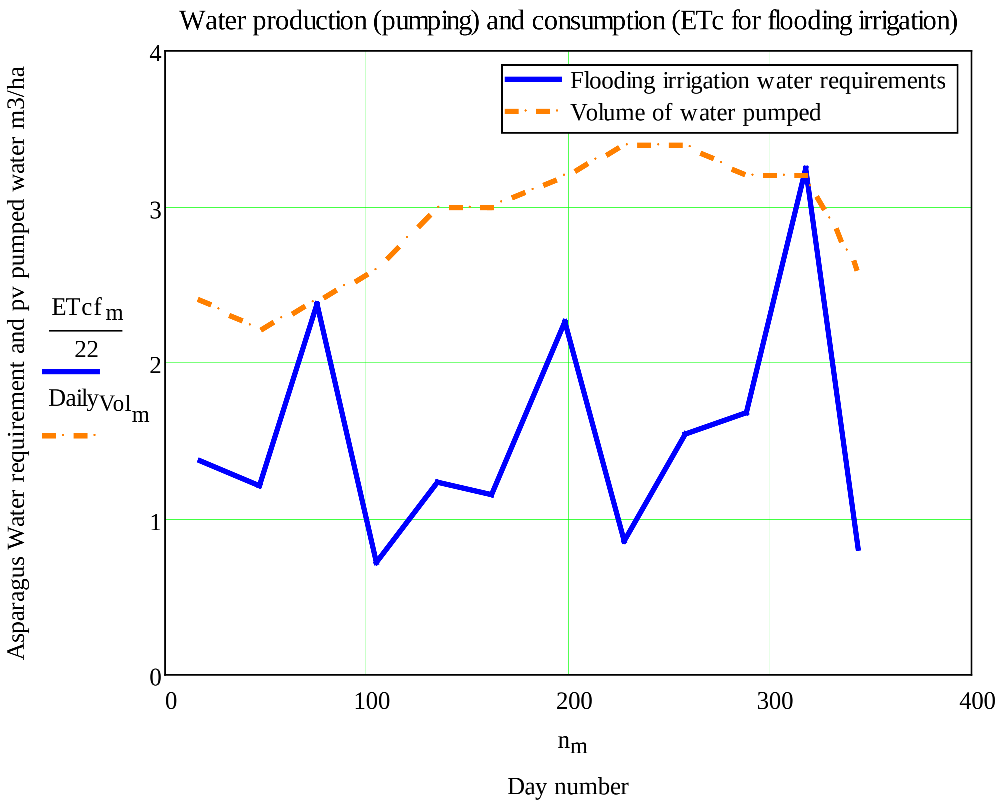
$$ETc_{Dicf} := \frac{\left(Kc_{fin} \cdot ETo_{cm_{11}}\right)}{40\%}$$

$$ETc := \begin{pmatrix} ETc_{Jan} \\ ETc_{Feb} \\ ETc_{Mar} \\ ETc_{Abr} \\ ETc_{May} \\ ETc_{Jun} \\ ETc_{Jul} \\ ETc_{Aug} \\ ETc_{Sept} \\ ETc_{Oct} \\ ETc_{Nov} \\ ETc_{Dic} \end{pmatrix} \quad \frac{m^3}{\frac{ha}{day}} \qquad ETcs := \begin{pmatrix} ETc_{Jans} \\ ETc_{Febs} \\ ETc_{Mars} \\ ETc_{Abrs} \\ ETc_{Mays} \\ ETc_{Juns} \\ ETc_{Juls} \\ ETc_{Augs} \\ ETc_{Septs} \\ ETc_{Octs} \\ ETc_{Novs} \\ ETc_{Dics} \end{pmatrix} \quad \frac{m^3}{\frac{ha}{day}}$$

$$\mathrm{ETcf} := \begin{pmatrix} \mathrm{ETc}_{\mathrm{Janf}} \\ \mathrm{ETc}_{\mathrm{Febf}} \\ \mathrm{ETc}_{\mathrm{Marf}} \\ \mathrm{ETc}_{\mathrm{Abrf}} \\ \mathrm{ETc}_{\mathrm{Mayf}} \\ \mathrm{ETc}_{\mathrm{Junf}} \\ \mathrm{ETc}_{\mathrm{Julf}} \\ \mathrm{ETc}_{\mathrm{Augf}} \\ \mathrm{ETc}_{\mathrm{Septf}} \\ \mathrm{ETc}_{\mathrm{Octf}} \\ \mathrm{ETc}_{\mathrm{Novf}} \\ \mathrm{ETc}_{\mathrm{Dicf}} \end{pmatrix} \frac{\mathrm{m}^3}{\frac{\mathrm{ha}}{\mathrm{day}}}$$


Water production (pumping) and consumption (ETc for drip, sprinkler and flooding)
Asparagus Water requirement and pv pumped water m3/ha
Day number
Drip Irrigation
Sprinkler Irrigation
Flooding Irrigation
PV Water Pumped
0
20
40
60
80
100
200
300


Water production (pumping) and consumption (ETc for sprinkler irrigation)
Sprinkler irrigation water requirements
Volume of water pumped
Asparagus Water requirement and pv pumped water m3/ha
$\frac{ETcs_m}{12}$
$Daily_{Vol_m}$
0
1
2
3
4
0
100
200
300
400
n_m
Day number


Water production (pumping) and consumption (ETc for flooding irrigation)
Asparagus Water requirement and pv pumped water m3/ha
$\frac{ETcf_m}{22}$
$Daily_{Vol_m}$
Flooding irrigation water requirements
Volume of water pumped
0
1
2
3
4
0
100
200
300
400
n_m
Day number

emitter flow

$$E_{flow} := \frac{.67}{1000} = 6.7 \times 10^{-4} \quad \frac{m^3}{hr}$$

distance between emitters

$$E_{dist} := 0.2 \quad m$$

distance between laterals

$$L_{dist} := 1 \quad m$$

Intensity of application

$$I_{app} := \frac{E_{flow} \cdot 1000}{E_{dist} \cdot L_{dist}} \qquad I_{app} = 3.35 \quad \frac{mm}{hr}$$

Irrigation time per day

$$Irr_{time_m} := \frac{ETc_m \cdot 0.1}{I_{app}} \quad hr$$

$$Irr_{tminutes_m} := Irr_{time_m} \cdot 60 \quad \text{minutes/day}$$

$Irr_{tminutes_m}$ =

5.106
4.473
8.833
2.691
4.57
4.298
8.373
3.187
5.722
6.219
12.018
3.022

Longitude of Lateral

$L_{lat} := 100 \quad \mathrm{m}$

Number of emitter per lateral

$Ne_{Lat} := \dfrac{L_{lat}}{E_{dist}} \qquad Ne_{Lat} = 500 \qquad \text{emitters}$

Flow per lateral

$Q_{Lat} := E_{flow} \cdot Ne_{Lat} \qquad Q_{Lat} = 0.335 \quad \dfrac{m^3}{hr}$

System's flow

$N_{Lat} := 50$

$Q_{sys} := N_{Lat} \cdot Q_{Lat} \qquad Q_{sys} = 16.75 \quad \dfrac{m^3}{hr}$

Pumped volume required

$Vol_{required_m} := Q_{sys} \cdot Irr_{time_m} \qquad m^3$

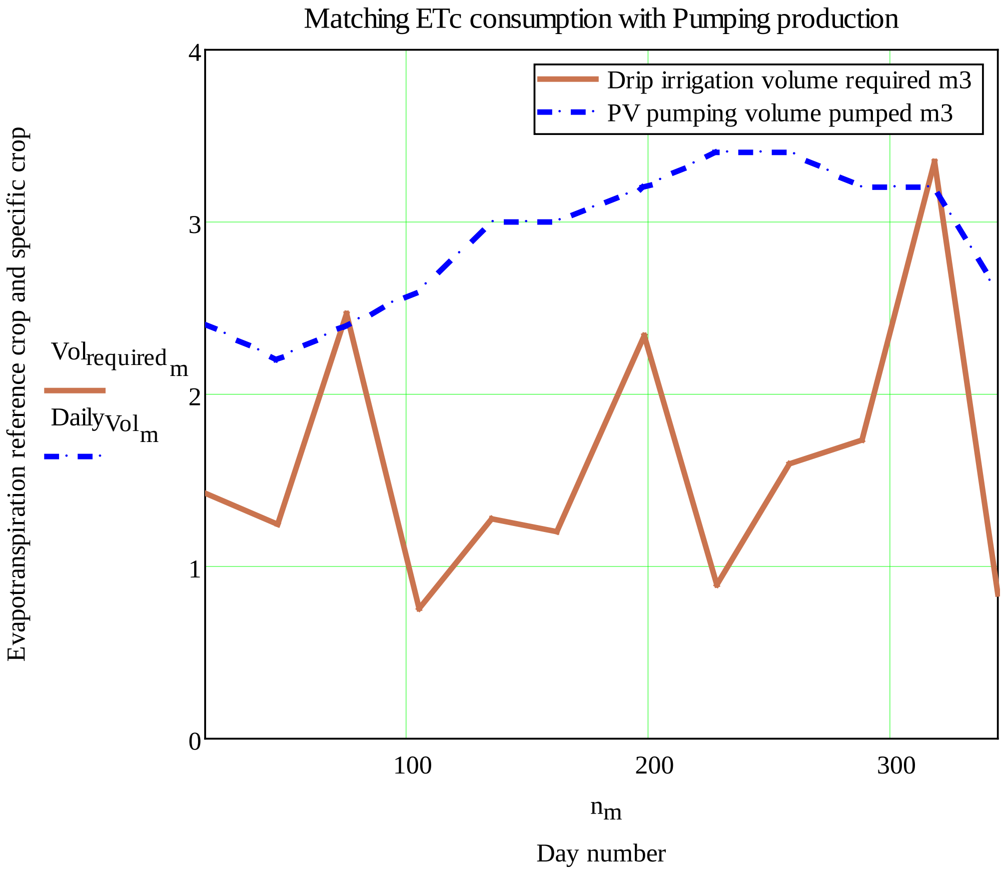
$Vol_{required_m}$

1.425
1.249
2.466
0.751
1.276
1.2
2.338
0.89
1.597
1.736
3.355
0.844

$area_{irr} := N_{Lat} \cdot L_{lat}$

$area_{irr} = 5 \times 10^3 \quad m^2$

$ha\% := \dfrac{area_{irr}}{10000} \qquad ha\% = 0.5$



Optimization for pumping times $N_{Cycl1} := 7$

Pump flow Jan

$DailyFlow1 := P_{flow} \cdot N_{Cycl1} \cdot N_{Min}$ lpd

Pump flow Feb $N_{Cycl2} := 6$

$DailyFlow2 := P_{flow} \cdot N_{Cycl2} \cdot N_{Min}$ lpd

$DailyFlow2 = 1.2 \times 10^3$

Pump flow March $N_{Cycl3} := 12$

$DailyFlow3 := P_{flow} \cdot N_{Cycl3} \cdot N_{Min}$

$DailyFlow3 = 2.4 \times 10^3$

Pump flow April $N_{Cycl4} := 4$

$DailyFlow4 := P_{flow} \cdot N_{Cycl4} \cdot N_{Min}$

$DailyFlow4 = 800$ lpd

Pump flow May

$N_{Cycl5} := 7$

$DailyFlow5 := P_{flow} \cdot N_{Cycl5} \cdot N_{Min}$

$DailyFlow5 = 1.4 \times 10^{3}$ lpd

Pump flow June

$N_{Cycl6} := 6$

$DailyFlow6 := P_{flow} \cdot N_{Cycl6} \cdot N_{Min}$

$DailyFlow6 = 1.2 \times 10^{3}$ lpd

Pump flow July

$N_{Cycl7} := 12$

$DailyFlow7 := P_{flow} \cdot N_{Cycl7} \cdot N_{Min}$

$DailyFlow7 = 2.4 \times 10^{3}$ lpd

Pump flow August

$N_{Cycl8} := 5$

$DailyFlow8 := P_{flow} \cdot N_{Cycl8} \cdot N_{Min}$

$DailyFlow8 = 1 \times 10^{3}$ lpd

Pump flow September

$N_{Cyc9} := 8$

$DailyFlow9 := P_{flow} \cdot N_{Cyc9} \cdot N_{Min}$

$DailyFlow9 = 1.6 \times 10^{3}$ lpd

Pump flow Oct

$N_{Cycl10} := 9$

$DailyFlow10 := P_{flow} \cdot N_{Cycl10} \cdot N_{Min}$

$DailyFlow10 = 1.8 \times 10^{3}$ lpd

Pump flow Nov

$N_{Cycl11} := 17$

$DailyFlow11 := P_{flow} \cdot N_{Cycl11} \cdot N_{Min}$

$DailyFlow11 = 3.4 \times 10^{3}$ lpd

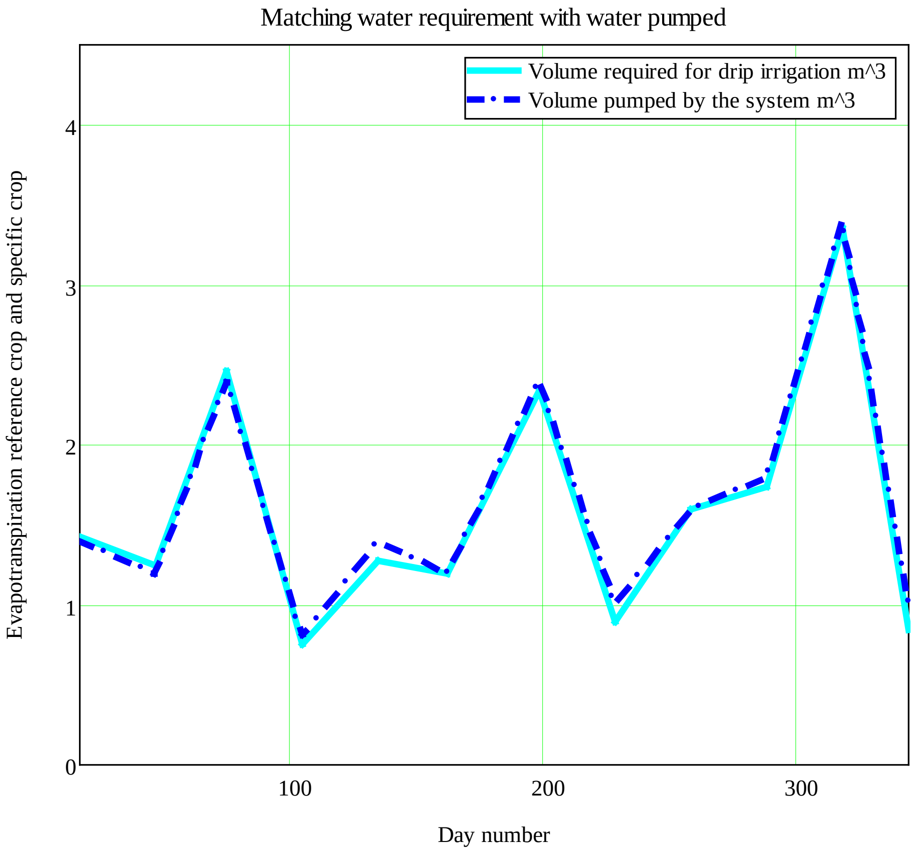
Pump flow December

$N_{Cycl12} := 5$

$DailyFlow12 := P_{flow} \cdot N_{Cycl12} \cdot N_{Min}$

$DailyFlow12 = 1 \times 10^{3}$ lpd

$$\text{Pumpflow}_o := \begin{pmatrix} \text{DailyFlow1} \\ \text{DailyFlow2} \\ \text{DailyFlow3} \\ \text{DailyFlow4} \\ \text{DailyFlow5} \\ \text{DailyFlow6} \\ \text{DailyFlow7} \\ \text{DailyFlow8} \\ \text{DailyFlow9} \\ \text{DailyFlow10} \\ \text{DailyFlow11} \\ \text{DailyFlow12} \end{pmatrix}$$


Matching water requirement with water pumped
Volume required for drip irrigation m^3
Volume pumped by the system m^3
Evapotranspiration reference crop and specific crop
0
1
2
3
4
100
200
300
Day number

Calculations to use in cost analysis

Energy cost diesel pump with drip irrig

$\mathrm{Yearly}_{W_m} := \mathrm{ETc}_m \cdot n_{\mathrm{days}_m}$ $\mathrm{Head} := 20\ \mathrm{m}$ $\mathrm{Effic}_{\mathrm{pump}} := 10\%$

$$\mathrm{Energy}_{\mathrm{diesel}} := \frac{\left(\sum \mathrm{Yearly}_W\right) \cdot \mathrm{Head}}{367\mathrm{Effic}_{\mathrm{pump}}}$$

$\mathrm{Energy}_{\mathrm{diesel}} = 634.616$

$\mathrm{Energy}_{\mathrm{diesel0.5}} := \mathrm{Energy}_{\mathrm{diesel}} \cdot 0.5$

$\mathrm{Energy}_{\mathrm{diesel0.5}} = 317.308$

Energy cost diesel pump surface

$\mathrm{Yearly}_{Wf_m} := \mathrm{ETcf}_m \cdot n_{\mathrm{days}_m}$

$$\mathrm{Energy}_{\mathrm{dieself}} := \frac{\left(\sum \mathrm{Yearly}_{Wf}\right) \cdot \mathrm{Head}}{367\mathrm{Effic}_{\mathrm{pump}}}$$

$\mathrm{Energy}_{\mathrm{dieself}} = 6.743 \times 10^3$

$\frac{\mathrm{kWh}}{\mathrm{ha}}$

$\mathrm{Energy}_{\mathrm{diesel0.5f}} := \mathrm{Energy}_{\mathrm{dieself}} \cdot 0.5$

$\mathrm{Energy}_{\mathrm{diesel0.5f}} = 3.371 \times 10^3$

$\frac{\mathrm{kWh}}{\mathrm{ha}}$

PV power operating point

From data sheet: $N := 36$ number of cells

$Vt := 22 \qquad Voc := \frac{Vt}{N} \qquad Isc := 2.2$ Amp $\qquad Vmax := 17$

Other constants $\qquad k := 1.38\cdot 10^{-23} \quad e := 1.602\cdot 10^{-19} \quad T := 273 + 25$

Find Io to use in the I-V equation:

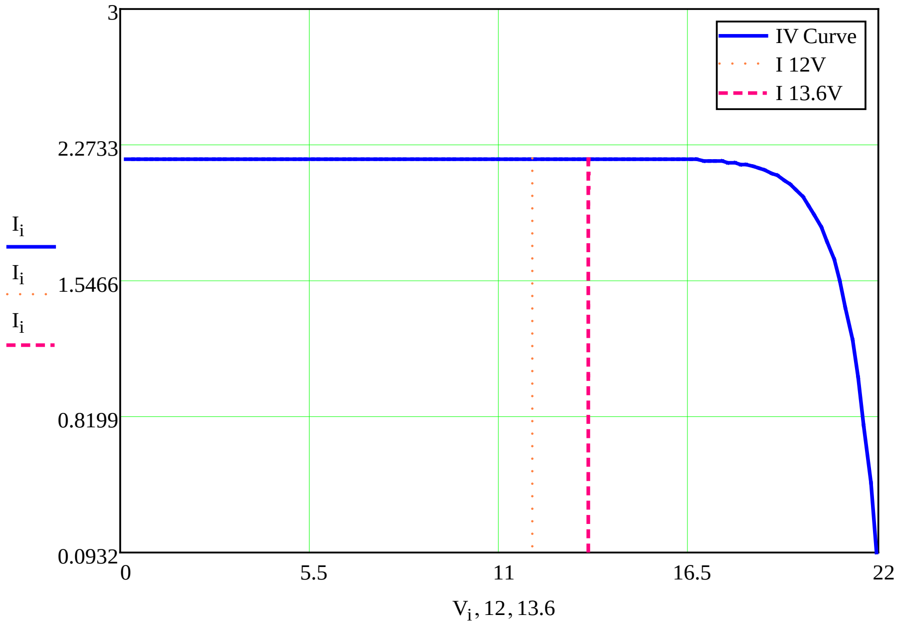
$$Io := \left(\exp\left(\frac{e\cdot Voc}{k\cdot T}\right) - 1\right)^{-1}\cdot Isc \qquad Io = 1.008\times 10^{-10}$$

IV characteristics of PV and battery load

$$i := 1, 2 .. \frac{Voc}{0.005} \qquad V_i := i\cdot 0.005\cdot N$$

$$I_i := \left[\max\left[0, Isc - Io\cdot\left(\exp\left(e\cdot\frac{\frac{V_i}{N}}{k\cdot T}\right) - 1\right)\right]\right]$$

PV curve



Power at 12V

$$I_{12v} := Isc - Io \cdot \left(\exp\left(e \cdot \frac{\frac{12}{N}}{k \cdot T} \right) - 1 \right)$$

$$I_{12v} = 2.2 \qquad P_{12V} := I_{12v} \cdot 12$$

$$P_{12V} = 26.399$$

Power at 13.6V

$$I_{13.6v} := Isc - Io \cdot \left(\exp\left(e \cdot \frac{\frac{13.6}{N}}{k \cdot T} \right) - 1 \right)$$

$$I_{13.6v} = 2.2 \qquad P_{13.6V} := I_{13.6v} \cdot 13.6$$

$$P_{13.6V} = 29.917$$

$$\Delta P := \frac{P_{13.6V} - P_{12V}}{P_{12V}} \cdot 100$$

$$\Delta P = 13.323\%$$

Calculation for a Permanent magnet Shurflo pump at a steady state with:

an applied voltage 13.6 VDC $E_a := 13.6\,V$

an assumed top speed of 1200 rpm $\omega_{max} := 1200 \cdot \frac{2\cdot\pi}{60} \frac{rad}{sec}$

assumed maximum torque 6.25 in-lbf $T_{stall} := 6.25 \cdot \frac{1}{12}\, ft \cdot lbf$

current at zero rotational speed 7.25amps $I_a := 7.25\, A$

We then calculate Km,Ra, and Kc

Constant proportional to the physical properties $K_c := \frac{E_a}{\omega_{max}}$ $K_c = 0.108\; V\cdot s$

Motor constant $K_m := \frac{T_{stall}}{I_a}$ $K_m = 0.072 \frac{ft\cdot lbf}{A}$

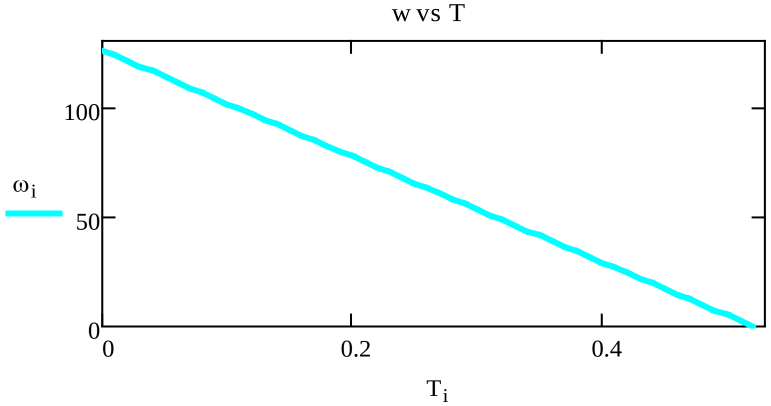
Armature resistance $R_a := \frac{E_a \cdot K_m}{T_{stall}}$ $R_a = 1.876\; \Omega$

Plotting vs T to verify

$i := 0, 1 .. 52$

$T_i := i \cdot .01$

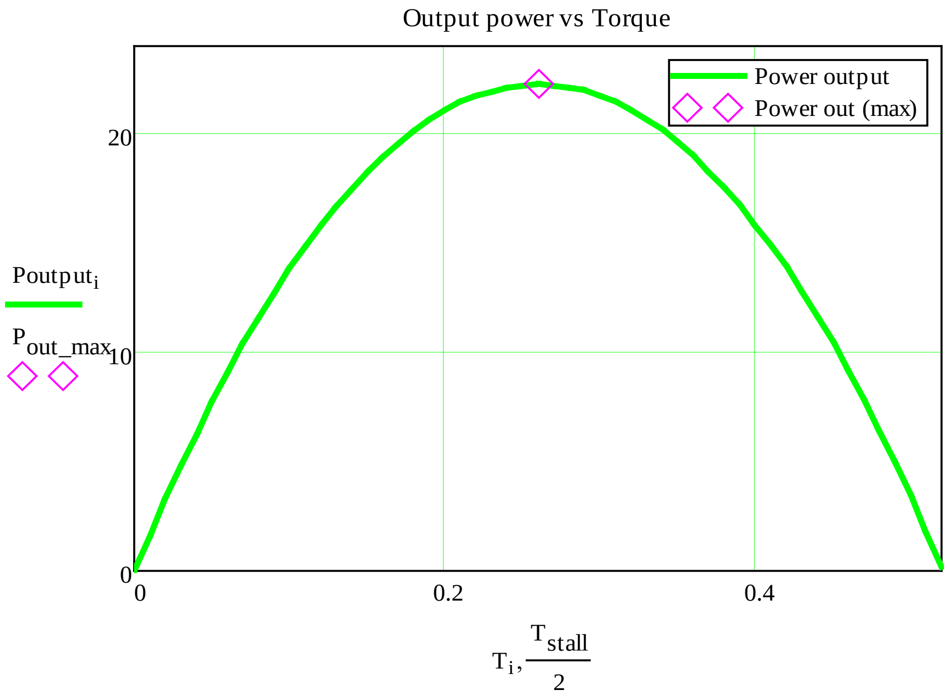
$$\omega_i := \frac{E_a - T_i \cdot \left(\frac{R_a}{K_m}\right)}{K_c}$$



Plotting output power vs Torque

$Poutput_i := T_i \cdot \omega_i \cdot 1.36$ $P_{out\_max} := \frac{T_{stall}}{2} \cdot \omega_{26} \cdot 1.36$ $P_{out\_max} = 22.289$ W

Or P_{out_max} $\frac{T_{stall}}{2} \cdot \frac{\omega_{max}}{2} \cdot 1.36 = 22.253$



Necessary input power at the maximum power point

$P_{in} := \frac{I_a}{2} \cdot E_a$ $P_{in} = 49.3$ W

Efficiency

$\eta := \frac{P_{out\_max}}{P_{in}} \cdot 100$ $\eta = 45.21$ %

Piping System from the pump to the tank

$\rho := 1.94$ density of fluid, lbf*s2/ft4

$K := 300000$ modulus of fluid, psi

$E := 400000$ modulus of material psi

$\mu := 0.0000234$ Dinamic viscocity lbf*s/ft4

$\gamma := 62.4$ lbf/ft3

$KL_{globe} := 0.25\cdot 2$ $KL_{Tee} := 1.5\cdot 4$

$KL_{elbow} := 1.5$ $KL_{reent} := 0.8$

$Q := 0.008466435$ ft3/s

$L := 330$ Ft $H := 30$ ft

$g := 32.17$Ft/s2 $H_{filter} := 1.6$ ft

$i := 0..6$

Inner diameter (ft) outer diameter(ft) Thickness(ft)

$$D := \frac{\begin{pmatrix} 0.622 \\ 0.824 \\ 1.049 \\ 1.38 \\ 1.61 \\ 2.067 \\ 2.469 \end{pmatrix}}{12} \quad D_o := \frac{\begin{pmatrix} 0.84 \\ 1.05 \\ 1.315 \\ 1.66 \\ 1.9 \\ 2.375 \\ 2.875 \end{pmatrix}}{12} \quad Th := \frac{\begin{pmatrix} 0.109 \\ 0.113 \\ 0.133 \\ 0.14 \\ 0.145 \\ 0.154 \\ 0.203 \end{pmatrix}}{12}$$

$$D_r := \frac{D_o}{Th}$$

Velocity ft/s

$$V_i := \frac{Q}{\left(\frac{\pi}{4}\right)\cdot\left(D_i\right)^2}$$

$V_i =$

4.012
2.286
1.411
0.815
0.599
0.363
0.255

Reynolds Number

$$Re_i := \frac{\rho\cdot V_i\cdot D_i}{\mu}$$

$Re_i =$

$1.724\cdot10^4$
$1.302\cdot10^4$
$1.022\cdot10^4$
$7.771\cdot10^3$
$6.661\cdot10^3$
$5.188\cdot10^3$
$4.344\cdot10^3$

Friction factor

$$f_i := \frac{0.316}{\left(Re^{\frac{1}{4}}\right)_i}$$

$$f = \frac{0.316}{Re^{1/4}}$$

$f_i =$

0.028
0.03
0.031
0.034
0.035
0.037
0.039

Pressure surge (PSI)

$$P_{surge_i} := \frac{\rho\cdot V_i}{4636.6}\cdot\left[4660\cdot\sqrt{1 + \frac{K\cdot\left(-2 + D_{r_i}\right)}{E}}\right]$$

$P_{surge_i} =$

17.976
11.338
7.233
4.604
3.566
2.357
1.58

Major loss head (ft)

$$h_{L_i} := f_i \cdot \left(\frac{L}{D_i}\right) \cdot \frac{\left(V_i\right)^2}{2g}$$

$h_{L_i} =$

43.929
11.55
3.669
0.997
0.48
0.146
0.063

Minor head loss (ft)

$$h_{l_i} := \left(KL_{globe} + KL_{elbow} \cdot 6 + KL_{reent} + KL_{Tee}\right) \cdot \left[\frac{\left(V_i\right)^2}{2 \cdot g}\right]$$

$h_{l_i} =$

4.078
1.324
0.504
0.168
0.091
0.033
0.016

Pipe line

$$P_{line_i} := \frac{\left(H + H_{filter} + h_{L_i} + h_{l_i}\right) \cdot \gamma}{144}$$

$$P_{max_i} := P_{line_i} + P_{surge_i}$$

$P_{line_i} =$

34.496
19.272
15.502
14.198
13.941
13.771
13.728

$P_{max_i} =$

52.472
30.61
22.735
18.803
17.507
16.128
15.307

Drip Irrigation design

Data

Tape specification Ro Drip (John Deere)

Spacement between lines

$S_f := 1$ m

Plant spacing

$S_p := 0.1$ m

Emitters spacing

$E_s := 0.2$ m

Flow rate

Lateral length

$Lm := 100$ m

Flow of manufacturer measurement

$Q := 335$ $\frac{LPH}{100m}$

Number of emitters per line

$N_e := \frac{Lm}{E_s}$ $N_e = 500$

Flow rate per emitter

$Q_e := \frac{Q}{N_e}$ $Q_e = 0.67$ LPH

Flow rate of laterals

$Q_L := N_e \cdot Q_e$ LPH

Number of laterals

$N_l := 50$

Number of emitters per unit area

$N_{epa} := \frac{1}{E_s \cdot S_f}$ $N_{epa} = 5$ $\frac{emitters}{m^2}$

Coefficient of variation $Cv := 0.03$ from manufacturer

Recommended percentage of wet area

$P_w := 60\%$

Wetted area by one emitter for sandy soils

$A_w := .2$

$D := \sqrt{\frac{(4 \cdot A_w)}{\pi}}$

Emitters per plant

$Ne_p := \frac{[(S_p \cdot S_f) \cdot P_w]}{A_w}$ $Ne_p = 0.3$

Distance between the emitters

$S_e := \frac{S_p}{Ne_p}$ $S_e = 0.333$

$W := D$

Confirming Pw

$Pw := \frac{(100 \cdot Ne_p \cdot .2 \cdot W)}{S_p \cdot S_f}$ $Pw = 30.278$

Not acceptablre for desert like wheaters

$Pw := \frac{(100 \cdot Ne_p \cdot .2 \cdot W)}{S_p \cdot S_f}$ $Pw = 30.278$

Not acceptablre for desert like wheaters

Minimum flow of sub-unit

$Qns := Q_e \cdot [1 - (1.278 \cdot Cv)]$ $Qns = 0.644$

Uniformity coefficient

$Cu := \left[\left[1 - \left(1.27 \cdot \frac{Cv}{\sqrt{N_{epa}}}\right)\right] \cdot \frac{Qns}{Q_e}\right] \cdot 100$ $Cu = 94.527$

Minimum working pressure per emitter

$$hn := \left(\frac{Q_e}{0.56}\right)^{\frac{1}{0.48}} \qquad hn = 1.453 \quad m$$

$$hns := \left(\frac{Qns}{0.56}\right)^{\frac{1}{0.48}} \qquad hns = 1.339 \quad m$$

$M := 3$

$$H_1 := M \cdot (hn - hns) \qquad H_1 = 0.341 \quad m$$

Lateral friction losses

$D := 16 \quad mm$

$$J_1 := 0.355 \cdot \frac{Q^{1.8}}{D^{4.8}} \qquad J_1 = 0.021 \quad m$$

Equivalent lenght of connection

$F_e := 0.11$ from table

$$J_2 := J_1 \cdot \left[\frac{(E_s + F_e)}{E_s}\right] \qquad J_2 = 0.032 \quad m$$

Lateral unitary losses

$F_1 := 0.33$ from table

$Hflat := J_2 \cdot F_1 \cdot Lm$

$Hflat = 1.058$ m

$i := \frac{0.5}{100}$

$ds := Lm \cdot i$ $ds = 0.5$

$Hm := hn + (0.73 \cdot Hflat) + ds$

$Hm = 2.725$ m

$hf := Hm - hn - ds$

$hf = 0.772$

$Hn := Hm - hf - ds$

$Hn = 1.453$ m

System's flow

$Q_{sys} := \frac{3.35}{3600}$ $\frac{m^3}{s}$

Diameter of distribution system

Required velocity 1.5 m/s for drip irrigation system (manufacturer)

$v := 1.5$

$Di := \sqrt{4 \cdot \frac{Q_{sys}}{\pi \cdot v}}$ $Di = 0.028$ m $Din := Di \cdot 39.37$

$Din = 1.106$ in

1 inch pipe is required to keep velocity at 1.5 m/s and the required flow of the system

VIII. BIOGRAPHICAL SKETCH OF THE AUTHOR

Carolina Barreto

Graduated with the highest marks from the National Engineering University of Nicaragua in May 2003 with a degree in Agricultural Engineering, Miss Barreto was granted with a Fulbright scholarship in 2006 to study her Masters in Energy Engineering: The Solar Option at UMASS Lowell. Previous to her academic experience in UMASS her technical renewable energy training includes Solar Photovoltaic Installation and Design, Wind Power, Micro hydro Power, Solar Water Pumping at Solar Energy International in Carbondale, CO (Aug 2004). Ms. Barreto has been transferring renewable energy technology to other developing world countries besides her own (Nicaragua) such as Haiti (Jan 2004), Mali (Mar 2005) and Peru (Jan 2007, June2007, Jan2008, June2008). Her goal is to find sustainable solutions to real problems and fight the abject poverty that third world countries suffer through the use of renewable energy.

Ms. Barreto worked for the Program of Alternative Energy Sources (PFAE) at the National Engineering University (UNI) in Nicaragua from March, 2003 to March 2006, and was the lead course facilitator for several workshops on solar micro-irrigation, PV assembly and rural electrification. She also worked for the Designated National Authority of the Clean Development Mechanism in Nicaragua (Jun 2005), coordinating renewable energy projects in order to certify the Carbon Emission Reductions in Kyoto Protocol market. After defending her master’s thesis on December 2008, Miss Barreto wants to continue her higher academic training by pursuing the Doctoral Energy Engineering Program at UMASS Lowell.