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Master's Thesis

TOPIC: VIABILITY OF MICRO HYDRO – SOLAR PV HYBRID IN RURAL ELECTRIFICATION IN RWANDA

A thesis submitted in partial fulfillment of the requirements for the award of Master of Science in Renewable Energy.

Thesis done and Submitted by

MUVUNYI RICHARD (Ref.No: 217036295)

Supervised by: Dr Venant KAYIBANDA

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VIABILITY OF MICROHYDRO – SOLAR PV FOR RURAL ELECTRIFICATION IN RWANDA

MUVUNYI RICHARD

A thesis submitted in partial fulfillment of the requirements for the award of Master of Science in Renewable Energy

DECLARATION

This Thesis is my original work and has not been presented for a degree in any other university.

Signature:..Date...

MUVUNYI RICHARD

This thesis has been submitted for examination with our approval as the University

Supervisor:

Signature: ....Date...

Dr VENANT KAYIBANDA

University of Rwanda

DEDICATION

To the Almighty God,

To my family,

To my workmates

To my classmates

This work is dedicated.

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LIST OF ACRONYMS

GoR	Government of Rwanda
PV	Photovoltaic
MPH	Micro Hydro Power
GPS	Global Position Surface
RET	Renewables Energy Technologies
RES	Renewables Energy Screen
GHI	Global Horizontal Irradiance
PHES	Pumped Hydroelectric System
NASA	National Aeronautics and Space Administration
PVGIS	Photovoltaic Global information System
PVSYST	Photovoltaic System Software
AC	Alternative Current
DC	Direct Current
REG	Rwanda Energy Group

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ABSTRACT

Electricity in Rwanda is available with only 51% of the households are connected to the central grid; even the above coverage is confined to major towns and cities. The village for this study, Mwogo Sector / Bugesera District is composed with more than 250 households without electricity for lighting and entertainment (TV and Radio). The estimation shows Mwogo sector among least populated with share of 4.9% inhabitants of total resident population of Bugesera District. And is touched by Akagera liver on its north boundary. The source of energy for lighting in Mwogo sector vary by area of residence. In urban areas, the three main sources of energy for lighting are electricity (48%), kerosene lamp (23.7%), and Candle (18.4%) whereas in rural areas, the common mainly used sources of lighting are kerosene lamps (37.4%), Candle (11.2%) and electricity (6%). This lack of electricity distribution contribute to lack of vital public services. And nothing has been done so far in developing the renewable energy resources such as small-scale hydro and solar energy in the village. In this study, feasibility of micro hydro/PV pump hybrid electric supply system to one pilot village in Rwanda was analyzed using PVSYST software as optimization and sensitivity analysis tool. Surface Metrology is used for the estimation of solar energy potentials. Electric load for the basic needs of the community, such as, for lighting, radio, television is estimated. One primary school, one community building for youth activities and one health Center are also considered for the community. As a result the integration of solar PV pump and micro hydro was simulated and proved to be a viable operational system that can work in rural area of Rwanda and thus proved to be less expensive compared to usually solar batteries normally accustomed to keep the supply working in the nights or in absence of sun familiar in other hybrid of PV solar/Micro Hydro.

CHAPTER ONE: BACKGROUND AND INTRODUCTION

1.1 General introduction

Electricity is the backbone and imperative condition for a country to be developed in terms of economy and the good quality in terms of lifestyle for the citizens. The estimation shows that in many developing countries several billion of people do not have mandatory and vital public services because of not having electricity. In most cases, the extension of electricity is either impossible because of geographic allocation, or because of high financial involved in the extension or not enough for the demand. Due to that, the adoption of an off-grid stand-alone RES constitute a useful option for electricity inadequacies in rural area of the developing countries in which the evolution in national grid extension continue to be slower than the population growth. (Saheb-koussa, 2009)

1.2 Background

Access to modern energy, especially in rural, remote areas would help significantly to reduce poverty, to get better health care and education, to facilitate modern communication and information systems. Further, it will reduce city migration and depletion of fossil fuel resources and deforestation as well as pollutant gas emission to the environment. With electricity, lines being confined to large cities and towns, developing countries lag far behind in many sectors when compared to industrialized countries. Rwanda, despite being the one of Eastern African country, has a very poor electricity penetration rate. Electricity is available with only 51% of the households are connected to the central grid; even the above coverage is confined to major towns and cities. Since the Rwanda Government advocates Green Economy Renewable energy sources (solar, wind, hydropower etc) are attracting and got more attention as an alternative energy sources than conventional biomass based energy system that accounts 85 % of the total primary energy consumption in the country (infrastructure, 2018). This is not only due to the diminishing fuel sources, but also due to environmental pollution and global warming problems. Among these sources is the solar and hydropower energy, which is the most promising, as the fabrication of less costly photovoltaic (PV) devices becomes a reality and Attractive exploitable capacity of Hydropower. However, using only one type of energy source may result shortage of reliable and sustainable energy supply for the country. Such kinds of problems arise due to large variances of PV output power under different insolation levels and reduction of stream flow during drought seasons. Hence an alternative option to overcome this, is by integrating Hydropower with Photovoltaic Panel which alleviates this problem. Hybrid energy systems are combinations of two or more energy conversion devices (e.g. Diesel/Wind with storage devices), or two or more Renewable energy resources (e.g. PV/Hydro), Hybrid systems provide a high level of energy security, and reliability through the integrated mix of complementary generation methods, and often will incorporate a storage system (battery, fuel cell) and backup system (Generator) to ensure consistent supply. (Uwamahoro, 2012)

1.3 Problem Statement

Generally, Rwanda is well endowed with renewable energy resources, but most potential still remains untapped. Micro hydro-power in particular constitutes a significant potential for rural power supply with many areas having ample rainfall and most streams and rivers unexploited. Solar irradiation is high between 4-6 $kWh/m^2/day$ but diffusion is hampered by high initial cost and limitations on high load usage. Currently (in 2018), the GoR has set a target of 100% electrification by 2024. According to the Rwanda Energy Group, 48% of Rwandan households will use off-grids solutions to meet their needs while 52% will be connected to the grid, to achieve this target (Group, 2014). Connectivity from central grid for rural electrification not always affordable due to the fact that most of the non-electrified parts are located in remote and difficult areas, like hilly regions, forests, and they are scattered, which demand enormous investment for grid. Secondly usage of PV solar for rural households electrification has resulted in lack of proper maintenance for malfunctioning batteries, faulty wiring, broken DC-appliances. With high population about 87% of the country living in rural area, to achieve the goal of 100% electrification much need to be done and small scale hybrid of micro hydro and solar PV is viable solution for rural electrification in Rwanda. A stand-alone off grid solar and micro hydropower Hybrid system consists of electric energy whereby energy produced by the photovoltaic system will be used to pump water during the day from a lower reservoir, in our case rivers to upper reservoir which is usually an artificial or semi- artificial dam. Water is released back through Fancis turbines& alternators to meet the energy commitments. (Uwamahoro, 2012)

1.4 Objectives

1.4.1 Main Objective

The main objective of this thesis is to study the feasibility of micro-hydro-photovoltaic system and energy storage for hybrid electrification of rural area of Rwanda to sustainably and efficiently satisfy the energy demand of population, where central grid electricity has not reached yet due to many geographical and economic constraints.

1.4.2 Specific Objectives

- Determine the present and near future electrical energy need of the community living in rural area of the country.
- Estimate the renewable energy resource of the area; micro hydro and solar radiation potential.
- Design a standalone hybrid system to meet the electrical energy demand of the population.
- Analyze the performance of the designed system by using a tool (PVSYST)
- Evaluate the technical performance of the micro hydro-PV Hybrid system and make sensitivity analysis.

1.5 Scope and Limitations

The scope of this study is to assess the technical feasibility of a standalone PV- Micro hydro hybrid energy system to supply the rural electrical load detached from national grid or with shortage of energy supply in Rwanda. This study shall collect and analyze relevant data and information to examine and select the most suitable systems configuration, recommend necessary action, necessary measures that configure a system to accommodate the current and near future electrical energy demand for rural area in the Country. The study only focuses on solar energy and micro-hydro resource assessment of among different renewable energy resource that we may have in our Country such as biomass, geothermal and biogas. And the limitations of this research shall then clearly be told as to give a way to next coming researchers and those who are interested in the area.

1.6 Report outline

This work is subdivided into five chapters:

- The first chapter provides the general introduction of this project;
- The second chapter provides the literature review;
- The third chapter provides the research methodology;
- The fourth chapter provides the system Modeling (PVSYST software) and results analysis;
- Finally, the fifth chapter is the conclusion and recommendation.

CHAPTER TWO: LITERATURE REVIEW

Several researches have been conducted in hybrid off-grid power generation all over the world and in Rwanda. Different scholars used different Technology options and approaches to evaluate the various configurations of renewable energy resources, such as solar energy, Wind energy, small hydropower and their hybrid configurations.

Nisingizwe Emmanuel and Cyrus Wekesa (2017) presented a case study for rural electrification in Rwanda entitled “Design of solar – Wind hybrid system for rural electrification in Rwanda”, the aim of this project was to study the feasibility of a Wind-PV hybrid system for local electricity production in order to power rural communities in Kayonza District where found strongest wind speed in the country by using a HOMER software, His objective was to develop a hybrid system cost competitive to supply energy for remote villages for a model community of 200 households with one primary, secondary school, one milling house, one health center and one government building which is used as office. His study intended to promote an efficient and cost competitive system configuration of hybrid power system to improve the life of the rural community not yet connected to the central grid. He concluded that renewable energy sources and/or their hybrid configuration are cost competitive although the huge capital investment of the renewable energy resources is the major limitation. However, from social point of view and improvement of the life of the people not connected from the central grid the cost is not significant matter and cannot be rejected. According to my suggestion he should indicate an option how the high initial capital cost can be reduced or replaced by locally available alternative energy source. (Nisingizwe, 2018)

Jeannine Uwibambe (2017) developed Design of Photovoltaic system for rural electrification in Rwanda. The main goal of his project work was to show how a photovoltaic system can be used to solve the problem of electricity access in Kanazi, the village located in Bugesera District. Since electricity from the grid is not easily available in this village due to the high cost of transmission lines per Km, photovoltaic technology such as solar home system and stand-alone solar systems are proposed in terms of cost and efficiency to generate electricity for households and public service applications. His study intended to promote an efficient and cost competitive system configuration compared to extension from main grid but she didn't mention measure that should go with the nature of Solar which is intermittency (not shining at night but also during daytime low insolation once there may be cloudy or rainy weather) and unpredictability that makes solar energy panels less reliable solution. However it becomes expensive when batteries are used to keep the supply working in the nights or absence of sun. (Uwibambe, 2017)

A research conducted by Odax Ugirimbabazi (2015), entitled "Analysis of power system options for rural electrification in Rwanda" his aim was to develop an hybrid power system solution from the best combination of RET (Renewable Energy Technology) that will use the resources which are available in Burera district Rwandan rural area to fulfill the electricity demand in a reliable, affordable and sustainable manner with a cost-effective solution using HOMER software. His study intended to promote an efficient and cost competitive system configuration of hybrid Renewable Energy power system to solve the problem of electricity in Burera and He concluded by finding out that hybrid of hydro and wind is not applicable due to problem that came to location near the equator which is not favorable for wind and then he chooses to a system of hydro and batteries-diesel generator incorporated together as storage medium. (Ugirimbabazi, 2015)

Almost all of the above scholar's paper shows the hybrid system either only PV/wind excluding hydro or Wind/Hydro excluding solar or solar alone. But in this study we combine PV with Micro-Hydro. This system configuration is best of all due to the reason Rwanda have plenty of solar resource especially in Eastern and Center of the Country, and Huge amount of Hydro potential in almost many parts of the country. In addition from the above literature reviews, it is observed that no researcher has done Renewable energy technology Screen or other simulation software for the design of hybrid micro-hydro-Solar PV and almost all of them dedicated to feasibility studies. Hence, PVSYST is widely used for most of the RES based systems. Thus, based on the above literature reviews, PVSYST software is taken for the purposes of this study to carry the feasibility assessment.

2.1 Micro Hydropower generation System

Water is the most common source of energy in Rwanda. It accounts 46 percent of the total energy mix. Hydropower engineering refers to energy produced from water (Kinetic energy ½ mv^2) stored in a dam or a barrage in other words hydropoweris the electricity produced from machines Turbine (Mechanical energy through shaft) and Generator (Electrical energy) that are run by moving water. (Saalthum, 1998)

2.1.1 Micro Hydropower basics

Micro-hydro power is the small-scale system in the range of 5-100 KW harnessing of energy from falling water; for example, harnessing enough water from a local river to power a small factory or village. Which means it does not have water storage capability. It will produce power only when water is running or it might have relatively small water storage capability. Micro-hydropower is an interesting prospect for providing electricity for rural communities. (Payne, 1988)

2.1.1.1 General principles of MHP

All hydro systems work on the same principle of converting the pressure in a head of water into rotary mechanical power, and then use a generator to turn the mechanical power into electricity. In every hydropower development, the two important parameters that help to determine available hydraulic power inherent in the system are the volumetric flow (which is how much water moves per unit time) and the available head. The head is defined as the vertical distance that water drops from a potential intake to turbine. This head is also a function of the characteristics of the channel or pipe through which the water flows. It is generally better to have more head than more flow rate; because less water will be needed to produce a given amount of power with smaller, less expensive equipment. Sites where the gross head is less than 20m would normally be classed as "low head". From 20-150m would typically be called "medium head". Above 150m would be classed as "high head". (Payne, 1988)

Flow is quantity of water available, and is expressed as "volume per unit of time", such as gallons per minute (gpm), cubic meters per second (m3/s), or liters per second (L/S). Design flow is the maximum flow for which the hydro system is designed. It will likely be less than the maximum flow of the stream (especially during the rainy season), more than the minimum flow, and a compromise between potential electrical output and system cost.

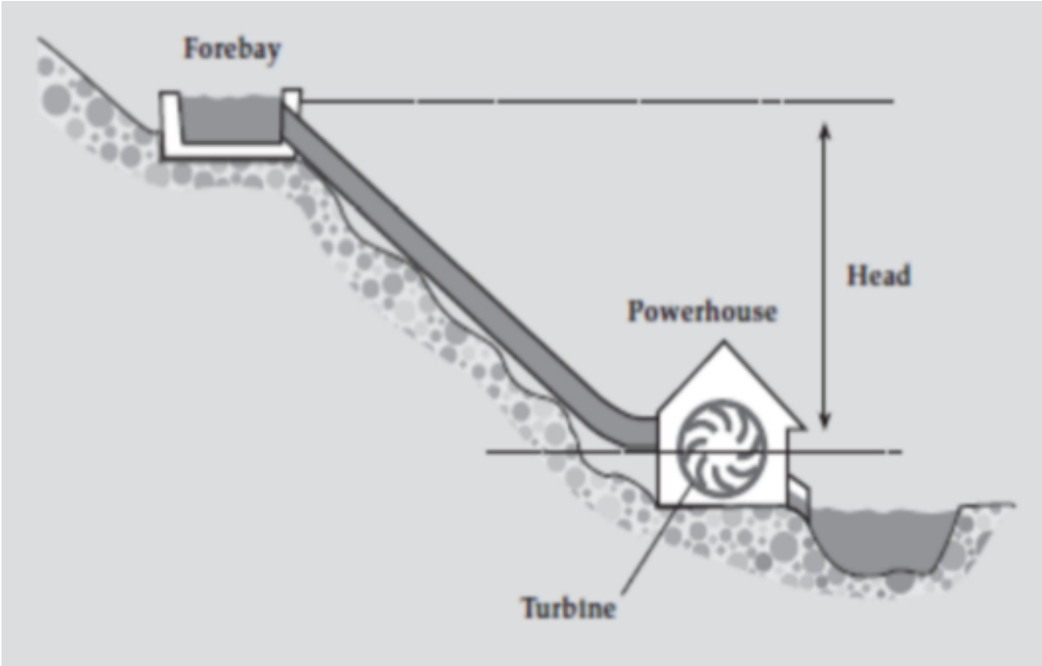


Figure 1: Head of Hydraulic Turbine (standards, 1996)

2.1.1.2 Power from Water

Water can generate power when it moves from a high potential energy state to a low potential energy state. How this happens?We consider: a mass of water **m,** water falling a height **h** through a gravitational field with constant gravitational acceleration **g**(g = 9.81m/s^2 sometimes rounded at 10 m/s^2).

The change in potential energy **PE** water is:

PE water = m $_{water}$**x g x h**, where height **h** is called the elevation or hydraulic head andg = 9.81 m/s^2

Dams with turbines and generators are used to convert the change in potential energy into mechanical kinetic energy.

The water behind a dam falls through an elevation **h**. If the density of water $\mathbf{d_{water}}$ is considered a constant, the mass of falling water can be written as:

$\mathbf{M_{water}} = \mathbf{d_{water}}$ **x** $\mathbf{V_{water}}$,where $\mathbf{V_{water}}$ is volume of water falling.

Substituting $\mathbf{M_{water}} = \mathbf{d_{water}}$ **x** $\mathbf{V_{water}}$

$\mathbf{PE_{water}} = \mathbf{d_{water}}$ **x g x h x** $\mathbf{V_{water}}$

The rate$\mathbf{Q_{water}}$falls through the effective head **h** depends on the volume of the penstock as indicated in figure below. (Arndt, 1991)

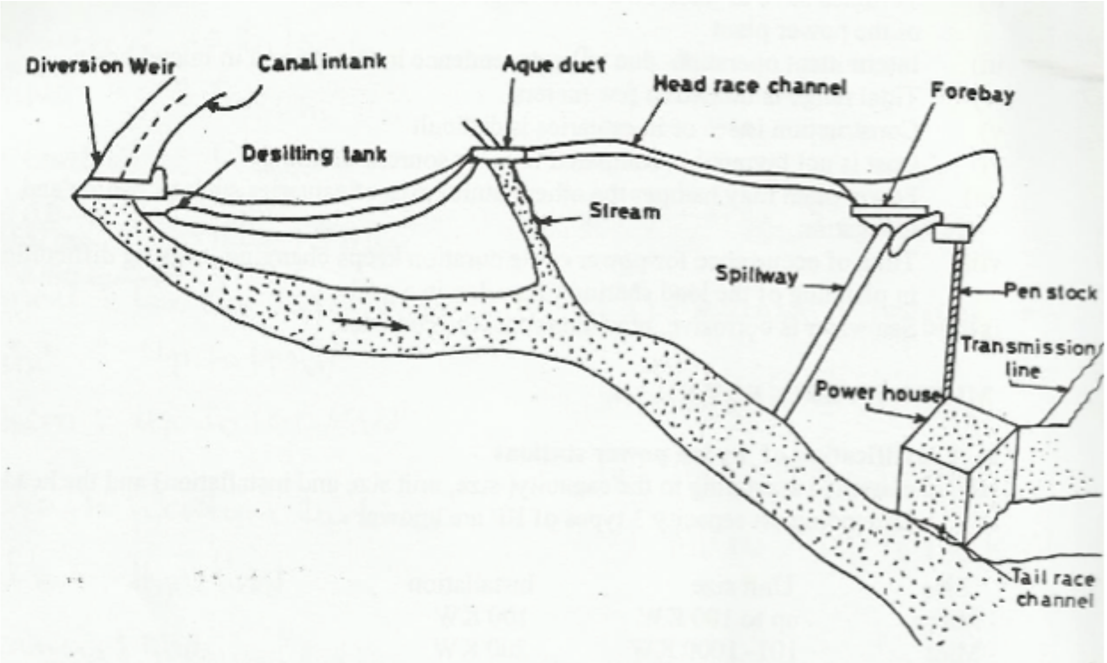


Figure 2: Typical arrangement of small Hydro power station (DuBow, 1981)

If the penstock volume is too small, the output power will be less than optimum because the flow rate $\mathbf{Q}_{water}$ could have been larger.

On the other hand, the penstock volume cannot be arbitrarily large because the flow rate $Q_{\mathbf{water}}$ through the penstock depends on the rate that water fills the reservoir behind the dam.

The volume of water in the reservoir, and corresponding height **h**, depends on the water flow rate into the reservoir.

During drought conditions, the elevation can decline because there is less water in the reservoir. During the rainy season, the elevation can increase as more water drains into the streams and rivers that fill the reservoir behind the dam.

Hydropower facilities must be designed the balance the flow of water through the electric power generator with the water that fills the reservoir through such natural sources as rainfall, Snowfall, and drainage. (Arndt, 1991)

2.1.1.2.1 Power from Dams

A hydropower station uses a dam, from which water will go down a height **h** and pass a turbine.The potential energy of water is converted into kinetic energy of the turbine, which is coupled to an electric generator.

A mass **m** with height **h** will have a **potential energy** ***mx h x g*****,** where **g** is the acceleration of gravity.

If flow **Q (m^3/s)** is passing the turbine, its mass will be **density of water**

D_{water}x Flow Q = D_w x Q = D x Q .

The mechanical power **P_m**the dam produces is:

P_m = D_wxQxh x g (J/s) = 10 Qxh (kW) because**D_{water} = 1000 Kg / m^3 and**

g = 9.81 rounded = 10 m/ s^2

The principal use of the dam is to use the reservoir to regulate the electric output by regulating the flow Q through the turbine. Besides storage as a second use, many dams also are used to regulate irrigation water to downstream agriculture. (Arndt, 1991)

2.1.1.2.2 Power from Rivers

The ***kinetic energy*** of flowing rivers in some places still is used to drive waterwheels. The rotational energy then is used directly for powering saws in the woodcutting industry for example. Modern waterwheels often convert the rotation of wheel into electric power.

For a flow with velocity **v** and mass ***m,*** the Kinetic energy equals **½ m xv^2.**

If**Q(m^3/s)** passes the water wheel or turbine its mass again will be **Q x d (kg/m^3)** ,

(d is density of water = 1000 kg/m^3), giving a mechanical power $P_{m.}$

P_m = ½ Q x d xv^2= ½ Q x v^2 (kW) (Arndt, 1991)

2.1.1.2.3 Comparison of dams and flowing rivers

The height ***h*** in equation **Pm = d x Q x g x h (J/s),** while the velocity **v** in the equation

P= ½ Q x d xv^2 (W) often is not much higher than **1 (m/s).** This implies that for the same amount Q of water passing, dams are 1,000 times as effective as flows.

Besides, in a dam one may use all the water from a water stream, while in a waterwheel usually only part of the stream is forced to pass the wheel.

The kinetic energy of flows only will be useful in specialized small- scale applications such as woodcutting**.** (Arndt, 1991)

a. Common components of micro hydropower plant

The components of HPP are the following:

- Diversion weir
- Canal in tank/intake
- Desilting chamber/ tank

- Water conductor system/ Head race channel
- Forebay /balancing reservoir
- Surge tank (if necessary)
- Penstock/ Pressure conduit
- Power house: Turbine, generator, Protection and control equipment, Drainage system, lighting and ventilation system.
- Tail race channel

b. Civil Work Components of Micro Hydro power

The common components of MHPP are indicated on the design of a typical arrangement of a Micro Hydro power station below:

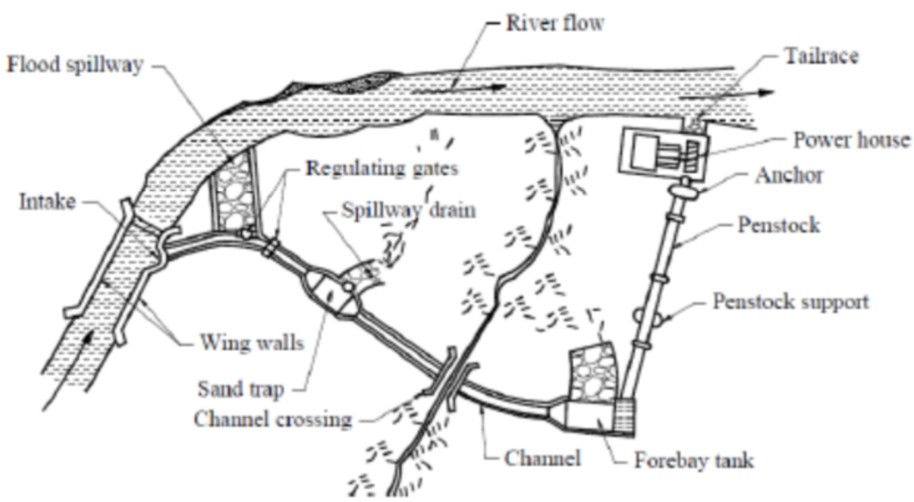


Figure 3: General layout of micro hydro power (Pandey, 2006)

i) Intake: Intake is the primary means of passage of water from the source of water. Intake could be of side intake type or the bottom intake type. Usually, trash racks have to be placed at the intake, which acts as the filter to prevent large water born objects to enter the waterway of MHP (Micro Hydro Project).

ii) Headrace Canal: Headrace canal conveys the water to the fore bay. Sometimes, pipes can also be used in place of the canals.

iii) Settling Basin: In order to reduce the sediment density, which has negative impact to other components of the MHS (Micro Hydropower System) de-sanding basins are used to capture sediments by letting the particles settle by reducing the speed of the water and clearing them out before they enter the canal. Therefore, they are usually built at the head of the canal. They are equipped with gate valves for flushing the settled undesirable sediments. De sanding basin is capable of settling particles above 0.2-0.3 mm of size.

iv) Forebay: Constructed in reinforced concrete of stone masonry. Storage capacity is usually 2 minutes. Balancing reservoirs is required in case of load fluctuation.

v) Penstock

- It feeds the machines with water.
- Diameter and thickness of penstock are important parameters to be well determined.
- Generally penstocks are fabricated of mild steel; PVC pipes can be used in order to reduce the cost of the HP station.

vi) Spillway

- Can be provided in form of channel or pipe
- Its role is to control the level of water therefore to avoid flood in the area where HPP is installed.

vii) Power house building

- It accommodates turbine, generator, control panels, auxiliary equipment etc..
- Height of building is kept about 3 to 5 m

viii) Tail race channel

It is a channel constructed in stone or brick masonry where water passes after flowing in the turbine; it has trapezoidal or rectangular shape. (Arndt, 1991)

2.1.2 Classification of MHPP (Micro hydro power plants)

The Micro-Hydropower Plants can be classified based on type of Operational feature, by demand of Electrical power, by installed capacity, available head at the inlet, discharge through the vanes and specific speed.

2.1.2.1 Classification of hpp according to head

The types of hydroelectric power plants classified according to Head are:

i) High head HEP: Head is more than 150 m.

They have a large reservoir on higher level and water from high level reservoir flows through pressure conduit/pipe to the turbine and is finally discharged into the tail race.

The upper reservoir is usually formed by constructing a dam on a river valley at high level. The excess water from the reservoir is discharged through the gates in the dam. The tail race water usually meets the river along the downstream. (Kayumba Epimaque, 2005)

ii) Medium head HEPP: Head 20m to 150 m.

They have a dam on a river forming the reservoir on the river side and a power house on the lower level. The tail race water usually meets the river along the downstream. (Arndt, 1991)

iii) Low head HEPP: Head 2m to 20 m.

They are usually with a barrage on a flowing river and Turbine- Generator units mounted within the nozzle shaped tubular passage through the barrage. (Kayumba Epimaque, 2005)

iv) Underground high head HEPP

They are built at lower level and inside a cave. The tail race water is discharged through a tunnel into the downstream path of the river.

v) Pumped storage HEPP

During off peak period the machine operates as motor-pump and converts electrical energy to potential hydro energy storage. During peak load on the electric grid, the machine operates in Turbine- Generator mode and converts Hydro energy to electrical energy.

2.1.2.2 Classification of hpp according to power output

i)large hpp > 100 Mw

ii) medium hpp > 15 Mw

iii) small hpp equal 15 Mw or less than 15 Mw

iv) mini hpp between 100 Kw to 1 Mw

v) micro hpp up to 100 Kw

2.1.2.3 Classification of Hydropower by Operational Feature

a) Conventional Hydro Electric scheme with large reservoir

Reservoir is created in a valley by building a dam across a river flowing through the valley at reasonably high level. Such locations are usually available where the river flows through valleys in high mountainous region.

The power plant is built on the downstream side of the dam. Water from the reservoir may be taken through pressure pipe, tunnel, penstock etc up to the turbine.
The plant rating range covers a few hundred kW to few thousand MW.
These schemes include High Head, Medium Head and Underground high head HEPP. (Habimana, 2005)

b) Run – of –the River Schemes

They are built across continuously flowing river with minor seasonal variation in flow. A barrage is built across the river and turbines are housed within the barrage.
The upstream side of the barrage has a small pool of water at higher level than the downstream side of the barrage. The run of the river plants are of Small, Mini or Micro size and employ low head.
The run of the river employ the following types of turbines:

a) Bulb turbine

b) Pit turbine

c) Tube turbine

c) Diversion Canal Schemes

These are also Run of the river Schemes. The part of the water is diverted by means of a flat canal to a Weir at a suitable geographic location. The run of the river plant is built in the weir. The tail race water flows to the main downstream of the original river. (Habimana, 2005)

d. Multi –Step River Valley Schemes

Three or more reservoirs are built at different levels along the path of flowing river. The discharge of first power plant is used to filling the second reservoir at lower level, and so on.

e. Pumped Hydro Energy Storage Scheme

Pumped-storage hydroelectricity (PSH), or pumped hydroelectric energy storage (PHES), is a type of hydroelectric energy storage used by electric power systems for load balancing. The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost surplus off-peak electric power is typically used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest.

They are large MW range energy storage plants to supply power during peak loads on the electrical network. Pumped storage plants have the advantages of generating electricity at lower cost compared to other peak load plants (gas and diesel power plants). Water is pumped back to the reservoir during off-peak loads (eg: during night times). This is the major advantage of pumped storage power plant. (Habimana, 2005)

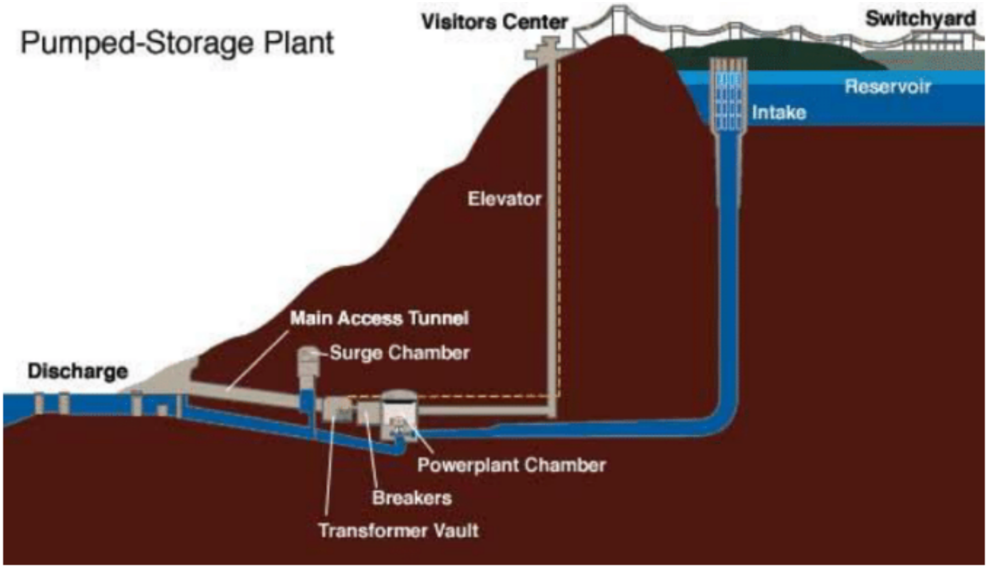


Figure 4: Pumped storage Hydroelectric turbine (Funkjoker, 2012)

How pumped storage plant works?

A pumped storage plant has two separate reservoirs, an upper and a lower one. When electricity is in low demand, for example at night, water is pumped into the upper reservoir. When there is a sudden demand for power, giant taps known as the head gates are opened.

Why pumped storage plants are useful?

In a hydroelectric power station water is stored behind a dam in a reservoir. This water has gravitational potential energy. At pumped storage hydroelectric stations water is pumped back into the reservoir when there are periods of low power demand.

2.1.3 Classification of hydro electric or hydraulic turbines

The device, which converts hydraulic energy into mechanical energy or vice versa, is known as Hydraulic Machines. The hydraulic machines, which convert hydraulic energy into mechanical energy, are known as hydraulic turbines. The hydraulic turbines are usually designed for specific applications and outputs, and services depending upon how much water is available every year. (Kayumba Epimaque, 2005)

1. Impulse type (Pelton) for high head

2. Reaction type (Francis and Kaplan) for medium and low head

Reaction types further has two versions:

2.1 Reaction type: Francis

2.2 Propeller type: Kaplan

2.1.3.1 Pelton hydro turbine (Impulse turbine)

Pelton turbine has a Head up to 1000 m and a power out up to 20 MW. It maintains a high efficiency over a wide flow range. It has a wheel of large diameter with buckets on the perimeter. The buckets are in two halves with a gap in between to allow flow of water without obstruction. Number of jets may be 1, 2, 4, 6.

Working principle of Pelton wheel:

In an impulse turbine (Pelton), water from high head received with high velocity and kinetic energy impinges on the buckets of the wheel and the wheel rotates**.**

Water jets at high speed are injected through the nozzle on buckets.

The water jets strike on the concave portion of the bucket with an impulse and the buckets receive the kinetic energy. The wheel rotates and the next buckets come in front of the jet and so on.

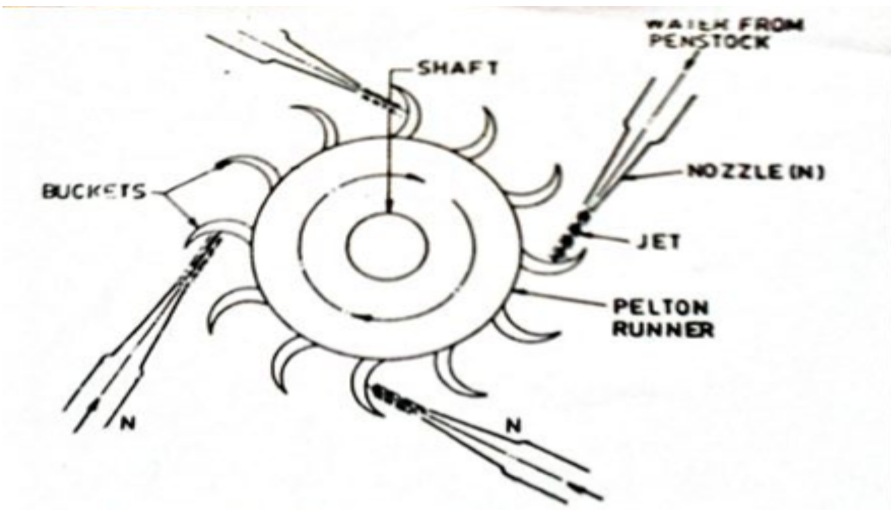


Figure 5: Principle of Impulse Turbine (Pelton wheel) (Hernandez, 2013)

2.1.3.2 Francis hydro turbine (Reaction turbine)

The Francis turbine is a type of water turbine that was developed by James B. Francis in Lowell, Massachusetts. It is an inward-flow reaction turbine that combines radial and axial flow concepts. Water enters from the penstock into spiral casing, and then passes through stationary stay guide rings and movable wicket gates over the turbine runner blades into draft tube and then to the tail race. The turbine runner blades are shaped such that water glides over them and create torque, the runner rotates. Francis turbines are preferred for a wide range of Medium Heads. Francis turbines are the most common water turbine in use today. They operate in a water head from 40 to 600 m (130 to 2,000 ft) and are primarily used for electrical power production. The electric generators which most often use this type of turbines have a power output which generally ranges just a few kilowatts up to 800 MW, though mini-hydro installations may be lower. Penstock (input pipes) diameters are between 3 and 33 feet (0.91 and 10.06 meters). The speed range of the turbine is from 75 to 1000 rpm. Wicket gates around the outside of the turbine's rotating runner control the rate of water flow through the turbine for different power production rates. Francis turbines are almost always mounted with the shaft vertical to isolate water from the generator. This also facilitates installation and maintenance.

Main parts of Francis hydro turbine are:

Spiral casing: The spiral casing around the runner of the turbine is known as the volute casing or scroll case. Throughout its length, it has numerous openings at regular intervals to allow the working fluid to impinge on the blades of the runner. These openings convert the pressure energy of the fluid into momentum energy just before the fluid impinges on the blades. This maintains a constant flow rate despite the fact that numerous openings have been provided for the fluid to enter the blades, as the cross-sectional area of this casing decreases uniformly along the circumference.

Guide or stay vanes: The primary function of the guide or stay vanes is to convert the pressure energy of the fluid into the momentum energy. It also serves to direct the flow at design angles to the runner blades.

Runner blades: Runner blades are the heart of any turbine. These are the centers where the fluid strikes and the tangential force of the impact causes the shaft of the turbine to rotate, producing torque. Close attention in design of blade angles at inlet and outlet is necessary, as these are major parameters affecting power production.

Draft tube: The draft tube is a conduit which connects the runner exit to the tail race where the water is discharged from the turbine. Its primary function is to reduce the velocity of discharged water to minimize the loss of kinetic energy at the outlet. This permits the turbine to be set above the tail water without appreciable drop of available head.

Working principle of Francis turbine

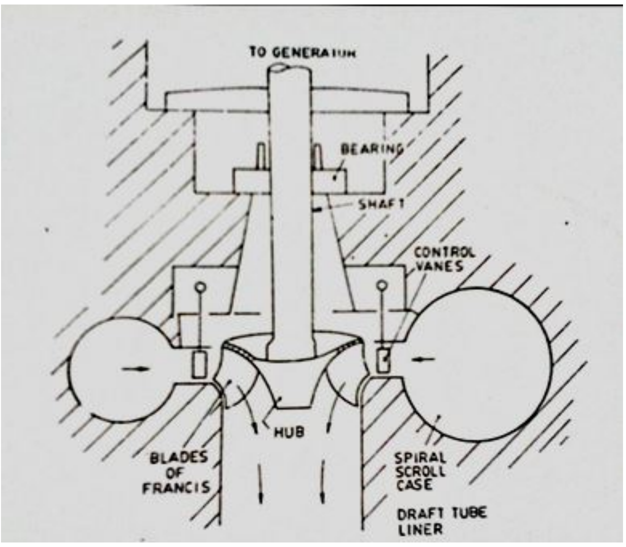


Figure 6: Design of Francis turbine with Generator and components (Brekke, 2002)

Data of a Francis turbine

Head	156 m
Runner diameter	5.15 m
Speed	150 RPM
Output	340 MW

2.1.3.3 Kaplan hydro turbine (Propeller turbine)

The Kaplan turbine is a propeller-type water turbine which has adjustable blades. It was developed in 1913 by Austrian professor Viktor Kaplan, who combined automatically adjusted propeller blades with automatically adjusted wicket gates to achieve efficiency over a wide range of flow and water level. The Kaplan turbine was an evolution of the Francis turbine. Its invention allowed efficient power production in low-head applications that was not possible with Francis turbines. The head ranges from 10–70 meters and the output from 5 to 200 MW. Runner diameters are between

2 and 11 meters. Turbines rotate at a constant rate, which varies from facility to facility. That rate ranges from as low as 69.2 rpm (Bonneville North Powerhouse, Washington U.S.) to 429 rpm. The Kaplan turbine installation believed to generate the most power from its nominal head of 34.65m is as of 2013 the Tocoma Power Plant (Venezuela) Kaplan turbine generating 235MW.Kaplan turbines are now widely used throughout the world in high-flow, low-head power production. The runner has only a few large blades (3 to 10) mounted on its hub. Blades are either fixed or adjustable. Kaplan runner is with a large hub at the top of shaft with a few large adjustable blades on the hub. Water flowing through spiral casing into the tail race propels the blades and rotates the shaft. Kaplan turbine is preferred for low heads. Even small hydro turbines are with Kaplan runner. (Arndt, 1991)

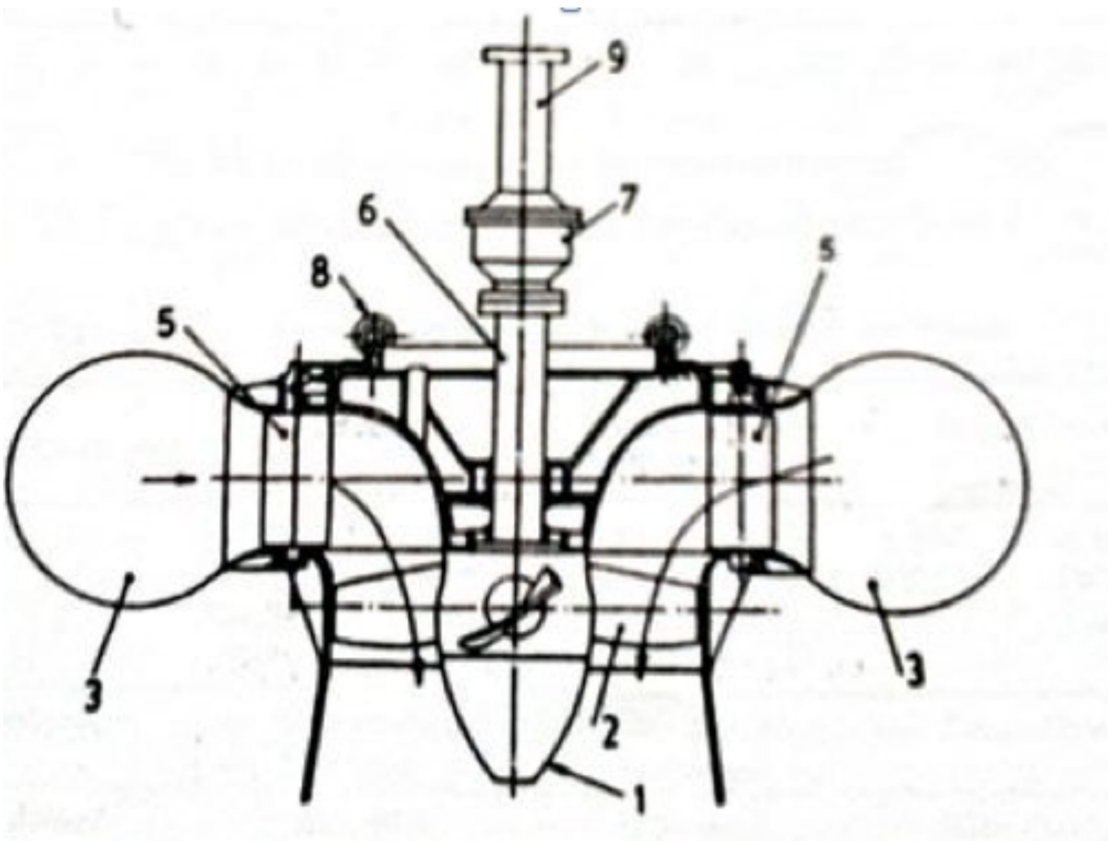


Figure 7: Design and Components of Propeller Turbine (Kaplan) (Arndt, 1991)

1. Hub of runner   2. Blades of Kaplan (Adjustable)
3. Spiral casing   4. Shaft   5. Wicket gate
6. Bearing   7. Generator

Table 1: Data of a Kaplan Turbine

Operating head	29 m	43 m
Output	102 MW	110 MW
Speed	100 RPM	100 RPM
Runner blades	4	6
Runner diameter	7.1 m	7.6 m

2.1.3.4 Bulb Hydro Turbines

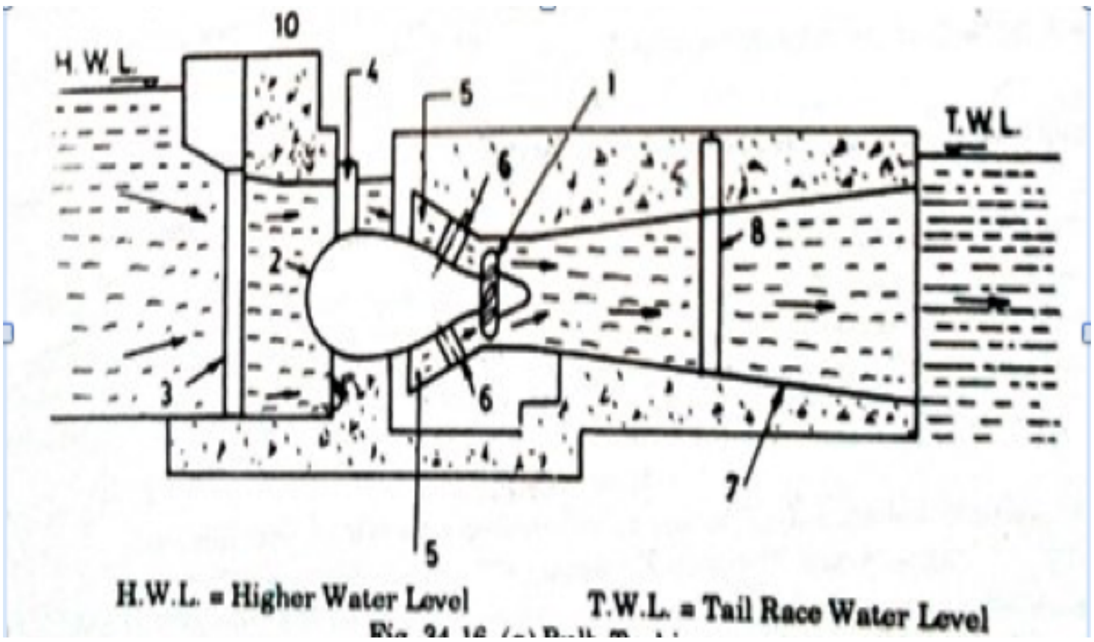


Figure 8: Design and components of Bulb Turbine (international, 1991)

Components

1. Runner of Turbine Rotor
2. Egg shaped enclosure of steel for generator, exciter, gear
3. Intake gate
4. Duct for bus bars
5. Passage for water
6. Wicket vanes
7. Draft tube lining
8. Tailrace gate

Description and working principle

The generator, gear, exciter etc. are enclosed in egg shaped steel Housing of large size. The Housing is in two halves and is sealed to forma water tight enclosure. The egg shaped watertight generator is installed axially in the passage of water and is supported by structure. The water glides smoothly over the egg shaped housing then through wicket gates through the axial flow Kaplan runner hub into the tail race. The generator shaft extends through the sealed egg shaped housing through water tight bearings and the turbine runner is external to the egg shaped housing.

Comparison between conventional vertical mounting of Generator- Turbine and axial bulb mounting

Compared to conventional vertical mounting of Generator-Turbine, the axial bulb mounting has the following advantages:

- Flow through turbine runner is more favorable since draft tube is eliminated.
- Power house structure can have low length, width and height
- Modest excavation is sufficient for power house
- Framework of water passage is simpler and less costly. (Arndt, 1991)

2.1.3.5 TUBE HYDRO TURBINES

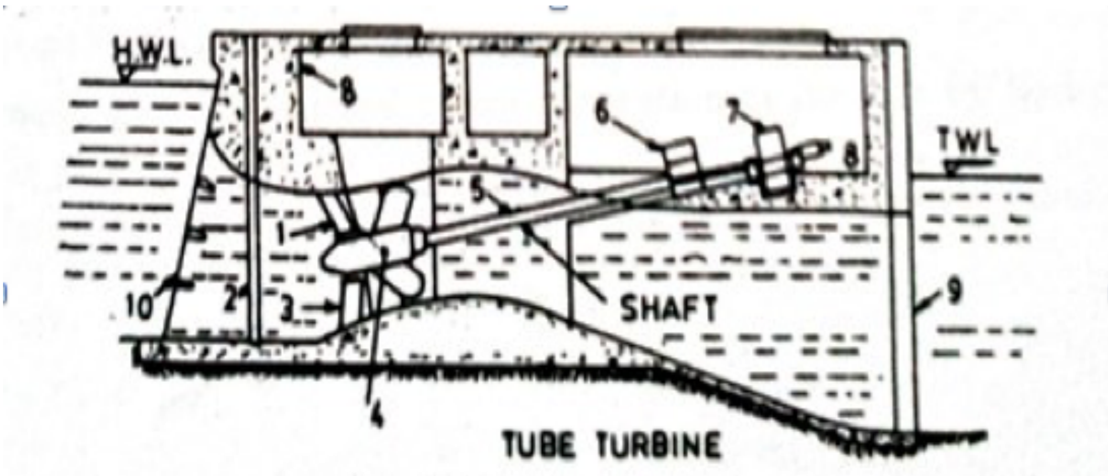


Figure 9: Design and components of tube turbine (international, 1991)

Description

The turbine is housed in a slightly curved tube shaped path. The turbine shaft is inclined and extends up to the generator room through the guide bearing. The generator is mounted away from the water passage tube, in either in upstream location or in downstream location.

2.1.3.6 Pit turbine

Description and working principle

The generator is housed in a watertight submerged enclosure (pit) made of civil work. There is no egg shaped steel housing. The pit is usually on upstream side and water passes through the ducts parallel to the axis towards the tail race through the wicket gates and the Kaplan runner (similar to tube turbine).

2.1.3.7 Choice of hydro turbine

The choice of hydro turbines is based on Head and Flow Rate.

The choice involves several decisive aspects including variation in head and flow rate, rating, economics, construction, earlier experience etc. (Arndt, 1991)

Table 2: Choice of Hydro Turbine based on Head

Range of Head (m)	Low Head	Medium Head	High Head
	4 to 50	20 to 500	200 to 1000
Type of Turbine	< 25 m < 50 m	< 200 < 500	< 500 < 1000
	Pit FBP	ABP FRAN PELT	FRAN
	Bulb ABP		
Type of storage	Run of river	Reservoir Reservoir	Large
Runner speed	50 – 250	150 – 600	200 – 1000
(RPM)			

ABP = Adjustable Blade Propeller
FBP = Fixed Blade Propeller

2.2 Photovoltaic Technology and Solar Energy Resources

2.2.1. Introduction

Solar cells also called photovoltaic (PV) cells, convert sunlight directly into electricity. PV gets its name from the process of converting light(photons) to electricity(voltage), which is called the PV effect. The PV effect was discovered in 1954, when scientists at Bell Telephone discovered that silicon(an element found in sand) created an electric charge when exposed to sunlight. Soon solar cells were being used to power space satellites and smaller items like calculators and watches. The PV cell is composed of semiconductor material which combines some properties of metals and some properties of insulators that makes it uniquely capable of converting light into electricity. When light is absorbed by a semiconductor, photons of light can transfer their energy to electrons allowing the electrons to flow through the material as electrical current. (Center, 1999)

2.2.2 Different semiconductor materials used in solar cells

i) Silicon:

Silicon is by far the most common material used in solar cells, representing approximately 90% of the modules sold today. It is also the second most abundant material on earth (after oxygen) and the most common semiconductor used in computer chips. Crystalline silicon cells are made of silicon atoms connected to one another to form a crystal lattice. This lattice provides an organized structure that makes conversion of light into electricity more efficient. Solar cells made out of silicon currently provide a combination of high efficiency, low cost, and long lifetime. Modules are expected to last for 25years or more, still producing more than 80% of their original power after this time. (S., 2007)

ii) Thin-film Photovoltaic:

A thin-film solar cell is made by depositing one or more thin layers of PV material on a supporting material such as glass, plastic, or metal. There are two main types of thin-film PV semiconductors on the market today; Cadmium(CdTe) and copper indium gallium diselenide(CIGS). Both materials can be deposited directly onto either the front or back of the module surface. CdTe is the second most common PV material after silicon and enables low cost manufacturing processes. While this makes them a cost-effective alternative, their efficiencies still aren’t quite as high. CIGS cells have favorable electronic and optical properties, though the complexity involved in combining four elements makes the transition from lab to manufacturing or challenging. Both CdTe and CIGS require more protection than silicon to enable long-lasting operation outdoors. (S., 2007)

iii) <u>Organic photovoltaic</u>:

Organic PV or OPV cells are composed of carbon-rich polymers and can be tailored to enhance a specific function of the cell, such as sensitivity to a certain type of light. This technology has the theoretical potential to provide electricity at lower cost than silicon or thin-film technologies. OPV cells are only about half as efficient as crystalline silicon and have shorter operating lifetimes, but could be less expensive to manufacture in high volumes. They can also be applied to variety of supporting materials making OPV able to serve a wide variety of uses. (S., 2007)

iv) <u>Concentration Photovoltaic</u>:

Concentration PV, also known as CPV focuses sunlight onto a solar cell by using a mirror or lens. By focusing sunlight onto a small area, less PV material is required. PV materials become more efficient at energy conversion as the light becomes more concentrated, so the highest overall efficiencies are obtained with CPV cells and modules. However more expensive materials manufacturing techniques and tracking are required so demonstrating the necessary cost advantage over today's high-volume silicon modules has become challenging. (S., 2007)

2.2.3 Photovoltaic Cells Classification

PV systems can be broadly classified in two major groups:

2.2.3.1 Stand-Alone

These systems are isolated from the electric distribution grid. Figure below describes the most common system configuration. The system described in Figure below is actually one of the most complex; and includes all the elements necessary to serve AC appliances in a common household or commercial application. An additional generator (e.g., bio-diesel or wind) could be considered to enhance the reliability but it is not necessary. The number of components in the system will depend on the type of load that is being served. The inverter could be eliminated or replaced by a DC to DC converter if only DC loads are to be fed by the PV modules. It is also possible to directly couple a PV array to a DC load when alternative storage methods are used or when operating schedules are not of importance. A good example may be water pumping applications where a PV module is directly coupled to a DC pump, water is stored in a tank through the day whenever energy is available.

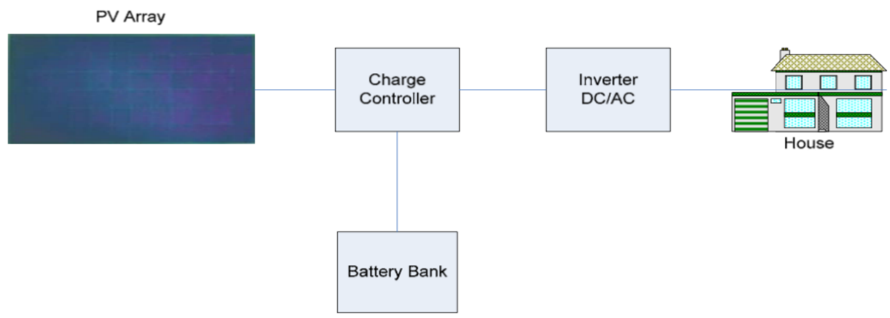


Figure 10: Standalone Photovoltaic system (Center, 1999)

2.2.3.2 Grid-Tied

These systems are directly coupled to the electric distribution network and do not require battery storage. Figure below describes the basic system configuration. Electric energy is either sold or bought from the local electric utility depending on the local energy load patterns and the solar resource variation during the day, this operation mode requires an inverter to convert DC currents to AC currents. There are many benefits that could be obtained from using grid-tied PV systems instead of the traditional stand-alone schemes. These benefits are:

- Smaller PV arrays can supply the same load reliably.

- Less balance of system components are needed.

- Comparable emission reduction potential taking advantage of existing infrastructure.

- Eliminates the need for energy storage and the costs associated to substituting and recycling batteries for individual clients. Storage can be included if desired to enhance reliability for the client.

- Takes advantage of the existing electrical infrastructure.

- Efficient use of available energy contributes to the required electrical grid generation while the client's demand is below PV output. [13]

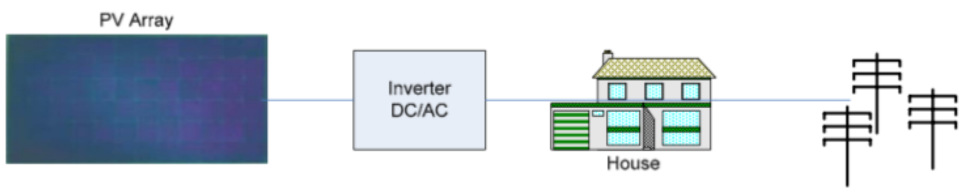


Figure 11: Grid-tied Photovoltaic System (Center, 1999)

Hybrid systems may be possible where battery storage or a generator (or both) can be combined with a grid connection for additional reliability and scheduling flexibility (at additional cost). Most of the installed residential, commercial and central scale systems use pre-fabricated flat plate solar modules, because they are widely available. Most available reports on PV system costs are therefore related to this kind of technology and shall be our focus in this project. Other specialized technologies are available (e.g., concentrating PV systems), but not as commercially available as the traditional PV module. (Center, 1999)

2.2.4 Principle of operation of Solar Cell

When photons of light fall on the cell, they transfer their energy to the charge carriers. The electric filed across the junction separates photo- generated positive charge carriers (holes) from their negative counterpart (electrons). In this way, an electrical current is extracted once the circuit is closed on an external load.

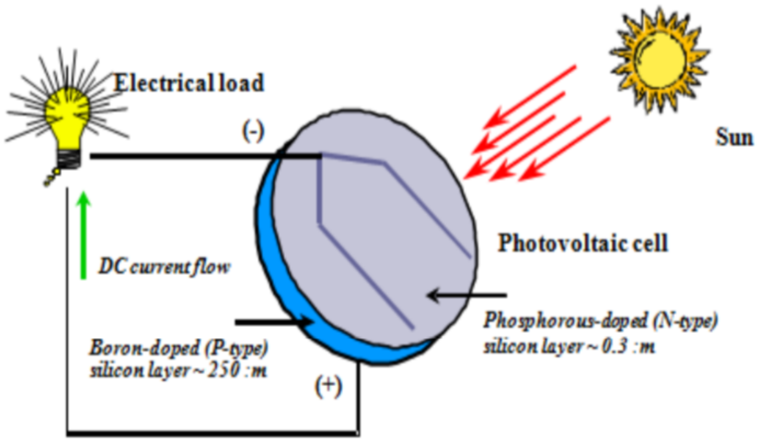


Figure 12: Solar Cell working principle (Center, 1999)

2.2.5 Main Components of Photovoltaic System

i) PV modules

A PV module is composed of interconnected photovoltaic cells encapsulated between a weatherproof covering (usually glass) and back plate (usually a plastic laminate). It will also have one or more protective by-pass diodes. The output terminals, either in a junction box or in a form of output cables, will be on the back. Most have frames. Those without frames are called laminates. In some, the back plate is also glass, which gives a higher fire rating, but almost doubles the weight. (S., 2007)

ii) Battery bank

For systems that require energy storage, like any system that needs to operate without the utility grid. A battery bank, multiple batteries wired together to achieve the specific voltage and energy capacity desired. The battery bank is typically housed in a container to keep the batteries safe. The PV array connects to it in order to provide charging a charge controller. The battery bank is also connected to the inverter to provide power for the AC loads. If the system also uses DC loads, the battery bank is wired to a DC load center. (S., 2007)

Common Batteries Used for Typical PV System:

i) Sealed batteries: these come in a sealed container that requires a reduced amount of maintenance by the end user.

ii) Flooded batteries

These come in an open (or flooded) container that requires a higher level of user interaction. All batteries give off gas when they are charging, releasing hydrogen. Sealed batteries release minuscule levels of hydrogen; flooded batteries can give off substantial levels of it. A wise choice (actually a requirement in most locations) is to keep all batteries inside a protective container that vents to the outside to avoid the possibility of hydrogen buildup and an explosion hazard. In this study, Surrette6CS25PS battery selected. (6CS25PS) is a modular construction 6-volt, dual container battery based on the high capacity CS plate. This unique battery design has each cell self- contained in a high temperature-retardant, durable polypropylene case. The outer container is made of high-density unbreakable polyethylene, providing double protection against breakage and leakage. Cell replacement is easy and quick using bolt-on connectors-allowing the battery to be assembled or repaired on location. The Rolls Surrette6CS25PS battery is rated for 3300 cycles at a 40% depth of discharge. (S., 2007)

iii) Charge Controller

A charge controller is a piece of electronics that is placed between the PV array and the battery bank. Its primary function is to control the charge coming into the battery bank from the PV array. Charge controllers can vary from a small unit intended to connect a single PV module to a single battery all the way to a controller designed to connect a multiple-kilowatt PV array to a large battery bank. (S., 2007)

iv) Inverter

Inverters turn the DC power produced by PV arrays or stored by battery banks into the AC power used in homes and community services. (S., 2007)

v) Loads

Loads are all the pieces of electrical equipment people want to use in their homes and offices.

2.2.6 Electric Characteristics of Photovoltaic Cells

2.2.6.1 Electrical Equivalent Circuit of PV cell

The complex physics of the PV cell can be represented by the equivalent electrical circuit shown in figure below. The following parameters cal for consideration. The current at the output terminals is equal to the light-generated current $_L$/less the diode I_{tD}/ and the shunt- leakage current$_{sh}$/. The series resistance R_S represent the internal resistance to the current flow, and depends on the p-n junction depth, impurities and contact resistance. The shunt resistance $R_{sh}$is inversely related to the leakage current to the ground. In an ideal PV cell R_S=0 and R_{sh}= the PV conversion efficiency is sensitive to small variations in R_S. But insensitive to variations in R_{sh}. A small increase in R_S can decrease the PV output significantly.[15]

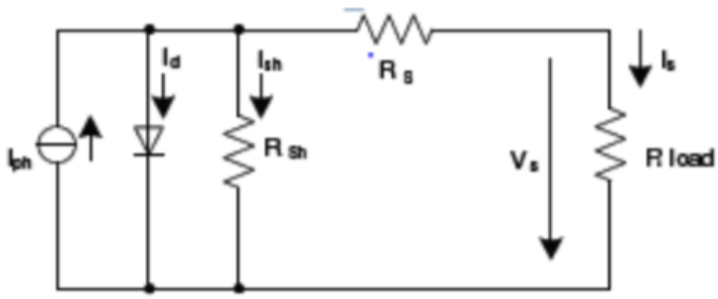


Figure 13: Electrical Scheme of PV Solar (S., 2007)

One recognizes the symbol of the diode(crossed by the current I_d), in parallel with the generator of current $I_{cc,}$ which corresponds to the flow of electrons generated by the flow of photons from the light(solar or otherwise) within the junction of the diode. Also in parallel to the diode there is the resistance R_{sh}(shunt resistance), which corresponds to the direct losses through the junction. In series towards the V_p and I_p usage, is the resistance R_s (series resistance) that corresponds, amongst other things, to the Joule losses in the wires.

The equation between Ip and Vp is the following: (Corkish, 2013)

$$\mathbf{Ip = ICC - Is\ (e^{\frac{Vp+IP.Rs}{KT/q}} - 1) - \frac{Vp+Ip\ .Rs}{Rsh}}$$

Where: Icc= Variable generated current according to light radiance

T= temperature in K

K= 1.38 10^{-23} J/K (Boltzmann constant)

q= 1.6 10^{-19} C(electron charge)

I_s= some nA (own characteristic of each charge diode)

The layout of the equation I_p=f(V_p) looks like:

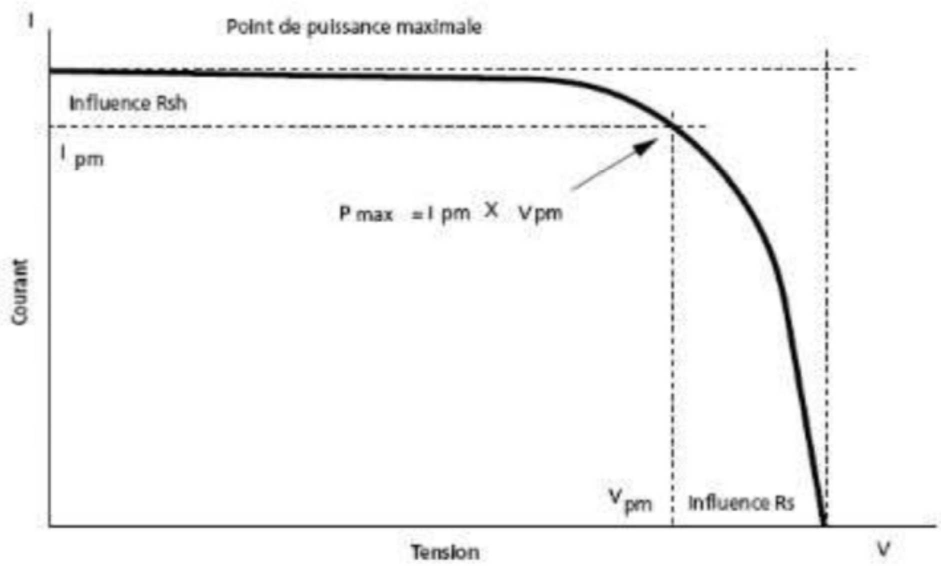


Figure 14: Equation Ip = f(Vp) (Corkish, 2013)

On this curve, one can recognize the curve of the diode (to the bottom because of the sign-in the equation) and shifted to the top of the value I_{cc} from the current generated by luminous radiance.

Characteristic Points on this curve for a crystalline silicon cell:

No-load Voltage (I_p=0A) V_{oc} = 0.6 V (power P=0W)

Short-circuit current (V_p=0V) = I_{cc} (variable according to radiance, power P=0W0

Charging Voltage V_{pm}= 0.5 V at the point of operation where the power is maximum current I_{pm}(variable according to radiance) at the point of operation where the power is maximum

Maximum Power: $P_{max} = I_{pm} \times V_{pm}$

Note that, while varying Vpm from 0 to Voc (or Ip from 0 to Icc), the power starts from 0W to go up to reach P_{max} then to go down again to 0W. [14]

The output of luminous energy conversion in electrical energy of a photovoltaic cell of surface S, of a P_{max} power under a luminous radiance I_{rrad} is the following:

$$\mathbf{R_{cell}} = \frac{\boldsymbol{Pmax(W)/S(m2)}}{\boldsymbol{Irrad\ (\frac{W}{m2})}}$$

One define also a factor of form (or fill factor), noted FF, representing the quality of a photovoltaic cell: (S., 2007)

$$\mathbf{FF} = \frac{\boldsymbol{Vpm\ x\ Ipm}}{\boldsymbol{Voc\ x\ Icc}}$$

The typical factors of form for various photovoltaic technologies are the following:

Crystalline silicon (m-Si): FF=0.83

Amorphous silicon a-Si: FF = 0.7

Cadmium Tellurium (CdTe): FF=0.76

Copper Indium Selenium: FF = 0.78

According to photovoltaic technologies of cells, the layout of the equation I_p=f(V_p) keeps the same form but the values of no-load voltage are slightly different and especially, for the same surface, the currents of short-circuit are different because the output conversion yields are different for each technology.

Layout of the equation I_p=f(V_p) for different photovoltaic technology of cells:

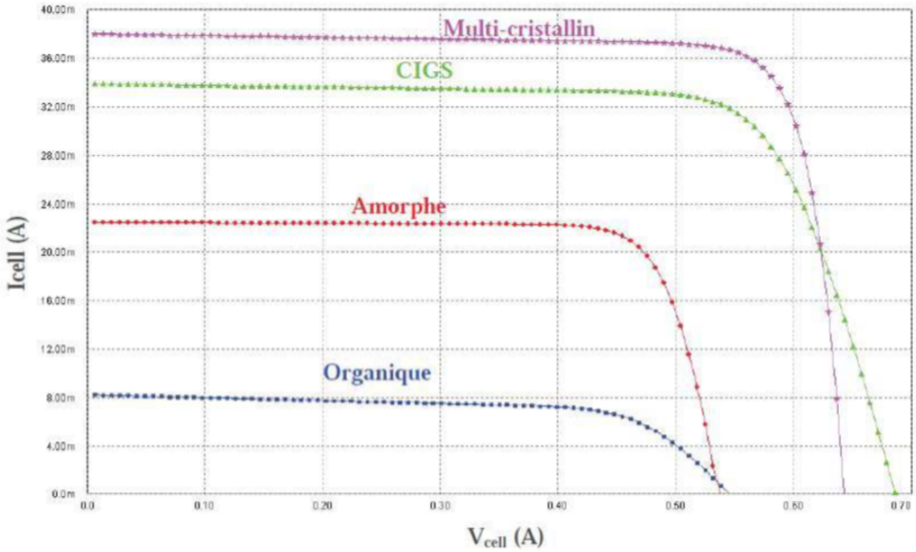


Figure 15: Layout of the equation Ip=f(Vp) for the different PV kind of Cells (S., 2007)

Here are the typical conversion efficiencies for various photovoltaic technologies:

Crystalline silicon (m-Si): from 15 to 17%

Amorphous silicon (a-Si): 6 to 8%

Cadmium Tellurium (CdTe): 11 to 12%

Copper Indium Selenium: 12 to 13%

Organic cell (still at research level): 5%(record at 11%)

CHAPTER THREE: METHODOLOGY

This chapter explains ways in which data was collected and software used to optimize Hybrid of PV solar and hydro whereby PV solar cells can power a motor used to pump water from lower reservoir to upper reservoir in storage pumped Micro hydro power plant and then power is generated by releasing the stored water through turbines in the same manner as a conventional hydropower station. The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Data obtained were analyzed by PVSYST software to determine whether a configuration is feasible or whether it can meet the electric demand under the conditions that specified such as components used to build the system like PV panels, inverter, water pump, regulator, basin of upper and lower reservoir, size of penstock, head, flow rate and all to meet the capacity needed for a plant. Literature review was used to understand deeply the requirements and the problem domain, where we tried to read different project of scholars carried out on lighting rural electrification in Rwanda. And technical information has been revised to improve the performance of hybrid of renewables for rural electrification in Rwanda putting into consideration environment impact of plant to the biodiversity and population of surrounded location to the plant.

3.1 Review of existing work

The revision and analysis of publication papers, scientific articles and reports relate to the thesis topic was done in order to have enough information about Solar-PHES. Several books and Internet resources were used for completing the literature review of the thesis and directing the whole project. This method helped to find out the gap between existing Hybrid of Solar - Hydro and the research problems of this research.

3.2 Global Horizontal Irradiance (GHI)

To Choose where solar energy potential for installation PV, the Global horizontal irradiance data is the essential factor to be putting into consideration whereas from NASA(National Aeronautics and Space Administration) Website we can get Insolation clearness Index which is the radiation we can get on earth’s surface once we consider the absence of atmosphere.

3.2.1 Global solar radiation calculation

Global radiation (**Global**$_{tot}$) is calculated as the sum of direct (**Dir**$_{tot}$) and diffuse (**Dif**$_{tot}$) radiation of all sun map and sky map sectors, respectively. (Ridley, 2010)

$$\textbf{Global tot = Dir tot + Dif tot}$$

Or

$$K_T = GHI/I_{ext} .\cos(Z_{angle})$$

Where K_T is Clearness index

$I_{ext}$is Extraterrestrial radiation

Z_{angle} is zenith angle

Whereas Direct radiation for a given location can be found on NASA website as Insolation clearness Index knowing latitude and longitude of that location. And in our case we used Mwogo Sector in Bugesera District as reference station of meteorology with Latitude (2.07^o S) and Longitude (30.14^o E).

3.2.2. Steps for calculating Global Solar radiation

1. Determine the radiation at the horizontal surface based on the day of the year and the site latitude and then establish a clearness index.
2. The clearness index is then used to calculate the direct, diffuse and random components of the radiation on a horizontal surface.
3. The total radiation is then calculated from the direct, diffuse and random values obtained.
4. Finally, the radiation on the surface of the panel is determined. It requires monthly average meteorological data at a specific site location as its input for the simulation of the solar radiation process at that site. The necessary data for simulation of solar are as follow:

3.2.2.1. Declination Angle

The declination is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper's equation (Duffie, 2013)

$$\delta = 23.45 \sin (360^{o} \frac{284+n}{365})$$

Where n is the day of the year

3.2.2.2. Extraterrestrial Solar Radiation

It states that the amount of solar radiation arriving at the top of the atmosphere over a particular point on the earth's surface. It assumes that the output of the sun is constant in time. But the amount of sunlight striking the top of the earth's atmosphere varies over the year because the distance between the sun and the earth varies over the year due to the eccentricity of earth's orbit. To calculate the extraterrestrial normal radiation, defined as the amount of solar radiation striking a surface normal (perpendicular) to the sun's rays at the top of the earth's atmosphere, it uses the following equation; (Duffie, 2013)

$$G_{on} = G_{sc} (1 + 0.033 * \cos \frac{360n}{365})$$

3.2.2.3 Sunset Hour Angle ωs

The angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive. (Duffie, 2013)

$$\cos \omega s = - \frac{\sin \emptyset \sin \delta}{\cos \emptyset \cos \delta} = - \tan \emptyset \tan \delta$$

Where $\emptyset$ is latitude of the location.

3.2.2.4 Zenith Angle θz

The angle between the vertical and the line to the sun that is, the angle of incidence of beam radiation on a horizontal surface. (Duffie, 2013)

$$\cos \theta z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta$$

3.3 Complementarity of Solar and Pumped Hydro Electric Storage (PHES)

In this project we designed a solar power plant to run the motor pump that pumps water in the storage at high level. The stored water is then used to generate hydraulic energy which is used to supply the population living nearby in Mwongo Sector/Bugesera district all the time. The system keeps water circulating and does not lead to dry of existing water source. This design is composed of 8 arrays of 25KW connected together to power the 2 pumps that are connected in parallel. The pumps supply water of 1400m^3 per dayin the upper storage during the sunny hours and this stored water is utilized to produce electricity on the regular basis. The proposed pumped storage scheme which consist of a pump powered by Solar PV and a separate turbine is shown in figure below; (association(ESA), 2014)

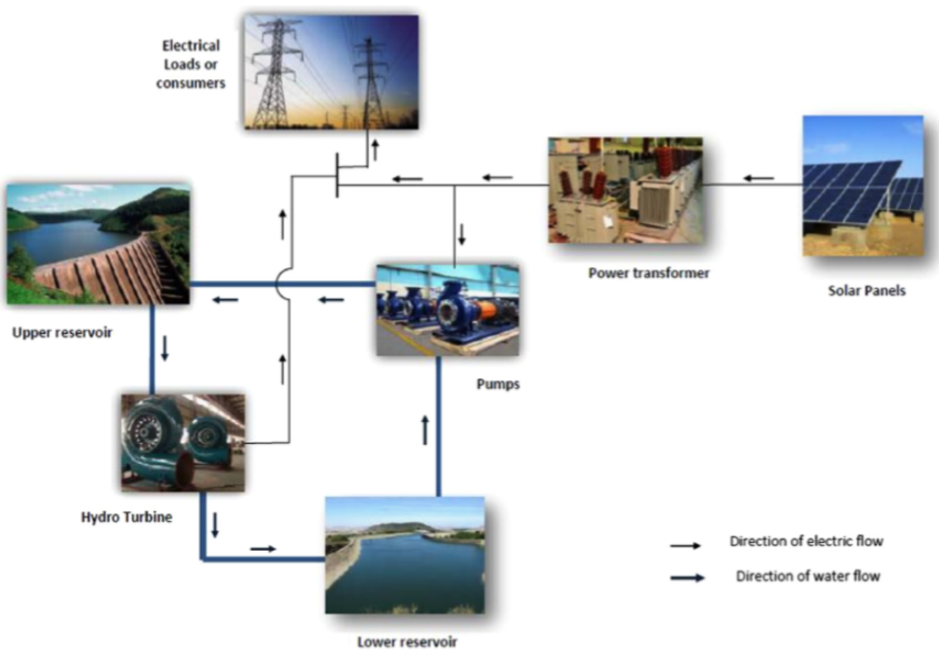


Figure 16: A conceptual Solar Photovoltaic based PHES (association(ESA), 2014)

3.3.1 Estimation of our Base case Assumption

Our Base case is in Mwogo Sector,Bugesera District and rural area of Mwogo Sector the community is composed with more than 250 households with ambition of electricity for lighting and entertainment (TV and Radio). Estimation with also security light taken into account, the total load is 25KW peak and 150KWh per day. The estimation shows Mwogo sector among least populated with share of 4.9%

inhabitants of total resident population of Bugesera District. And is touched by Akagera liver on its north boundary. The source of energy for lighting in Mwogo sector vary by area of residence. In urban areas, the three main sources of energy for lighting are electricity(48%), kerosene lamp(23.7%), and Candle(18.4%) whereas in rural areas, the common mainly used sources of lighting are kerosene lamps(37.4%), Candle(11.2%) and electricity(6%).This lack of electricity distribution contribute to lack of vital public services and due to high financial involvement of extension of electricity from national grid, an off grid hybrid of hydro and PV stand-alone constitute a useful platform for electricity inadequacies for households in rural area of Mwogo Sector. (Fourth population and housing Census, 2015)

Table 3: Mwogo Base case assumptions

Source of power	Solar PV
Storage requirement (Kwh)	125
Peak load (Kw)	25
Vertical distance between two reservoirs (meters)	60
Days of energy storage	4
Average sun hours per day	5

3.3.1.1 Usable Electric Energy

The formula below represents the usable Energy available from a volume of water falling from an upper reservoir to a lower reservoir; (A buyer's guide, 2004)

$$\mathbf{E_{usage}\ g\ V\ h_t = \rho\eta_t}$$

Where E_{usage} is the energy released (Joules)

V is the required volume of water (m^3)

h is the total head (m)

ρis the density of fresh water (1000kg/m^3)

g is the gravitation acceleration (9.81 m/s^2)

η_t is combined turbine, generator and pipe efficiency

3.3.1.2 Solar pumps

Usage of multiple pumps has its advantage to maintaining constant efficiency and outage of a single pump does not affect the whole micro hydro system by much. To calculate the number of solar pumps needed to store sufficient water to meet the storage requirement, following equation is used; (A buyer's guide, 2004)

$$\mathbf{N} = \frac{\boldsymbol{V}}{\boldsymbol{m}\,\boldsymbol{d}}$$

Where N is number of pumps

V is Volume of the reservoir (m^3)

d is the storage day

m is the amount of water that each pump can pump in one day(m^3/day)

3.4 Introduction to PVSYST Software

PVSYST deals with grid-connected, stand-alone pumping and DC-grid PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools. This software is geared to the needs of architects, engineers, and researchers. It is also very helpful for educational training. PVsyst offers different levels stages in the development of real project such as; (P. Schaub, 1993)

3.4.1 Pre sizing Step of the project

In this mode the system yield evaluations are performed very quickly in monthly values, using only a very few general system characteristics or parameters, without specifying actual system components. A rough estimation of the system cost is also available. For Pumping systems, given water requirements and a depth for pumping, and specifying some general technical options, this tool evaluates the pump power and PV array size needed. As for stand-alone systems, this sizing may be performed according to a specified probability that the water needs are not met over the year. (P. Schaub, 1993)

3.4.2 Project Design

It aims to perform a thorough system design using detailed hourly simulation. Within the framework of a project, the user can perform different system simulation runs and compare them. He has to define the plane orientation (with the possibility of tracking planes or shed mounting), and to choose the specific system components. He is assisted in designing the PV array (number of PV modules in series and parallel), given a chosen inverter model, battery pack or pump.

In a second step, the user can specify more detailed parameters and analyze fine effects like thermal behavior, wiring, module quality, mismatch and incidence angle losses, horizon (far shading), or partial shadings of near objects on the array, and so on. The "Loss Diagram" is particularly useful for identifying the weaknesses of the system design. An engineer report may be printed for each simulation run, including all parameters used for the simulation, and the main results. (P. Schaub, 1993)

CHAPTER FOUR: RESULTS AND DISCUSSION

Results on Viability of hybrid of Solar PV and Micro hydro are discussed in this chapter. Calculation of Global horizontal irradiance was done in order to know if a certain location of Rwanda is potential for solar PV project. Moreover the integration of solar PV power plant to keep refilling the upper water storage at upper level which generate hydraulic energy was simulated with PVSYST to demonstrate real evidence of operation of system.

4.1 Solar Resource Assessment of Rwanda

The solar radiation and clearness index for 5 years average was obtained from the NASA surface meteorology, solar map of Rwanda was obtained from PVGIS.

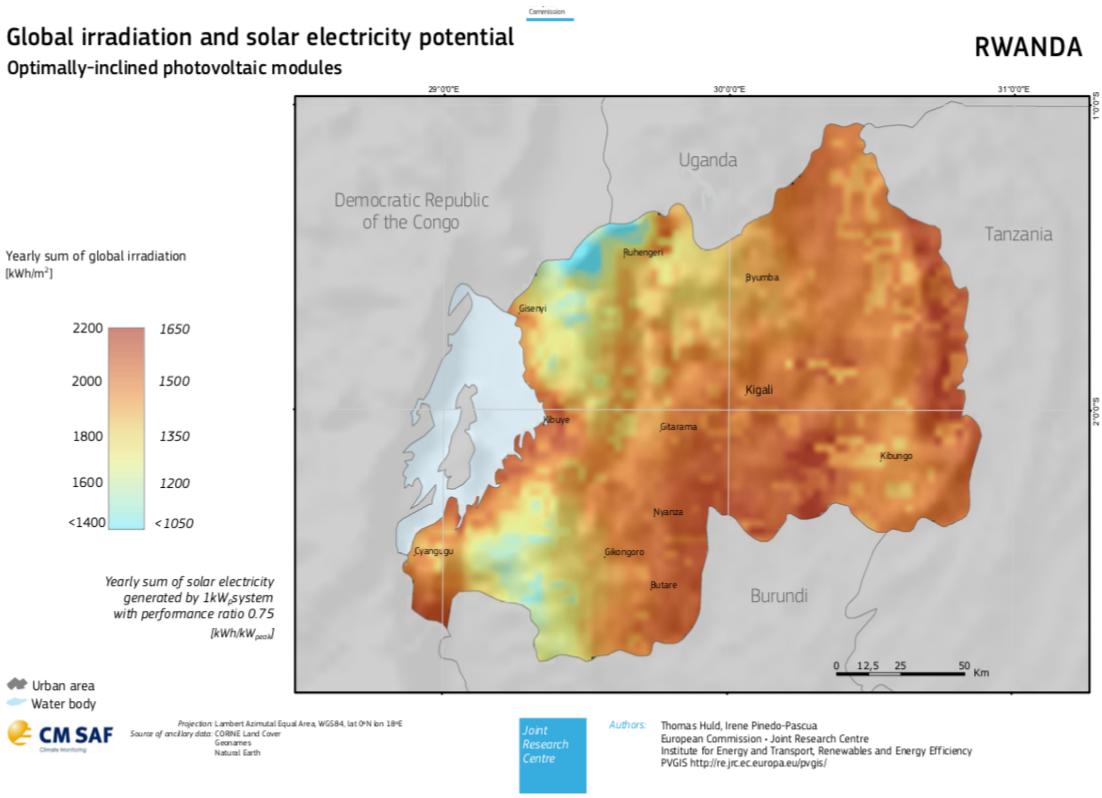


Figure 17: Global irradiation of Rwanda (commission, 2019)

And based on this map, the country manifest potential in solar in Eastern Province and Centre of the country reason why we choose our study in one sector of Eastern province notably Mwogo Sector.

4.1.1 Solar resource assessment of Mwogo Sector

The 5 years monthly average solar resource of the village varies from 5.52kwh/m^2/d in August and 4.88 kwh/m^2/d in November, which is the summer of Rwanda, is and clearance index are obtained from NASA. An average solar radiation for the village is 5.17 kWh/m^2/d. the clearance index and daily radiation the village is obtained from NASA surface metrology at latitude 2.07^o S and longitude of 30.14^{o}E. for a photovoltaic system to supply sustainable power, the daily radiation should be greater than 4 kWh/m^2/d which means our location is eligible for PV Solar.

Table 4: Solar resource profile for Mwogo Sector

Month	Clearness Index	Daily radiation(Kwh/m^2/day)
January	0.506	5.23
February	0.472	5.09
March	0.462	5.14
April	0.448	5.04
May	0.5	5.12
June	0.534	5.25
July	0.562	5.31
August	0.5	5.52
September	0.446	5.21
October	0.442	5.27
November	0.416	4.88
December	0.466	4.97

4.2 Simulation of PVSYST

In this project we designed a solar power plant to run the motor pump that pumps water in the storage at high level. The stored water is then used to generate hydraulic energy which is used to supply the population living nearby in Mwongo Sector/Bugesera district all the time. The system keeps water circulating and does not lead to dry of existing water source. This design is composed of 8 arrays of 25KW connected together to power the Two pumps that are connected in parallel. The pumps supply water of 1400m^3 per dayin the upper storage during the sunny hours and this stored water is utilized to produce electricity on the regular basis. We used PVsyst software to simulate the design of the solar power plant to keep refilling the upper water storage which is designed with four days autonomy to run hydraulic generator.

4.2.1 Design parameters

4.2.1.1 Orientation parameters of PV modules

Tilt and Azimuth angle are parameter to choose in order to avoid dust and maximize radiation on panels.

Field type: Fixed Tilted Plane

Plane tilt/azimuth = 15° / 0°

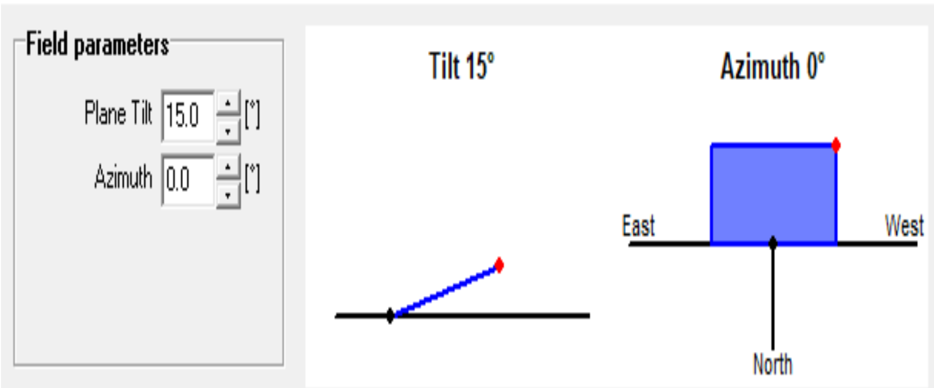


Figure 18: Orientation parameters and graph of PV modules

4.2.1.2 Shadow Analysis

The figure below shows how insolation are arriving during all sun hour of the day, peak hours here are from 10h:00 O'Clock up to 14h:00 O'Clock which means our panels should work within 5hours to maximize the power. And after 17h:00 and before 7h:00 O'Clock there is a shadow which means no PV operation.

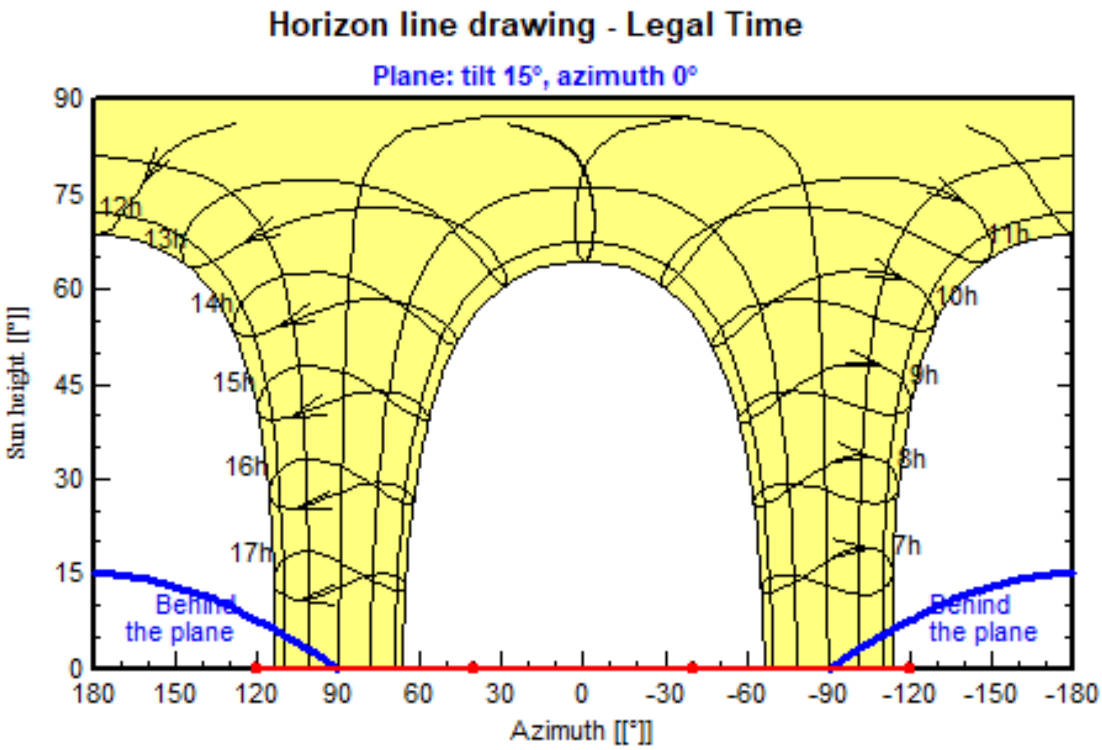


Figure 19: Sun path and Shadings

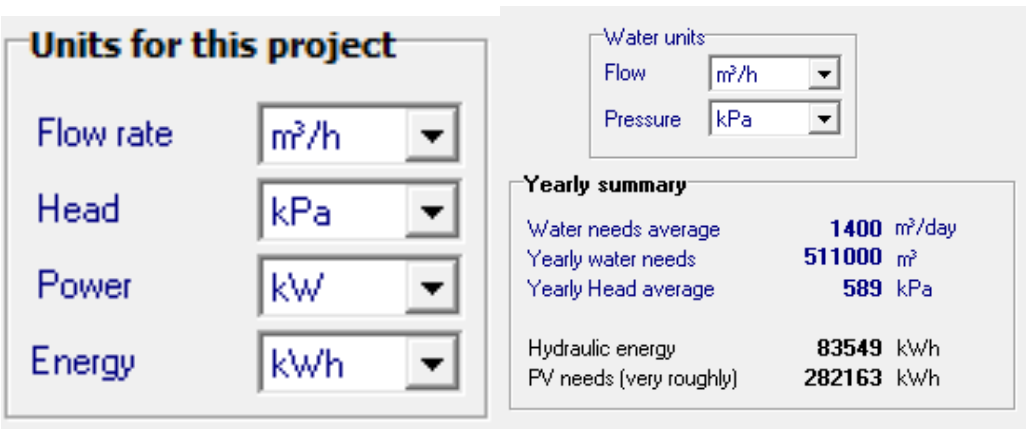


Figure 20: Units and Summary of water needs to power our MHPP

4.2.1.3 Schematic diagram of a PV power pumping system

In this diagram lower and upper tank are shown, a three phase inverter and PV array generator (PV in series and parallel together) are also shown.

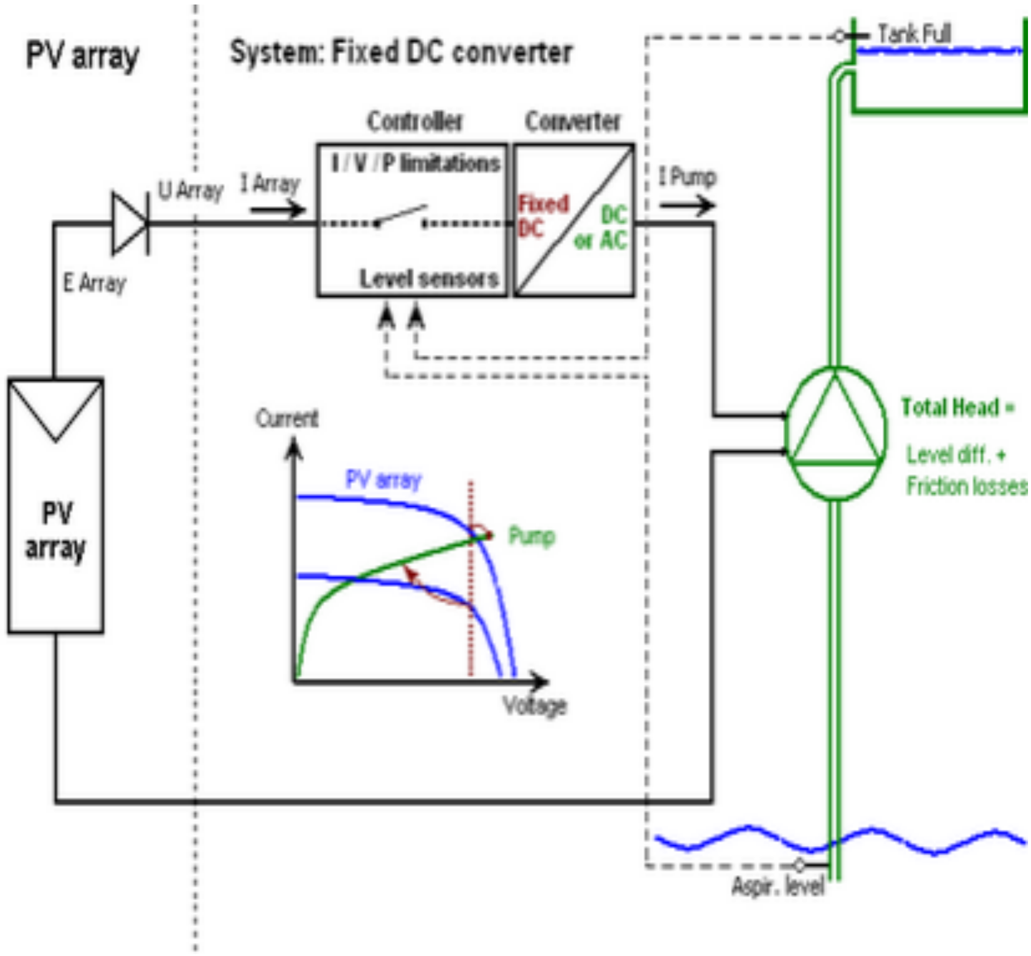
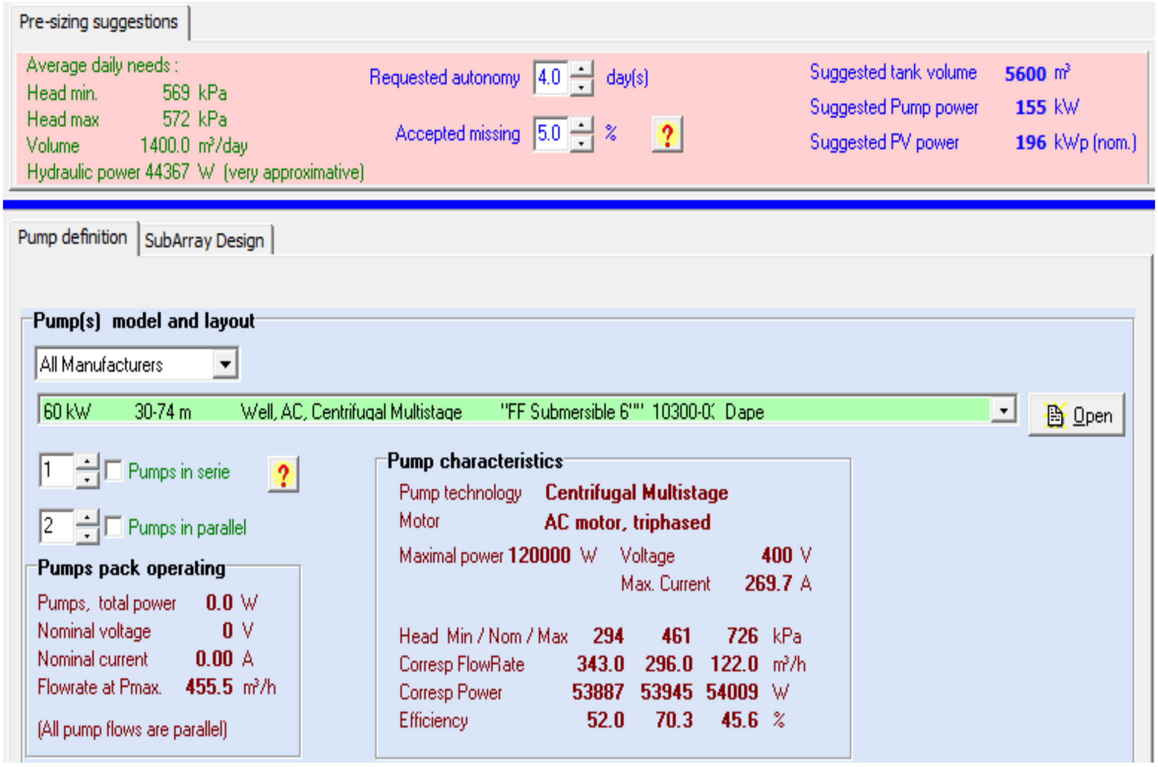


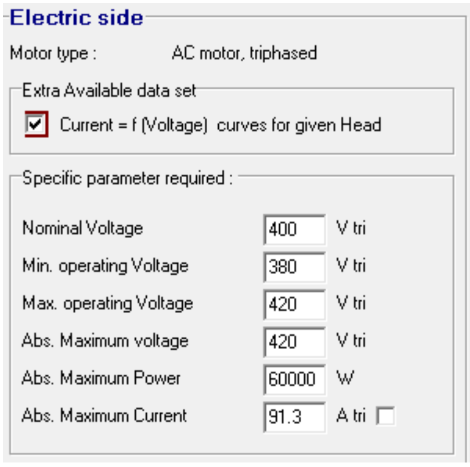
Figure 21: Schematic diagram of PV pumping system

4.2.2 Pre-sizing suggestions and pump sizing

Here we need to choose appropriate pump for our project and some factor need to be considered such as Pressure Head (kPa), Discharge (m^3/h) and Wattage consumption (Watt). Therefore our head should be between 569 kPa and 572kPa, discharge or flow rate that passing through the pump should be 296 m^3/h which can justify our volume needed per day because with our pump working within 5 hours of peak we can get more than 1400m^3 target per day. Wattage consumption should be 60 kW for each pump and here we choose two pumps for mitigating any inconvenience.

Table 5: Pump characteristics


Pre-sizing suggestions
Average daily needs :
Head min. 569 kPa
Head max 572 kPa
Volume 1400.0 m³/day
Hydraulic power 44367 W (very approximative)
Requested autonomy 4.0 day(s)
Accepted missing 5.0 %
Suggested tank volume 5600 m³
Suggested Pump power 155 kW
Suggested PV power 196 kWp (nom.)
Pump definition
SubArray Design
Pump(s) model and layout
All Manufacturers
60 kW 30-74 m Well, AC, Centrifugal Multistage "FF Submersible 6"" 10300-0: Dape
Open
1 Pumps in serie
2 Pumps in parallel
Pumps pack operating
Pumps, total power 0.0 W
Nominal voltage 0 V
Nominal current 0.00 A
Flowrate at Pmax. 455.5 m³/h
(All pump flows are parallel)
Pump characteristics
Pump technology Centrifugal Multistage
Motor AC motor, triphased
Maximal power 120000 W
Voltage 400 V
Max. Current 269.7 A
Head Min / Nom / Max 294 461 726 kPa
Corresp FlowRate 343.0 296.0 122.0 m³/h
Corresp Power 53887 53945 54009 W
Efficiency 52.0 70.3 45.6 %


Electric side
Motor type : AC motor, triphased
Extra Available data set
Current = f (Voltage) curves for given Head
Specific parameter required :
Nominal Voltage 400 V tri
Min. operating Voltage 380 V tri
Max. operating Voltage 420 V tri
Abs. Maximum voltage 420 V tri
Abs. Maximum Power 60000 W
Abs. Maximum Current 91.3 A tri

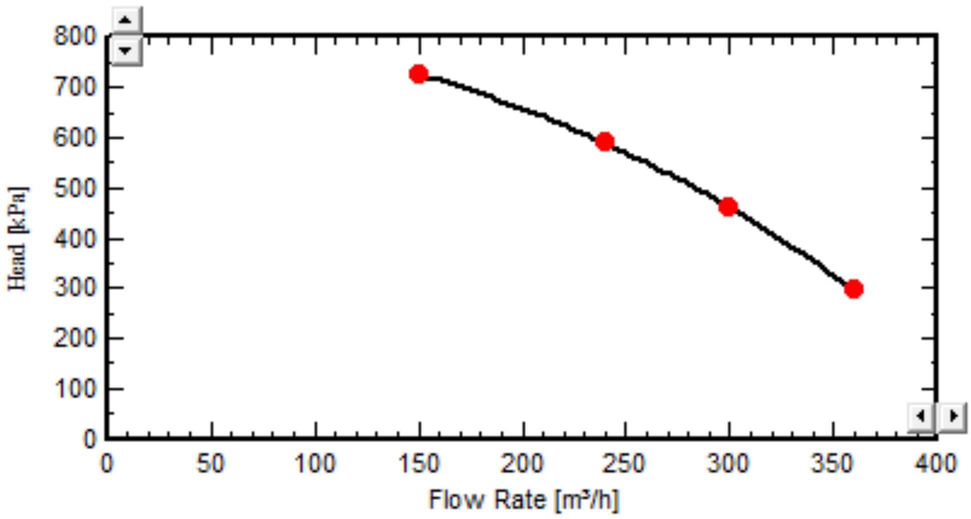


Figure 22: Flow rate vs Head

This figure shows how when quantity of water passing through pump is high, the head which is the distance water travel from one point to another point reduced.

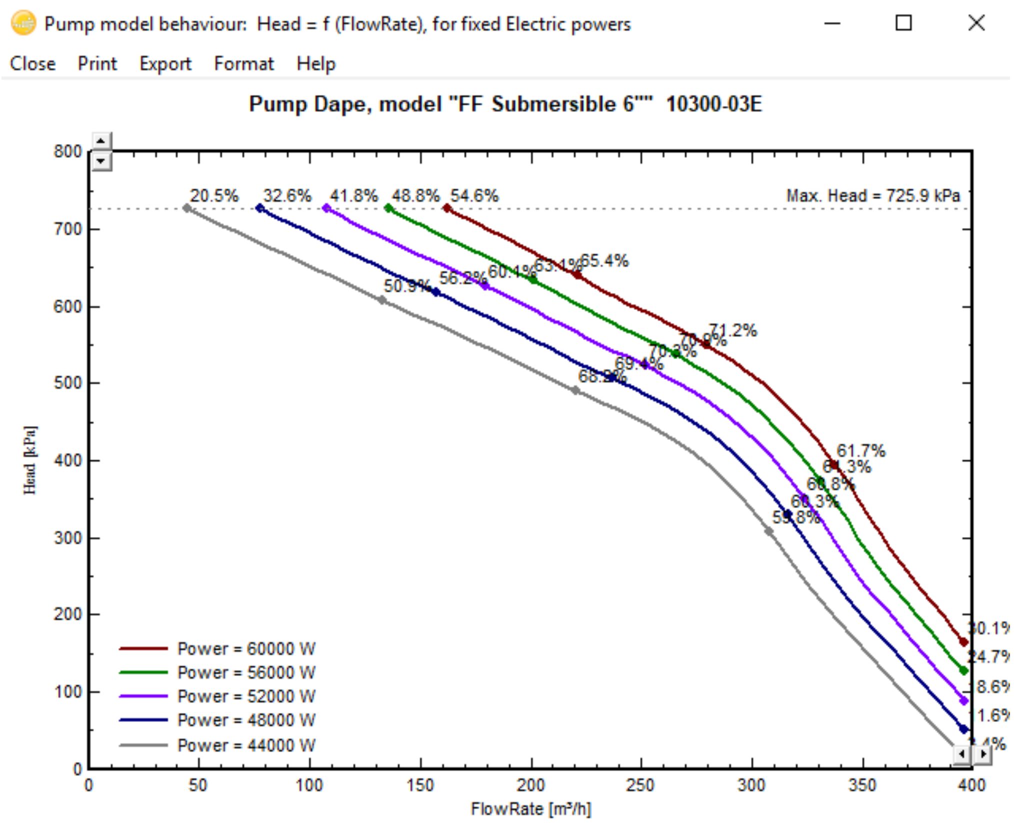


Figure 23: Pump model behavior when varying power

This figure shows comparison of head and discharge when varying power and in our case the required power is 60Kw, so when working below that power you can see that efficiency is reduced and secondly when head decrease automatically discharge or flow rate increase and thirdly when working with high power, the discharge increase too.

4.2.3 Simulation of a single 25kw of solar power plant without batteries with PVsyst software

PVSYST V6.70		04/07/19	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**Mwogo pumping project**				
Geographical Site		**Mwogo**		Country	**Rwanda**
Situation		Latitude	-2.07° S	Longitude	30.14° E
Time defined as		Legal Time	Time zone UT+2	Altitude	1346 m
		Albedo	0.20		
Meteo data:		**Mwogo**	Meteonorm 7.1, Sat=100% - Synthetic		

Simulation variant :	**mwogo pv pump design**				
		Simulation date	04/07/19 12h04		

Simulation parameters		System type	**No 3D scene defined**		
Collector Plane Orientation		Tilt	15°	Azimuth	0°
Models used		Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon		Free Horizon			
Near Shadings		No Shadings			
PV Array Characteristics					
PV module	Si-poly	Model	**YES Perform 60PQ 250**		
Original PVsyst database		Manufacturer	Your Energy Germany		
SolarEdge Power Optimizer		Model	**P800s**	Unit Nom. Power	800 W
PV modules on one optimizer		in series	2	in parallel	1
Nb. of optimizers		In series	28	In parallel	2 strings
Total number of PV modules		Nb. modules	112	Unit Nom. Power	250 Wp
Array global power		Nominal (STC)	**28.00 kWp**	At operating cond.	24.99 kWp (50°C)
Output of optimizers		U oper	750 V	I at Poper	33 A
Total area		Module area	**185 m²**		
Inverter		Model	**SE25K**		
Original PVsyst database		Manufacturer	SolarEdge		
Characteristics		Operating Voltage	750 V	Unit Nom. Power	25.0 kWac
Inverter pack		Nb. of inverters	1 units	Total Power	25 kWac
				Pnom ratio	1.07
PV Array loss factors					
Thermal Loss factor		Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss		Global array res.	301 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss				Loss Fraction	-0.5 %
Module Mismatch Losses				Loss Fraction	0.0 % (fixed voltage)
Incidence effect, ASHRAE parametrization		IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
User's needs :		Unlimited load (grid)			

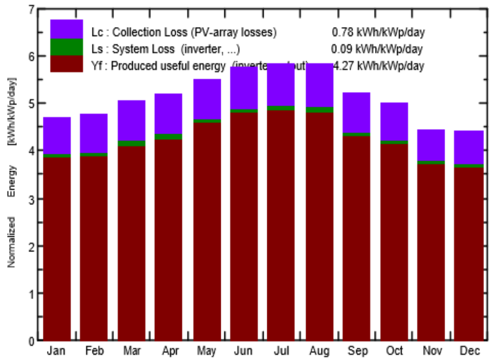
Project :	Mwogo pumping project
Simulation variant :	mwogo pv pump design

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	YES Perform 60PQ 250	Pnom	250 Wp
PV Array	Nb. of modules	112	Pnom total	**28.00 kWp**
Inverter	Model	SE25K	Pnom	25.00 kW ac
User's needs	Unlimited load (grid)			

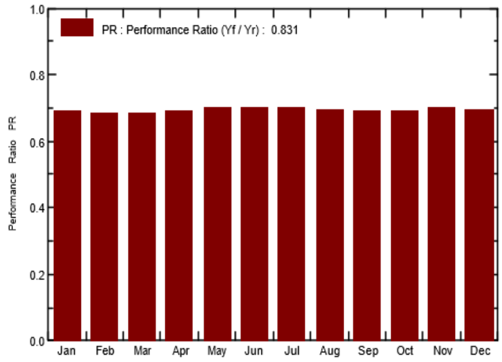
Main simulation results				
System Production	**Produced Energy**	**43.60 MWh/year**	Specific prod.	1557 kWh/kWp/year
	Performance Ratio PR	83.12 %		

Main simulation results				
System Production	**Produced Energy**	**43.60 MWh/year**	Specific prod.	1557 kWh/kWp/year
	Performance Ratio PR	83.12 %		

Normalized productions (per installed kWp): Nominal power 28.00 kWp



Performance Ratio PR

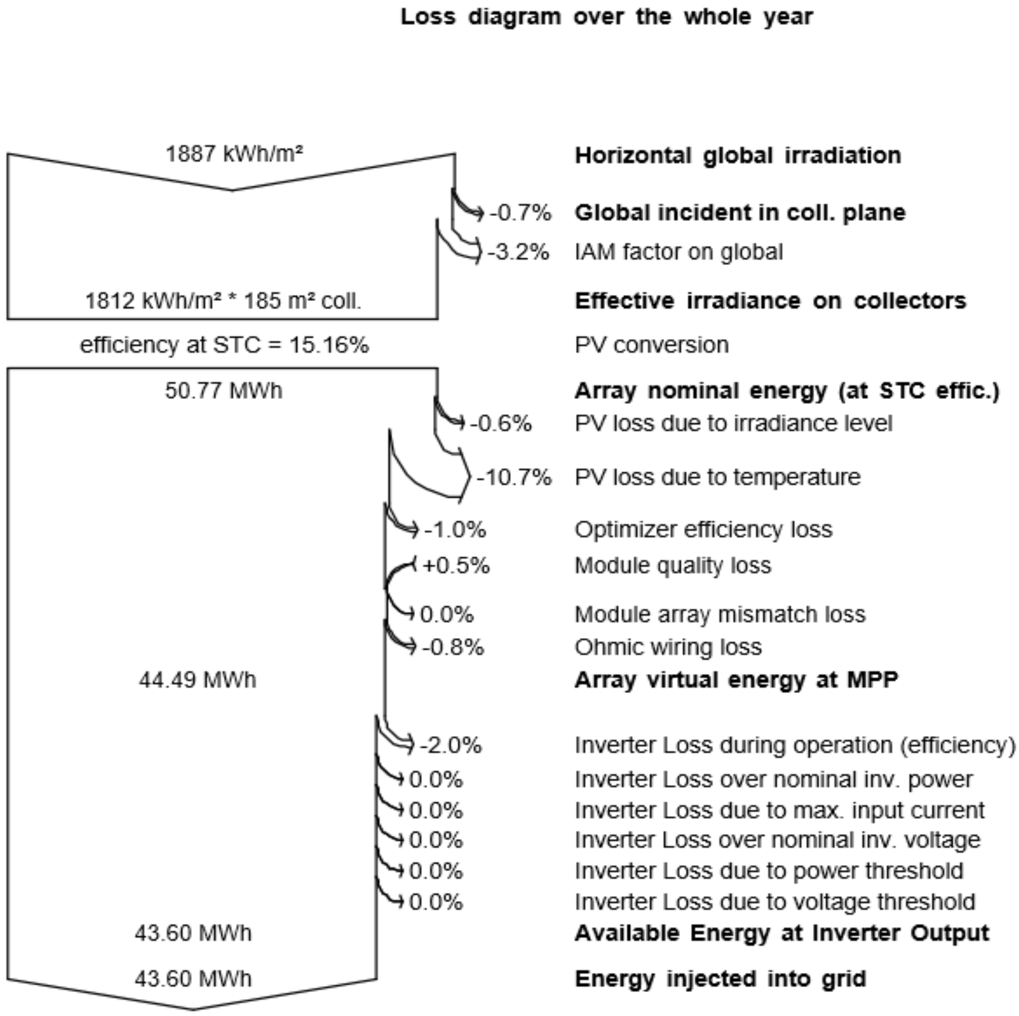


Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	162.2	71.14	21.49	145.1	139.2	3.431	3.361	0.827
February	142.4	68.47	22.38	133.1	128.3	3.125	3.061	0.821
March	159.2	74.85	22.21	156.2	151.1	3.654	3.580	0.819
April	151.1	69.67	21.00	155.1	150.5	3.659	3.585	0.826
May	158.8	75.68	20.69	170.1	165.1	4.076	3.995	0.839
June	157.5	61.08	19.68	172.7	168.3	4.127	4.046	0.837
July	164.6	64.36	19.39	180.5	175.5	4.318	4.232	0.838
August	171.2	72.18	19.75	179.9	174.8	4.286	4.201	0.834
September	156.3	71.21	20.33	156.2	151.4	3.702	3.628	0.829
October	163.5	72.58	21.31	155.3	149.9	3.670	3.596	0.827
November	146.4	79.81	20.62	133.3	127.8	3.207	3.142	0.842
December	154.2	73.06	21.37	136.1	130.2	3.240	3.174	0.833
Year	1887.3	854.10	20.84	1873.5	1812.2	44.494	43.602	0.831

Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

4.2.3.1 Losses over the whole year



4.2.3.2 Summary of the system

Results overview

System kind	**No 3D scene defined**	
System Production	**43.6**	MWh/yr
Specific production	**1557**	kWh/kWp/yr
Performance Ratio	**0.831**	
Normalized production	**4.27**	kWh/kWp/day
Array losses	**0.78**	kWh/kWp/day
System losses	**0.09**	kWh/kWp/day

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this project of viability of hybrid of solar PV and micro hydro power plant, solar insolation on the whole land of Rwanda was studied and realize that Eastern, Southern and Centre province of the country are good potential for solar PV. Second, the Country is situated in Great Lakes region where water is available in significant quantity which means potential electric energy. The global horizontal radiation was calculated using data from NASA solar surface meteorology to make sure if our chosen case study is eligible for solar PV installation. The integration of solar PV pump and micro hydro was simulated and proved pump required to pump water to upper reservoir. The upper and lower reservoir was calculated and the system keeps water circulating and does not lead to dry of existing water source because it will acquire water from rain and the evaporation of reservoir will be negligible compared from water coming from rain. According to Rwanda population of about 87% living in rural area, to achieve the goal of 100% electrification in 2024 much need to be done and A stand-alone off grid solar-micro hydropower Hybrid system consisting of photovoltaic system running water pump supplying hydro power plant storage is viable solution compared to batteries system normally used to keep the supply working in the nights or absence of sun that are expensive.

5.2 Recommendations

The following recommendations are made out of this research; some of them are directed to other researchers while the others are directed to GoR. Rwanda has a huge potential of renewable energy resources, which can be used for rural electrification through the off-grid system. There are, however, many challenges like unfavorable conditions towards the extension of grid to far region of the country which proved to be expensive. Thus the government, non-governmental organizations and private sectors should make combined efforts to improve the low rate of rural electrification in Rwanda. The implementation for this hybrid system in the village can serve as a pilot system fort he whole country. As far as the environmental aspects are concerned, this kind of hybrid energy systems have to be wide spread in order to cover the energy demands of rural communities, and in that support GoR Green Economic Police and the deforestation of the environment in general.

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APPENDICES

1. Table of Interannual Insolation clearness index

-BEGIN HEADER-
NASA/POWER SRB/FLASHFlux/MERRA2/GEOS 5.12.4 (FP-IT) 0.5 x 0.5 Degree Interannual Averages/Sums
Dates (month/day/year): 01/01/2013 through 12/31/2018
Location: Latitude -1.9632 Longitude 30.1357
Elevation from MERRA-2: Average for 1/2x1/2 degree lat/lon region = 1623.87 meters Site = na
Climate zone: na (reference Briggs et al: http://www.energycodes.gov)
Value for missing model data cannot be computed or out of model availability range: -999
Parameter(s):
KT SRB/FLASHFlux 1/2x1/2 Insolation Clearness Index (dimensionless)
-END HEADER-

LAT	LON	PARAMETER	YEAR	JAN	FEB	MAR	APR
-1.96319	30.13571	KT	2013	0.5	0.51	0.41	0.47
-1.96319	30.13571	KT	2014	0.48	0.47	0.47	0.45
-1.96319	30.13571	KT	2015	0.56	0.49	0.49	0.42
-1.96319	30.13571	KT	2016	0.45	0.46	0.5	0.42
-1.96319	30.13571	KT	2017	0.54	0.43	0.44	0.48

IAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
0.51	0.61	0.6	0.5	0.44	0.46	0.4	0.42	0.4
0.48	0.51	0.56	0.45	0.41	0.46	0.41	0.48	0.4
0.5	0.45	0.56	0.54	0.49	0.4	0.41	0.46	0.4
0.52	0.55	0.59	0.58	0.46	0.46	0.45	0.5	0.
0.49	0.55	0.5	0.43	0.43	0.43	0.41	0.47	0.4

2. Table of Irradiation at Mwogo/Bugesera district

	Global [kWh/m².day]	Diffuse [kWh/m².day]	Temper. [°C]
January	5.23	2.29	21.5
February	5.09	2.45	22.4
March	5.14	2.42	22.2
April	5.04	2.32	21.0
May	5.12	2.44	20.7
June	5.25	2.04	19.7
July	5.31	2.08	19.4
August	5.52	2.33	19.8
September	5.21	2.37	20.3
October	5.27	2.34	21.3
November	4.88	2.66	20.6
December	4.97	2.36	21.4
Year	**5.17**	**2.34**	**20.9**