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MASTER THESIS IN ENERGY ENGINEERING

DESIGNING A SOLAR WATER PUMPING SYSTEM IN SUDAN

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List of Abbreviations

SCER Sudanese Center of Energy Research.

GHI Global Horizontal Irradiation.

STC Standard Test Conditions**.**

SPV Solar Photovoltaic.

MPP Maximum Power Point.

BWT Bottom Water Level.

DLDL Drawdown Lower Dynamic Level.

PR Performance Ratio.

LS System Losses.

SP Submersible Pump.

SF Solar Fraction.

GLOBEff Global Efficiency.

EArrMPP Energy at the Maximum Power Point.

E pmpop Energy during Pump Operation.

TKFull Tank Fullness.

H Pump The Hydraulic Head.

WPumped Volume of Water Pumped.

W Used Volume of Water Used.

W Miss Volume of Water Missed.

Pvsyst Solar Design Software.

AH Hour Angle.

Dedication

To those who have been by guiding lights in the journey of knowledge and discovery.

This project is dedicated with profound gratitude and respect to esteemed advisor [**Stoppato**] whose expertise, understanding, and patience, added to my graduate experience.

To my loving **parents**, whose endless love, support, and sacrifices have paved the way for my academic pursuits. Your belief in me has been my greatest motivation.

To my **siblings**, for their unwavering encouragement and for always being there through the highs and lows.

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This achievement is not just my own, but a culmination of the efforts and support of everyone who has been a part of my life during this significant phase. Thank you.

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Abstract

Nowadays, the primary source of energy is fossil fuel, that covers approximately 79% of the primary energy consumed in the world, **[71]** including transportation, heating, and electrical generation. But there are limited reservoirs of fossil fuels on the Earth that will eventually run out.

So, it has become clear that to find alternative source for energy, **[58]** especially solar energy which is very abundant in Sudan.

Sudan is in the transition to renewable energy sources after it lost its oil – rich south part in a referendum in 2011 **[12**].

This project aims to design a system to pump water from the wells, solar powered using solar panels, the selection of system components has been made in a way that lights harmonically. Also, it included a study of the theory including explaining all system components in theory and practical design work using the PVsyst & SOLD WORKS program of the project.

The project concluded that with the necessary pumping quantity specified in advance, data energy account and found (4 KW) were selected (64 capacity of 200 W), also the pump type was selected and it was equipped with its own control compatible with the quantity and height specified in advance submersible pump (PS4000 C-SJ8-15) and controller PS4000 were selected. Tilt angle also been identified (15° on the horizontal level).Also the thesis included the use of design software to design a water-pumping under water quantity (104m^3/day) and depth(160m) as compared to the results of the program the results of a similar program for the same data and found the difference in the energy account (+0.0035%) and full compatibility in choosing components the system.

As well as the efficiency of the system account and found (38.89%), and finally study included a comparison between the techniques used in water pumping systems and comparing them with the technology of solar energy use and the results are economical compared to solar-powered (1.783% electrical) and (29.456% internal combustion engines), as the study included compared to the same environmental with discussion of the future of solar energy in Sudan solar energy as an alternative partially.

Chapter 1

1.1 Introduction:

The Sun is an immense source of power that emits light and energy over a series of wave lengths. The amount of solar radiation reaching the Earth's surface varies due to changing atmospheric conditions and the position of the sun during the day and the year. This power of the sun can be classified to thermal power (Indirect Power), **[96]** and solar power (direct power) where photovoltaic cells PV are used to convert sun light directly into direct current DC and then pump DC or pump AC using inverters. .

Private households and farms need stable and consistent water supply, however this can be particularly difficult in areas far off cities where there are no regular water pipe supply systems available but only resources in forms of wells deep in the ground. During hot months of the year and in hot areas the requirement for water is high. Furthermore, in some scarcely inhabited areas where regular irrigation for watering feels is crucial, **[12]** often the poor infrastructure electricity makes regular irrigation complicated, significantly driving operational and maintenance costs. Countering such complications and difficulties, solar water pumps are the optimal solution to both offset infrastructural limitations and reduce operational and maintenance costs. In addition, solar water pumps are particularly economic and crucial appliances.

As a result of the soaring prices of fuel and power sources, instability, air and water pollution, the main research problem was to find a solar pumping system which can be more cheaply and stable.

The main objectives of the project are to design and program a solar water pumping system to reduce usage of electricity, water, and air pollution to be more economic and environmentally friendly.

1.2 Research problem:

The problem is to reduce the usage of electricity in Sudan, as Sudan suffers from many problems in generation, also to reduce pollution because of fuel usage in IC engine in pumping, in addition to save water in areas which suffer from water shortage.

1.3 Research significance:

There are many significances of the project: firstly, a system that depends on a solar energy has no emissions gases, no greenhouse gases (Environmentally friendly) and no noises. System will not depend on electricity network so covering areas which have not been supplied by electricity lines, especially in rural Sudan.

Also, solar pumping is so cheap because there is no maintenance cost compared to other pumping systems, in addition it is portable. And an important significance of the system is that the source of power is sustainable.

1.4 Objectives:

Many villages in Sudan have no electricity and don not even have a grid near them for distribution of electricity to household or usage of conventional electrical pumps. Due to this we must think about an alternative power source to supply a pumping system, which is especially important for agriculture. Solar pumping system is a water pumping system run by Solar cell. So, we object through this study:

- To design a solar of water pumping system
- To simulate the performance of the system under specific conditions.
- To drawing the project by using SOLID WORK PROGRAM

1.5 Scope of work:

Many areas in Sudan suffer from the shortage of water sources especially areas so far from the river Nile stream and electricity lines, there we can use thermal engines to obtain subsurface water,

Chapter 2

Literature review and previous studies:

2.1 Background:

In retrospect, nobody predicted that in the age of global warming the annual average global temperature would remain unchanged for so long. As the statistical significance of the standstill increased, the debate about its potential importance grew among many branches of science, even though many prominent scientists and institutions, and all the media, were steadfast looking the other way.

Renewable energy refers to energy that occurs naturally and repeatedly in the environment. This can be energy from waves, wind, the sun, and geothermal heat from the ground. Renewable energy can also be produced from plant sources, such as wood or crops. Organic fuel sources can also be found in by-products from manufacturing and other processes. Under certain circumstances, **[6]** these can be converted to renewable energy using environmentally acceptable processes. As the term suggests, renewable energy will not run out, unlike energy from fossil fuels.

2.2 Solar energy:

The most important source of renewable energy source is the sun. Every day, the sun radiates (sends out) an enormous amount of energy called solar energy. It radiates more energy in one day than the world uses in one year. This energy comes from within the sun itself. Like most stars, the sun is a big gas ball made up mostly of hydrogen and helium gas. The sun makes energy in its inner core in a process called nuclear fusion.

It takes the sun's energy just a little over eight minutes to travel the 93 million miles to Earth. Solar energy travels at the speed of light, or 186,000 miles per second, or 3.0 x 108 meters per second.

Only a small part of the visible radiant energy (light) that the sun emits into space ever reaches the Earth, but that is more than enough to supply all our energy needs. Every hour enough solar energy reaches the Earth to supply our nation's energy needs for a year! Solar energy is considered a renewable energy source due to this fact.

Today, people use solar energy to heat buildings and water and to generate electricity.

Here are the main advantages of solar energy:

- One of the cleanest forms of energy
- Harmonious with nature
- Easy to install, operate and maintain.
- Long life. Solar panels can last up to 20 years or more.
- Modular design, hence easy to expand.
- Ideal for remote areas, where electricity is not dependable, and diesel is difficult to obtain.
- Safe to manage. Once installed properly, most devices can be used by laypeople without risk.
- Freedom from grid, which is often unreliable especially in remote areas.

- Can be used as standalone or grid connected systems as well as with other energy sources as hybrid systems.

2.3.1 Types of solar energy:

There are two kinds of solar energy:

- **Solar thermal:**

Solar thermal systems use the sun’s energy to provide hot water. The technology is well established, but its success depends on several locations and orientation-based factors, and it is usually economically viable only when installed in buildings with a sufficiently high hot water demand.

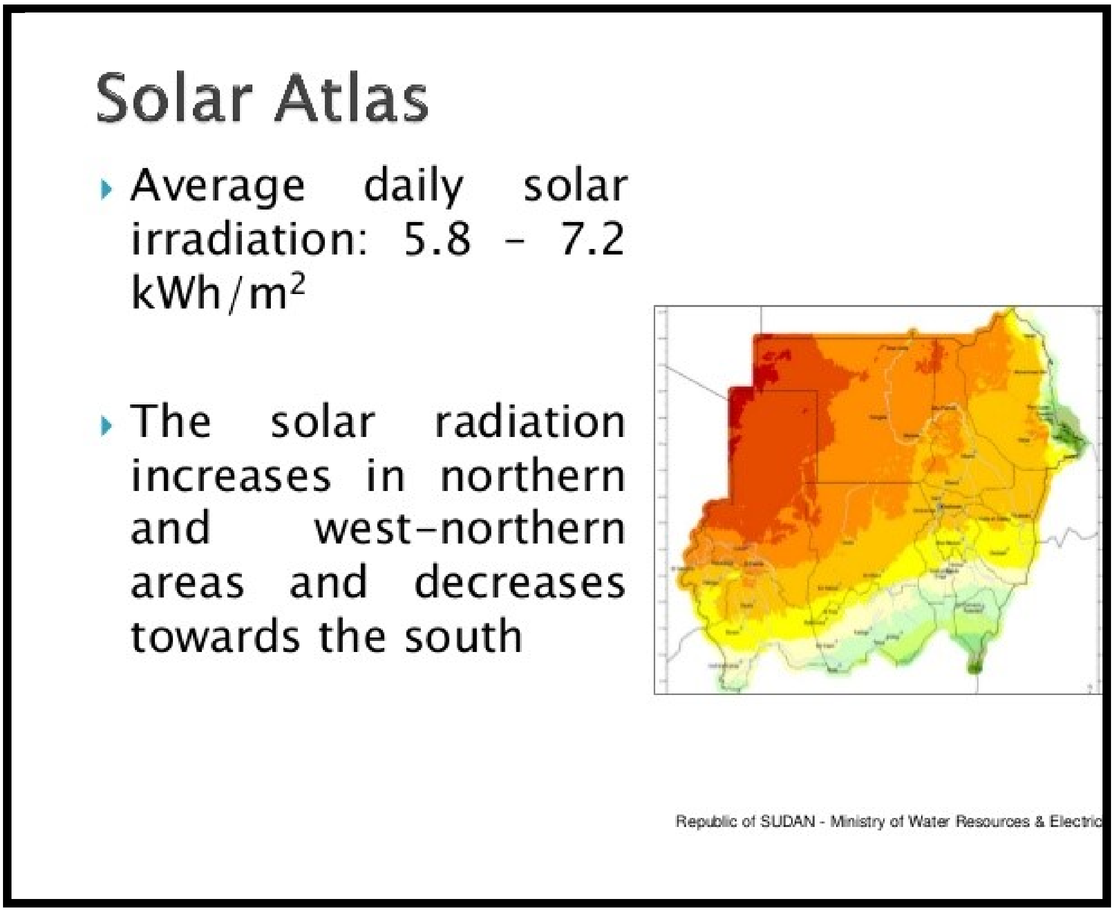
Figure (2.1): Example of solar thermal applications **[8]**

- **Solar photo voltaic:**

Solar Photo voltaic (PV) uses the sun's energy to generate electricity. PV panels are increasingly recognized by the public and make a strong visual statement about sustainability. It is an installation that converts sunlight into electricity. PV electricity generation uses the energy in the light from the sun to cause an electrical current to flow between different atomic energy levels in specially processed materials. PV, like solar thermal, **[58]** is a truly intermittent renewable energy technology and requires the user to obtain electricity from an alternative source during the night when it cannot generate electricity, or to utilize a battery back-up system where some of the energy generated can be stored during the day, for use at night we can utilize the solar energy for many purposes especially irrigation system. In 1991 Sudan had a large modern irrigated agriculture sector totaling more than 2 million hectares there potentially. Gravity flow was the main form of irrigation, but about one-third of irrigated area was served by pumps.

In Sudan, the solar radiation is so large, and number of day hours is so more than in other countries that we can benefit from this huge free power special because we have many problems in power generation **[25]**.

The following picture illustrate the amount of solar radiation in Sudan states.



Solar Atlas

- Average daily solar irradiation: 5.8 - 7.2 kWh/m^2
- The solar radiation increases in northern and west-northern areas and decreases towards the south

Republic of SUDAN - Ministry of Water Resources & Electric

Figure (2.2): solar atlas of Sudan

2.3 Review of some traditional method of pump in Sudan:

The waters of Nile in Sudan have been used for centuries for traditional irrigation, taking advantage of the annual Nile flood. Some use of this method continued I the early 1990s, and the traditional Shaduf (a device to raise water) and waterwheel were also used to lift water to fields in local irrigation projects but were rapidly being replaced by more efficient devices. The farmer used traditional pumps run by oil, more expensive and unfriendly, **[3]** so we should look for an optimal alternative.

Figure (2.3): Some pumping methods in Sudan **[3]**

Figure (2.4): some pumping methods in Sudan

As we saw, traditional methods in irrigation pump have more power consummation, environmental injuries, costly special maintenance, and operations cost. Subsequently we have thought to use clean, cheap, and sustainable source of power and this was solar.

2.3.1 Solar Irrigations Pump:

A solar powered pump is a pump running on the power of the sun. It makes.

Efficient use of solar energy and converts it into electrical energy for pumping water to great heights. A solar powered pump can be very environmentally friendly and economical in its operation. This system operates on power generated using solar PV (photovoltaic) system. The photovoltaic array converts solar energy into electricity, **[25]** which is used to run the motor pump set. The pumping system draws water from the open well, bore well, pond etc. The water pumping system can be used to irrigate land when the water is to be pumped from a depth of a well or a pond.

Figure (2.5): Solar pumping system.

Advantages of Solar Water Pumps:

It helps in saving Energy:

- There is no fuel cost - as it uses available free sunlight.
- No electricity required.
- Can be operated lifelong.
- It is highly reliable and durable.
- Easy to operate and maintain.
- It is also useful for cleaning, drinking water sanitation and irrigation.
- The dependence on rain is reduced.

2.4 Design specifications for pumping system:

The requirements to be met by any pumping system are specified as:

- Discharge flow rate for transfer of liquid from suction to discharge reservoir.
- Total pressure had to be overcome by the pumping system.

2.4.1 Specification of the discharge flow rate required:

The discharge flow rate required is stated in liters per second (l/s), or cubic meters per second (m^3/s). It is determined by a study of water demand. Water demand is determined by segregating the total demand into categories such as:

1. Irrigation demand
2. Domestic demand
3. Industrial demand
4. Commercial demand
5. Institutional demand

For irrigation, the water demand is derived from the total area to be irrigated and the water required per unit of area irrigated. The water demand required per unit area irrigated depends on the crop, the climatic conditions, and the soil conditions. For categories of demand except irrigation, the population to be served and its per capita water consumption is estimated, and from this data, the aggregated water demand is computed. The water quality for categories of demand other than irrigation will be to human health standards.

In practice, demand for irrigation will usually be isolated and designed for separately, **[125]** because the location where it occurs, and the water quality demanded is often different.

2.4.2 Specification of the total Pressure head to be overcome by pumping system:

The total pressure head (H) to be overcome by a pumping system is stated as meters of water, (mw). This total pressure head is also referred to as the dynamic head. This is because it is the sum of the static head and the friction head. It is referred to as dynamic because it incorporates the head loss due to fluid friction in pipeline, which arises only during the dynamic conditions of fluid flow.

2.5 The main components of the system (SWPS):

Solar Photovoltaic water pumping system consists of many elements that are considered especially important for the system stability.

2.5.1 PV Array:

- **Photovoltaic cell:**

Photovoltaic is the conversion of light directly into electricity through semiconductor materials. The basic component of a PV system is solar cells. If light with adequate energy falls onto silicon arranged to form a p-n junction and penetrates to a point near the junction, then, because of the photo-electric effect, it will create free electrons near the junction. These electrons immediately move under the influence of the p-n junction's electric field. The electrons continue to move through the cell to the surface of the cell. On the way towards the surface of the cell some of the electrons may be re-absorbed by the silicon atoms, but many electrons still reach the surface of the cell. These electrons can be collected by a metallic grid and an electric current will flow if the grid is connected to the metal contact on the other side of the cell by an external circuit.

➢ PV modules:

PV modules or solar modules have dc. Electrical output power even though there are no moving parts and no pollutants emitted. PV systems are modular which gives it an advantage of being able to increase its size even after it has been installed. It is flexible, easy, and quickly coordinated and constructed into an array or a PV plant.

There are three types of PV modules:

- Amorphous silicon modules
- Mono crystalline solar cells
- Poly crystalline solar cells

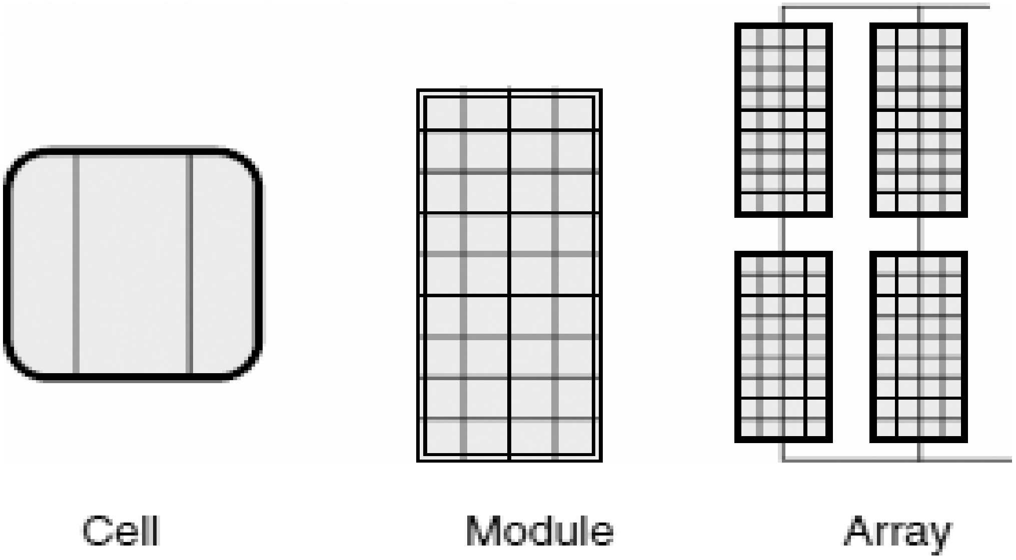


Figure (2.6): Cell, Modules, Array

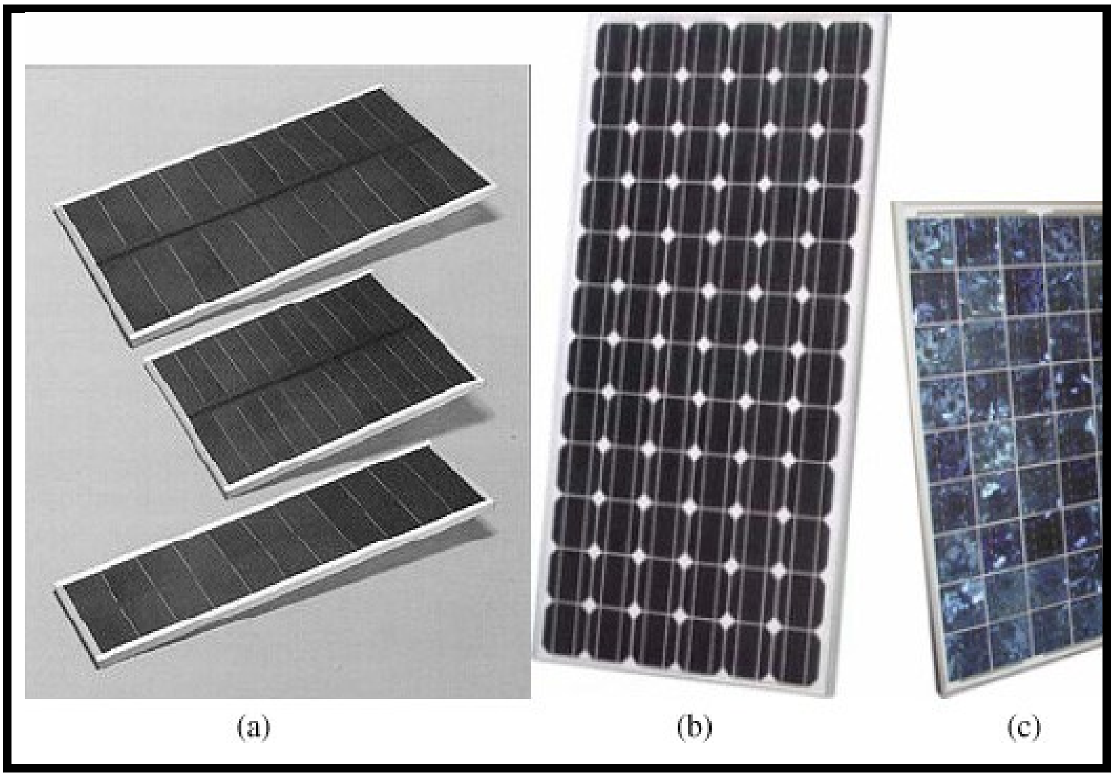


Figure (2.7): Types PV modules.

Capacity in the range of 200 Wp to 10 kWp. These ranges of Solar Photovoltaic (SPV) Water Pumping Systems are for "Irrigation" applications. However, these may also be used for "Drinking Water Applications wherever such capacities are required." PV Array should be mounted on a suitable structure with a provision of tracking the sun.

The SPV water pumping system should be operated with a PV array capacity in the range of *200* W peak to 10000 W peak, measured under Standard Test Conditions (STC). Enough modules in series and parallel could be used to obtain the required PV array power output. The power output of individual PV modules used in the PV array, **[129]** under STC, should be a minimum of 125 W peak, with adequate provision for measurement tolerances. Use of PV modules with higher power output is preferred. Indigenously produced PV module (s) containing mono/ multi crystalline silicon solar cells should be used in the PV array for the SPV Water Pumping systems.

2.5.2 Motor Pump Set (Surface or submersible):

There are two kinds of pumps, submersible, and surface pump. For example, submersible pumps are used in far depths and surface ones are used in depths not exceeding three meters. So that and because in wells those have been used in irrigations are deeper, we have used submersible pump (SP).

Also, solar pumps are classified into two kinds of DC motor pump (use direct current), and AC Motor Pump (use alternative current) set with a suitable inverter. At this study we have used DS pump because it is more economic.

The pumps used for solar application should have a 5-year warranty, so it is essential that the construction of the pump be made using parts which have a much higher durability and do not need replacement or corroded for at least 5 years.

Submersible pumps could also be used according to the dynamic head of the site at which the pump is to be used. It is recommended that all parts of the pump and the motor of the submersible pumps should be made of stainless steel.

Provision for remote monitoring of the installed pumps must be made in the controllers or the inverters either through an integral arrangement or through an externally fitted arrangement. It should be possible to ascertain the daily water output, the power generated by the PV array, the up time of the pump during the year.

Submersible pump forms principal components and they are motor, inlet or suction part, out part, chamber stack, and figure (2.9) explain these parts.

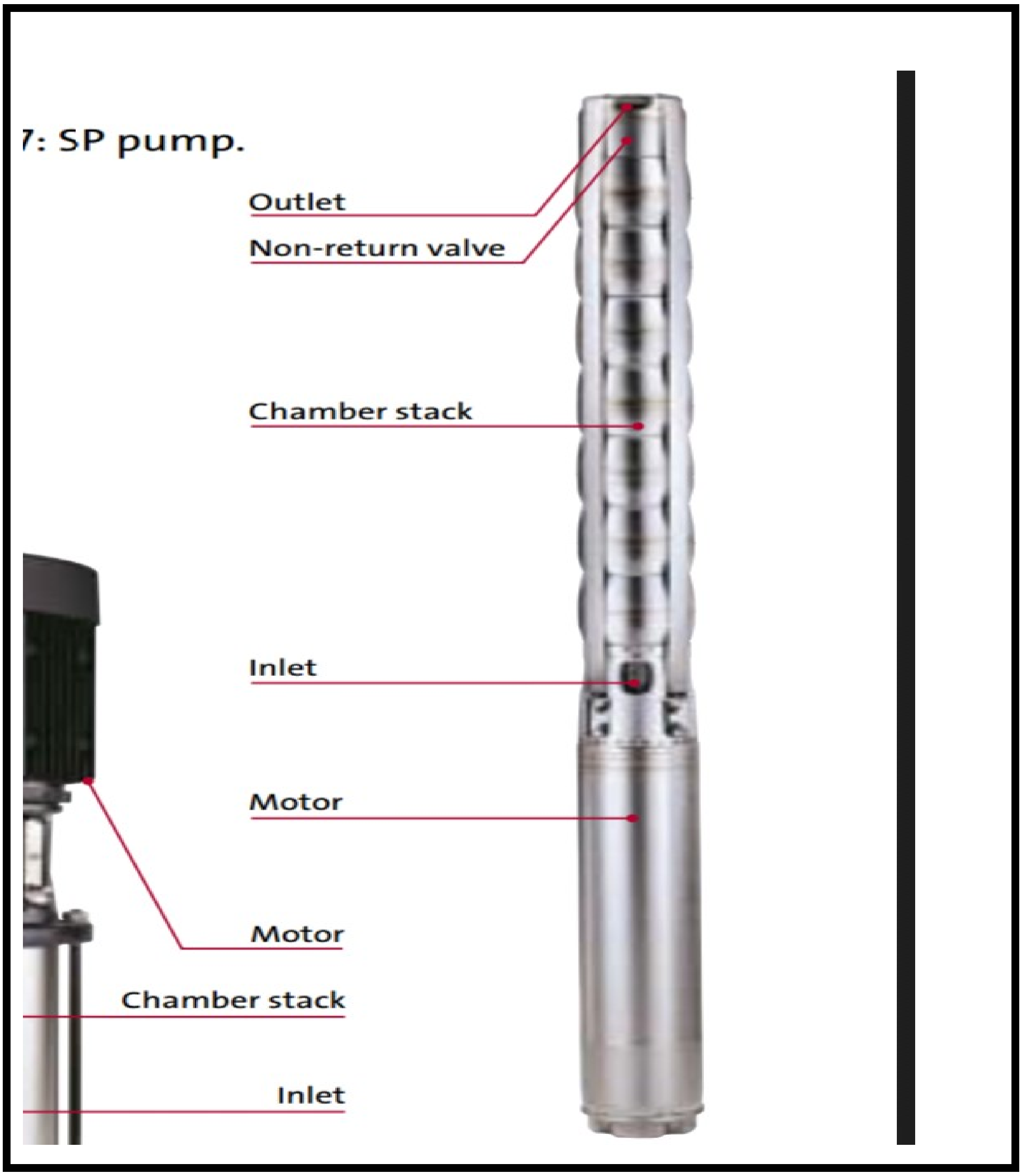


Figure (2.9): Submersible parts.

2.5.3 Reservoir:

Reservoirs are used to store water that had been pumped by pump to be use in night or day irrigation. We have used reservoir instead of batteries in night irrigation. Batteries are costly and more damaging, also electric store operations are so difficult and limited; therefore, we have used reservoir.

We have designed reservoir-like room by dimensions agreeing with the mount of daily required water by using more available material such as red bricks, sands, and cements. Using these materials is better than other kinds of reservoir as metal reservoir which suffers from corrosion.

2.5.4 Controllers:

This component is especially important for the system, and the usage of controllers is shaped in regulating current into pump, protecting pump from overload and over temperature, therefore any submersible pump must relate to PV panel through PS controller to save operation.

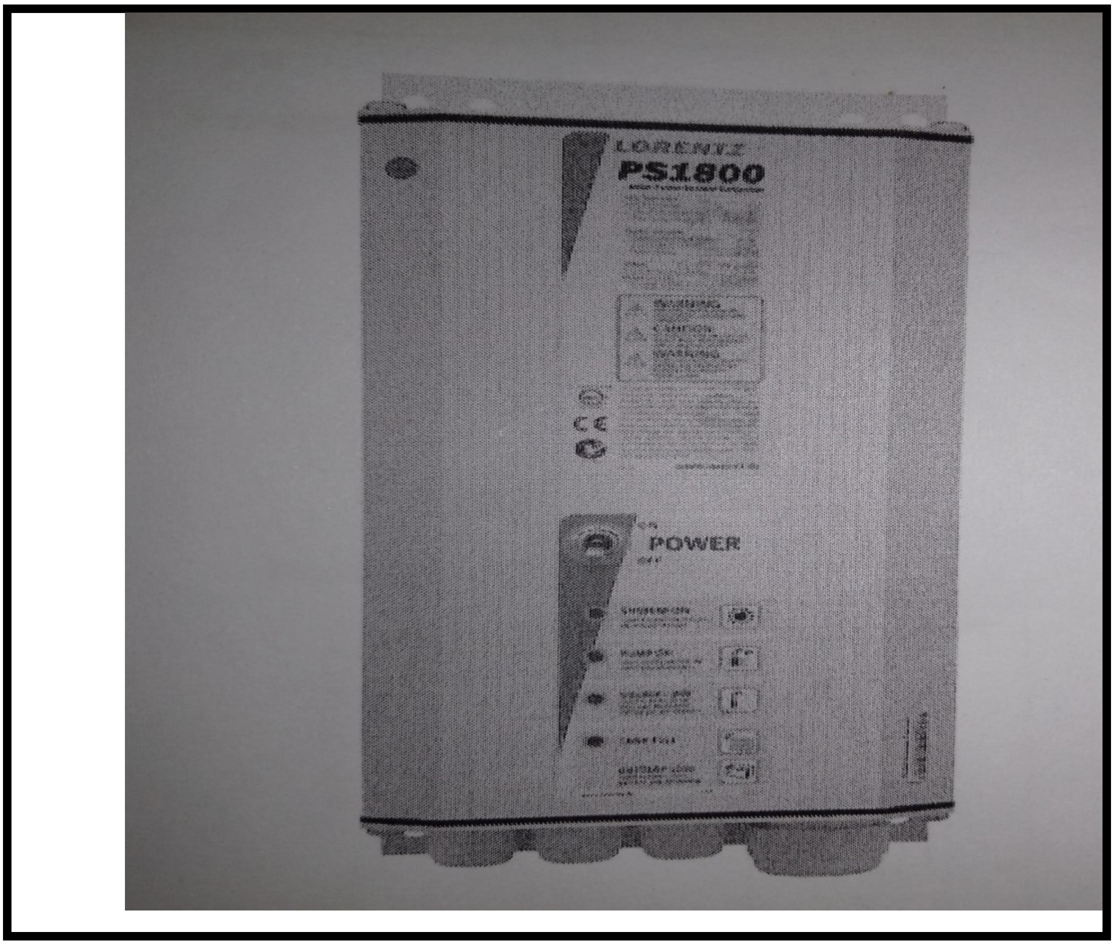


Figure (2.10): PS controller.

2.5.5 Tubes:

Tubes those have been used must be made from stainless steel material which has small roughness factor that decrease the friction losses, as it is no corrosion and the important thing because tube will stay a long time inside water for many years (at least 5 years) that tube will be damaged.

2.5.6 Fittings:

In irrigation practices fittings that are popular being used are T fitting, elbow fitting (90 deg), valves, as it is fitting must be few to decrease losses in power. And they are used in controlling the water flow.

2.6 Methodology:

Firstly, we have studied the theoretical side of the project, the components of the system especially the basic components such as the PV panels and pumps, and other important components such as control unit, pipes, and the PV directing mechanism. Then we collected data about their types, work theory and classifications.

Secondly, we have regulated these data and distributed them to units or chapters so they could be used use.

Third, numerical study to calculate amount of power in (kW) which has been developed by PV panels then number of PV panels modules which give the required demand of water per meter cubic.

Fourthly, we have drawn, and water animated by using SOLID WORKS SOFT WARE PROGRAM.

Fifthly, we have simulated the performance of the system under specific conditions by using PVsyst SOFT WARE PROGRAM.

2.7 Project out line:

The project contains nine chapters as follow:

- **Chapter one:** contains a general introduction of the project, definition of the problem, significances and objectives, scope of work, the methodology of a project and timetable of project activities.
- **Chapter two:** takes the theoretical sides of all project sections, literature reviews.

- **Chapter three:** takes a little introduction, the project methodology, flow chart and software programs.
- **Chapter four**: talks about geographical features of Sudan, beside the study for the climate and terrains.
- **Chapter five**: talks about designing the model and its components.
- **Chapter six**: describes PVsyst software and the procedures for implementing the project.
- **Chapter seven**: it contains the validation and the main results for the project by using the PVsyst software.
- **Chapter eight**: talks about the calculation and discussion of the results.
- **Chapter nine**: is the last one containing the recommendations and conclusions.

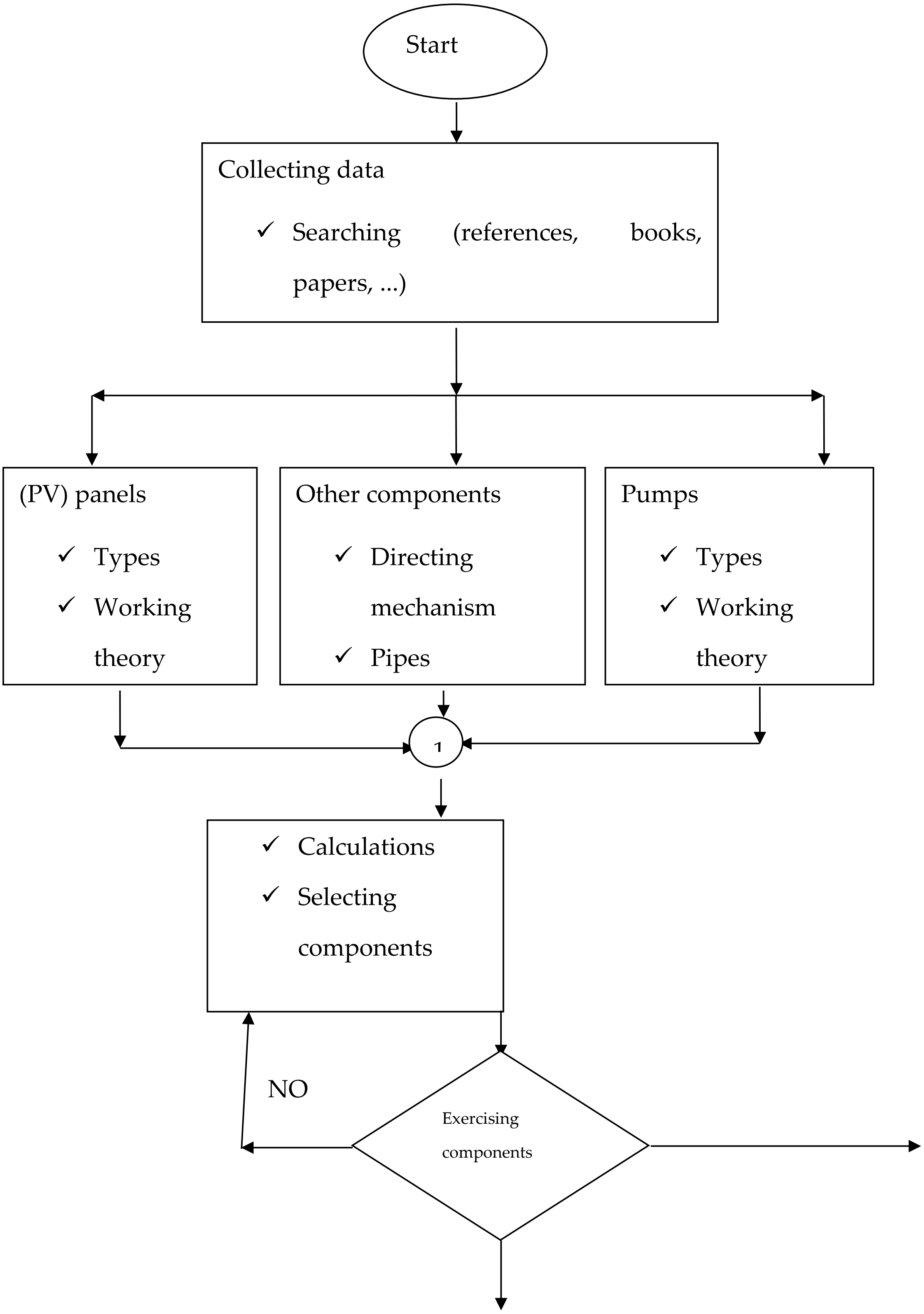
Chapter 3

3.1 Introduction:

After collecting required and important data we have transferred to the designing stages by using mechanics of fluids equation (BERNOULLI's equation, fluids continuity and power equation, losses in pipes equation). In addition of the sun slope angle equation in Sudan. Then determining number of (PV) panels, after that modeling, simulation, and programming.

3.2 Flow chart:

It is a simple method to explain the logical arrangement of the project activities as it is shown below.


Start
Collecting data
✓ Searching (references, books, papers, ...)
(PV) panels
✓ Types
✓ Working theory
Other components
✓ Directing mechanism
✓ Pipes
Pumps
✓ Types
✓ Working theory
1
✓ Calculations
✓ Selecting components
NO
Exercising components

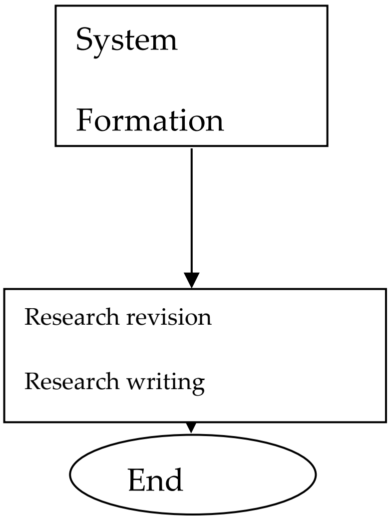


Figure (3.1): The flow chart of the project.

3.3 Equations of the project:

In any pumping system, the role of the pump is to provide sufficient pressure to overcome the operating pressure of the system to move fluid at a required flow rate. The operating pressure of the system is a function of the flow through the system and the arrangement of the system in terms of the pipe length, fittings, pipe size, the change in liquid elevation, pressure on the liquid surface, etc. To achieve a required flow through a pumping system, we need to calculate what the operating pressure of the system will be to select a suitable pump.

3.3.1 Power Equations:

The principle and especially important equation at this side of the project is the power equation that calculates our required power to give a certain amount of water in (Watt).

$$P = \frac{Q*H*G*\rho}{\eta m*\eta p} \qquad (3.1)$$

Where:

P ≡ total power that system needs (w)

Q ≡ flow rate of water (m^3/s)

H ≡ total head (m)

G ≡ constant of the gravity (m/s^2)

ϱ ≡ density of water (kg/m^3)

Ƞm ≡ efficiency of motor (%)

Ƞp ≡ efficiency of pump (%)

Then after that we can find the number of modules of the (PV) panels by using this equation:

$$N = \frac{P}{n} \qquad (3.2)$$

Where:

N ≡ number of modules of (PV) panels (once)

n ≡ capacity of modules (watt)

P ≡ total power that system needs (watt)

3.3.2 Head and losses equations :(3.3 refer)

We have two kinds of head static and dynamic head where total head equals the summation of static and dynamic head.

$$Htotal=Hd+Hs+(P1-P2) \qquad (3.3)$$

Note:

The term of the pressure difference (P1-P2) is often neglected because it is so small in value.

Hdmin=discharge level-reservoir level (TWL) (3.4)

Hsmax=discharge level-reservoir level (BWL) (3.5)

Hd=$\frac{K*V^2}{2G}$ (3.6)

$K = \mathrm{n}K(pipes) + nK(fittings)$ (3.7)

$k(pipes) = \frac{fL}{D}$ (3.8)

And we can find f from The Colebrook equation: **

$$f = \frac{0.25}{\left[\log\left\{\frac{\mathrm{k}}{3.7*\mathrm{D}} + \frac{5.74}{\mathrm{Re}^{0.9}}\right\}\right]^2} \quad (3.9)$$

$$Re = \frac{VD}{\upsilon} \quad (3.10)$$

Where:

Htotal ≡ total system head (m)

Hsmin ≡ minimum static head (m)

Hsmax ≡ e maximum static head (m)

TWL≡ top water level (m)

BWT ≡bottom water level (m)

Hd ≡ dynamic head (m)

K ≡ losses coefficient

V ≡ velocity of water (m/s)

G ≡ constant of the gravity (m/s^2)

D ≡ internal diameter of pipe between the reservoir and the source of water (m)

f ≡ coefficient of friction

L ≡ pipe length between the reservoir and the source of water (m)

n ≡ number of components

Re ≡ Renold number (nondimensional)

k (small letter) ≡ the pipe roughness factor (m)

υ ≡ kinematic viscosity (m^2/s)

P1 ≡ pressure on the water source surface (N/m^2)

P2 ≡ pressure on the reservoir surface (N/m^2)

Note:

- The losses coefficient of fittings (F (fittings)) is standard values and obtained from standard tables.
- The pipe roughness factor k is standard value obtained from standard tables and is based upon the material of the pipe, including any internal coating, and the internal condition of the pipeline.

Table (3.1) following gives the losses coefficient value of many.

commonly used fittings.

Table (3.1): Losses coefficient value of fittings (*)

Fitting Items	K fittings Value
Pipe Entrance (bellmouth)	0.05
90 o Bend (short radius)	0.75
45 (degree) Bend (short radius)	0.3
Butterfly Valve (Fully Open)	0.3
Non-Return Valve	1
Bellmouth Outlet	0.2

The table following gives the roughness coefficient of many common materials that are used in pipe productions.

Table (3.2): Roughness coefficient table

Channel surface material	Roughness coefficient
Asbestos cement	0.011
Brass	0.011
Brick	0.015

Cast-iron, new	0.012
Concrete, steel forms	0.011
Concrete, wooden forms	0.015
Concrete, centrifugally spun	0.013
Stainless steel	0.015
Corrugated metal	0.022
Galvanized iron	0.016
Lead	0.011
Plastic	0.009
Steel-coal-tar enamel	0.01
Steel –new unlined	0.011
Steel –riveted	0.019
Wood stave	0.012
Polyvinyl chloride PVC - smooth	0.009-0.011
Steel smooth	0.012
Glass	0.010
Steel smooth	0.012
Copper	0.011

3.3.2 Velocity equation:

It is necessary to calculate the velocity of water that is used in many equations.

$$V = \frac{Q}{A} \qquad (3.11)$$

$A = \frac{\pi D^2}{4}$ (3.12)

Where:

Q ≡ flow rate of water (m^3/s)

V ≡ velocity of water (m/s)

A ≡ the internal section area (m^2)

D ≡ the internal pipe diameter (m)

Also, we can use this equation which it is known as Torricelli equation to determine the initial velocity of any static fluid:

$V = \sqrt{}(2 * g * h)$ (3.13)

Where:

V ≡ velocity (m/s)

g ≡ the constant of the gravity (m/s^2)

h ≡ high level of water (m)

Tilt angle:

There are many methods to determine the tilt angle of the PV panels, but these methods are so complicated. And because we will use sun tractor therefore, we have used the easiest one. As we have seen, determining the tilt angle depends on the latitude as we have at this table.

Table (3.3): Tilt angle selection table

Site latitude (degree)	Tilt angle (degree)
0 to 15	15
15 to 25	Same as latitude
25 to 30	Latitude +5
30 to 35	Latitude +10
35 to 40	Latitude +15
Above 40	Latitude +20

Finally, the design process can be structured in sequential steps:

3.4 Steps of designing a Solar Pumping System:

Step 1 - Determining basic amount of water required per day.

Step 2 - Calculating the total dynamic.

Step 3 - Determining the solar insulation for location.

Step 4 - Selecting the pump, controller, and solar array.

Step 5 - Selecting the correct solar array mounting method.

Step 6 - Selecting the right size pump cable and pipe.

Step 7 - Using water level sensors and pump controls.

Chapter 4

GEOGRAPHICAL FEATURES:

Sudan is in the northeastern part of Africa and occupies 1,886,000 square kilometers. Since ancient times Sudan has been the largest African country with an area that represented more than 8 percent of the

African continent and 2% of the world's total land after the separation of South Sudan from the north in 2011. Sudan is divided into eighteen states and every state with special administrative status **[35]**.

4.1 States of Sudan are:

1. Khartoum
2. North Kordofan
3. Northern
4. Kassala
5. Blue Nile
6. North Darfur
7. South Darfur
8. South Kordofan
9. Gezira
10. White Nile
11. River Nile
12. Red Sea
13. Al Qadarif
14. Sennar
15. West Darfur

16. Central Darfur

17. East Darfur

18. West Kordofan.

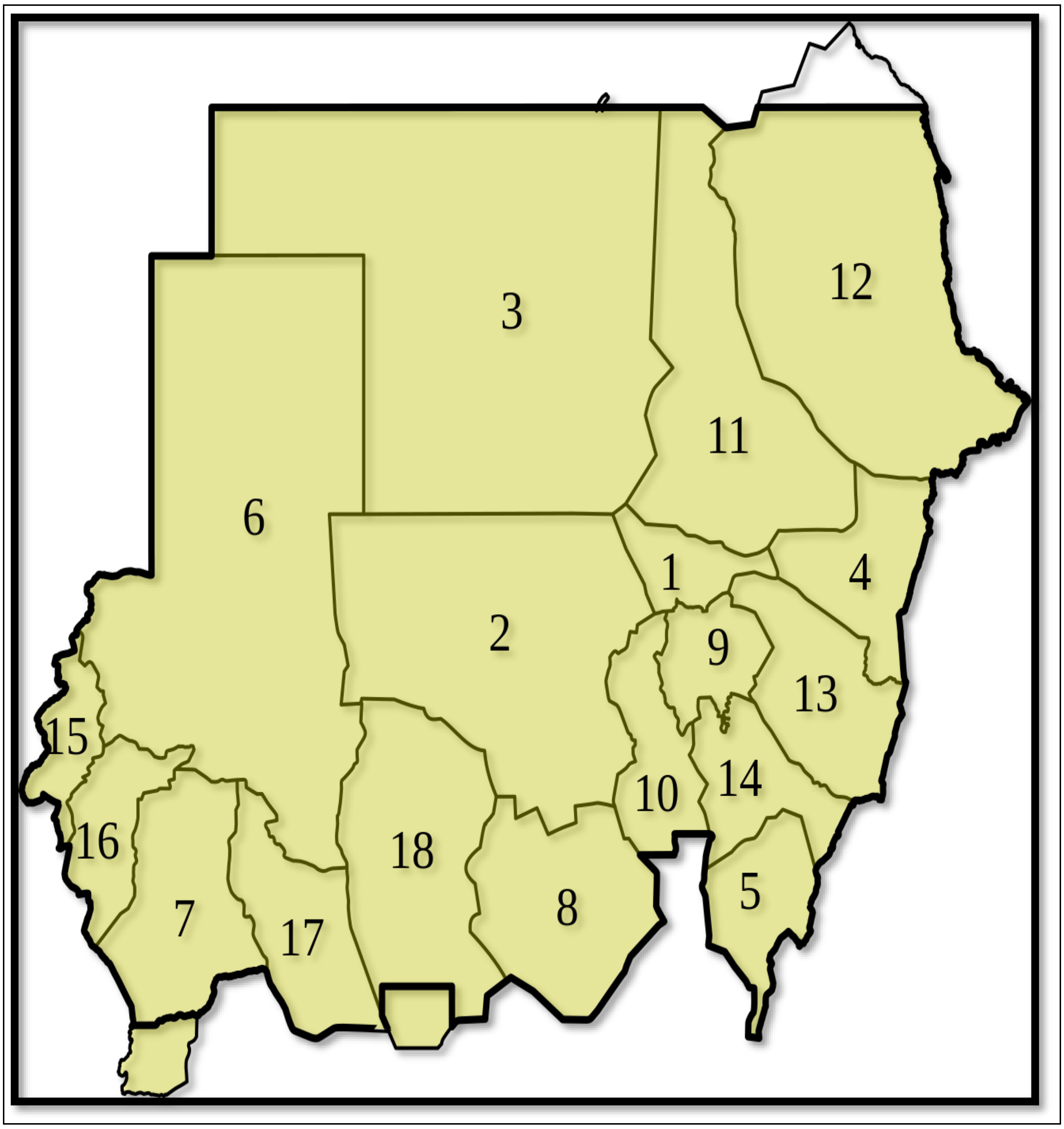


Figure 4.1: states of Sudan **[34]**.

4.1.2 Terrain:

Sudan is flat, featureless plain; mountains in the far south, west, and northeast; **[29]** desert dominates the north especially.

4.1.3 Climate Study of Sudan:

Climate change poses significant challenges to Sudan. Climate Change is not merely an environmental issue that is defined by precipitation and temperature changes; it represents a serious sustainable development problem that affects everyone in the country, **[28]** particularly those in rural communities who are the most vulnerable. Therefore, Sudan considers effective and ongoing efforts to adapt to climate change a national priority.

Although Sudan lies within the tropics, the climate ranges from arid in the north to tropical wet-and-dry in the far southwest. Temperatures do not vary with the season in any way.

Location: the most significant climatic variables are rainfall and the duration of the dry season. Variations in the length of the dry season depend on which of two air flows predominates, **[25]** dry northeasterly winds from the Arabian Peninsula or moist southwesterly winds from the Congo River basin.

From January to March, the country is under the influence of the dry northeasterlies. There is no rainfall in the Sudan except for a small area in northwest Sudan in where the winds have passed over the Mediterranean bringing occasional light rains. By early April, the moist southwesterlies have reached southern Sudan, bringing heavy rains and thunderstorms. By July, the moist air has reached Khartoum, and in August it extends to its usual northern limits around Abu Hamad, although in some years the humid air may even reach the Egyptian border. The flow becomes weaker as it spreads north. In September, the dry northeasterlies begin to strengthen and to push south and by the end of December they cover the entire country. Yambio, close to the border with Zaire, has a nine-month rainy season (April-December) and receives an average of 1,142 millimeters of rain each year; Khartoum has a three-month rainy season (July, September) with an annual average rainfall of 161 millimeters; **[28]** Atbarah receives showers in August that produce an annual average of only 74 millimeters.

In some years, the arrival of the south westerlies and their rain in central Sudan can be delayed, or they may not come at all. If that happens, drought and famine follow. The decades of the 1970s and 1980s saw the southwesterlies frequently fail, with disastrous results for the Sudanese people and economy.

Temperatures are the highest at the end of the dry season when cloudless skies and dry air allow them to soar. The far south, however, with only a short dry season, has uniformly hot temperatures throughout the year. In Khartoum, the warmest months are May and June, when average highs are 41° C and temperatures can reach 48° C. Northern Sudan, with its short rainy season, has hot daytime temperatures year-round, except for winter months in the northwest where there is precipitation from the Mediterranean in January and February. Conditions in highland areas are cooler, and the hot daytime temperatures during the dry season throughout central and northern Sudan fall rapidly after sunset. Lows in Khartoum average 15° C in January and have dropped as low as 6° C after the passing of a cool front in winter**[11]**.

The haboob, a violent dust storm, can occur in central Sudan when the moist southwesterly flow first arrives (May through July). The moist, unstable air forms thunderstorms in the heat of the afternoon. The initial downflow of air from an approaching storm produces a huge yellow wall of sand and clay that can temporarily reduce visibility to zero.

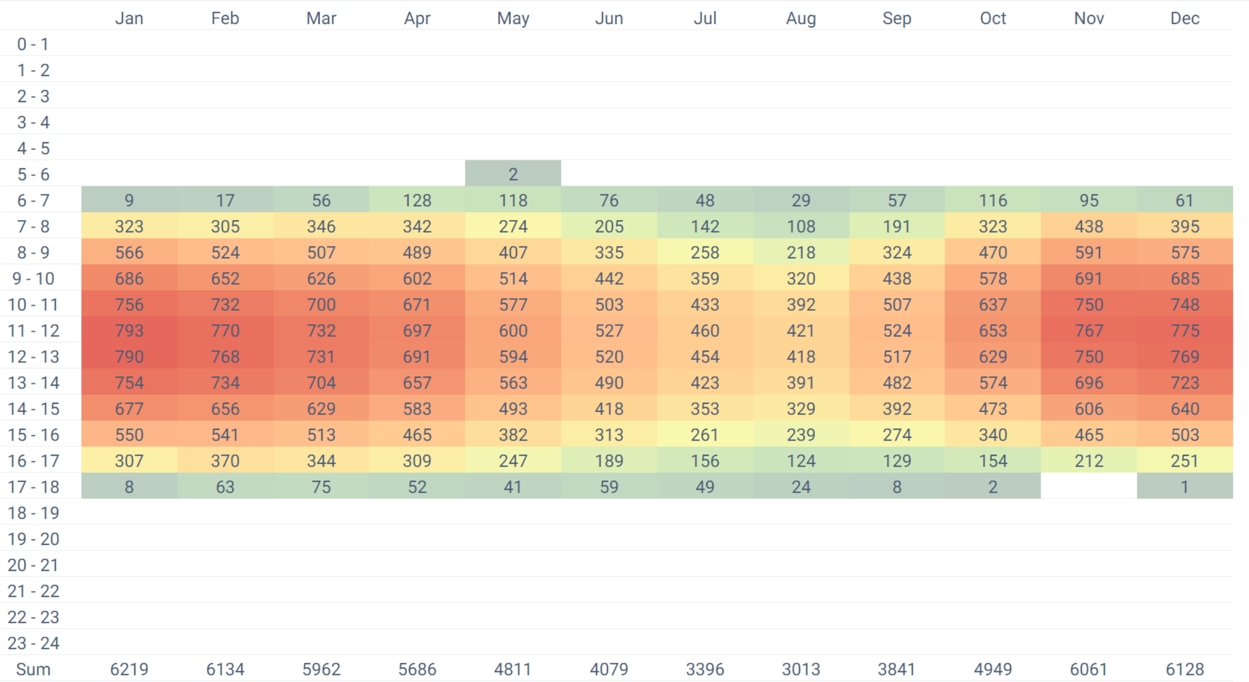
The capital is Khartoum:

Location :15.563597° N, 032.534912° E, elevation 385(m)

Time zone: UTC+02, Africa/Khartoum [CAT]

Average hourly profiles:

Direct normal irradiation [Wh/m²]



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6					2							
6 - 7	9	17	56	128	118	76	48	29	57	116	95	61
7 - 8	323	305	346	342	274	205	142	108	191	323	438	395
8 - 9	566	524	507	489	407	335	258	218	324	470	591	575
9 - 10	686	652	626	602	514	442	359	320	438	578	691	685
10 - 11	756	732	700	671	577	503	433	392	507	637	750	748
11 - 12	793	770	732	697	600	527	460	421	524	653	767	775
12 - 13	790	768	731	691	594	520	454	418	517	629	750	769
13 - 14	754	734	704	657	563	490	423	391	482	574	696	723
14 - 15	677	656	629	583	493	418	353	329	392	473	606	640
15 - 16	550	541	513	465	382	313	261	239	274	340	465	503
16 - 17	307	370	344	309	247	189	156	124	129	154	212	251
17 - 18	8	63	75	52	41	59	49	24	8	2		1
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	6219	6134	5962	5686	4811	4079	3396	3013	3841	4949	6061	6128

Figure 4.2: average hourly profiles in Khartoum, Source: globalsolaratlas.info

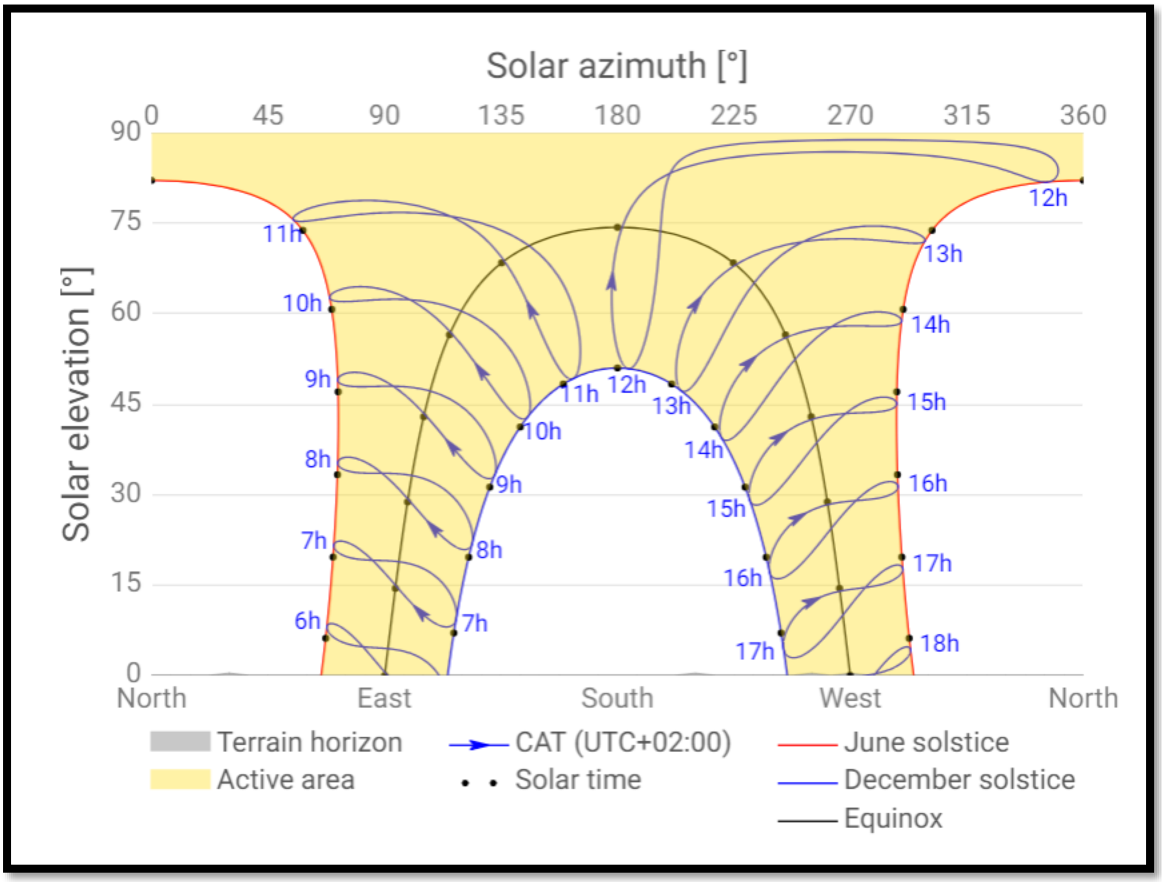


Figure 4.3: Horizon and sun path.

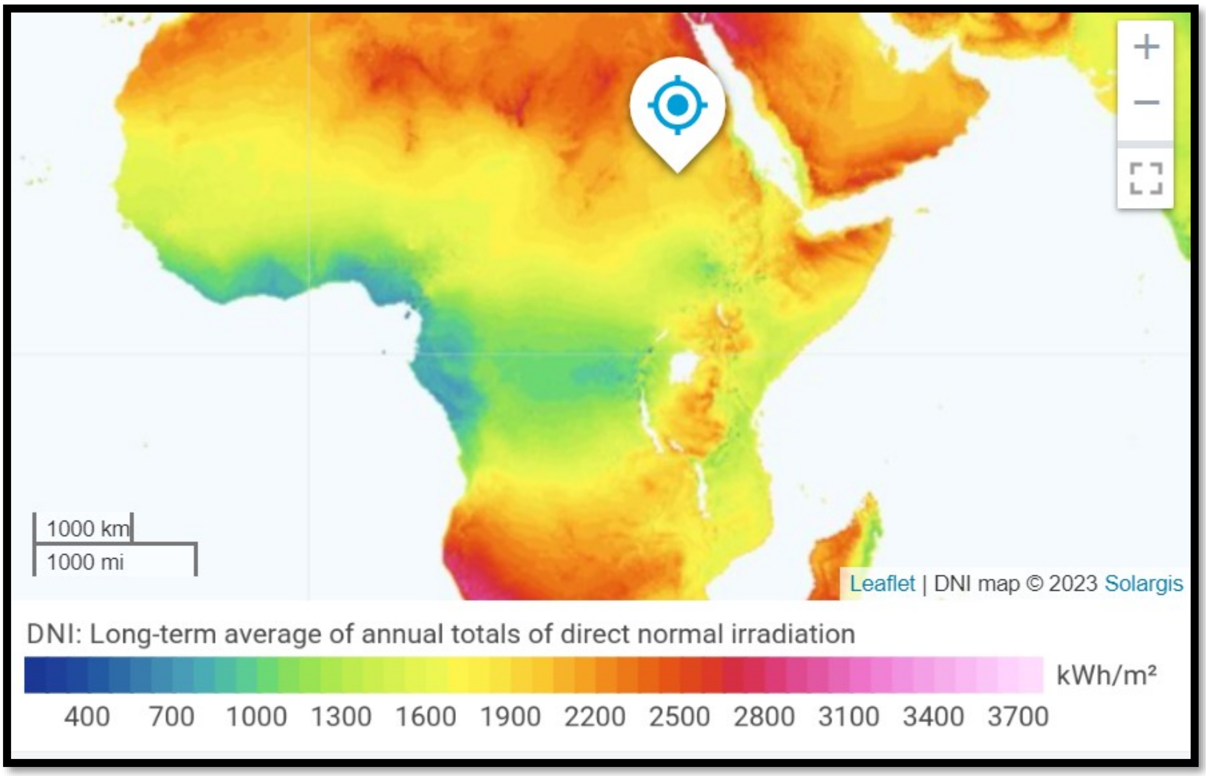
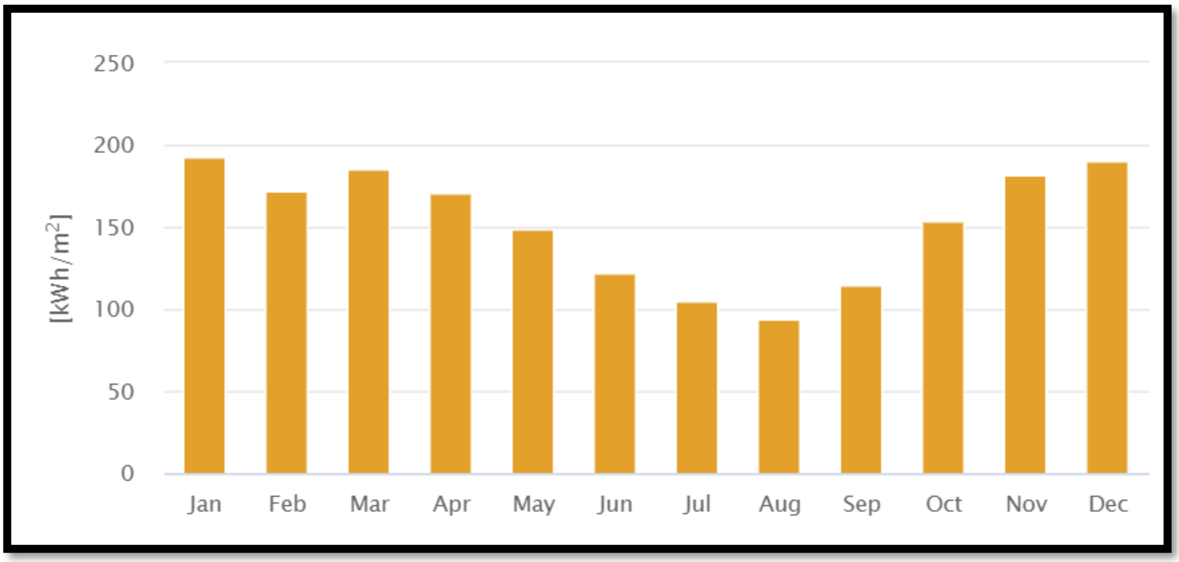


Figure 4.4: Sudan DNI MAP

Figure 4.5: Monthly rate of direct normal irradiation.



The average daily horizontal irradiation 5.8 – 7.2 kw/m2/day

4.2.1Sudan’sStatesRankingByAverageYearly Temperatures:

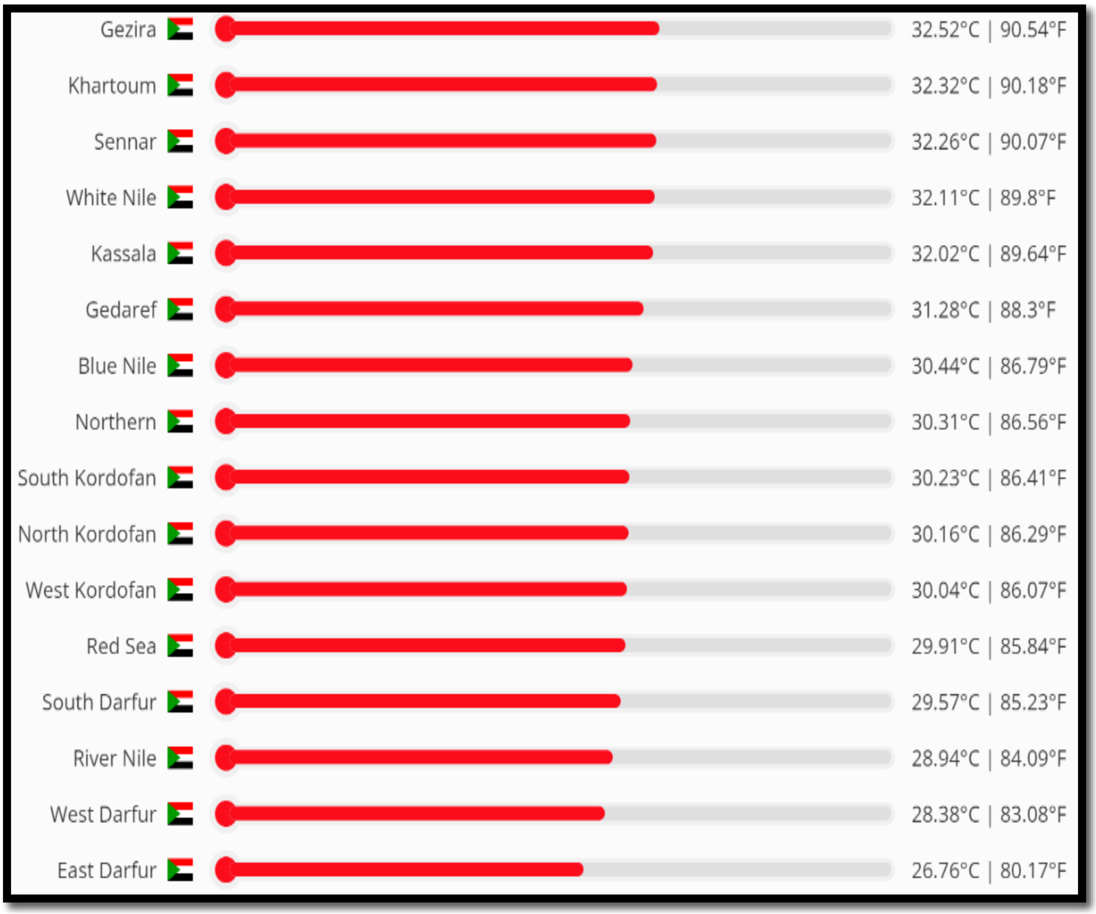


Figure 4.6: shows average temperature in Sudan **[28]**.

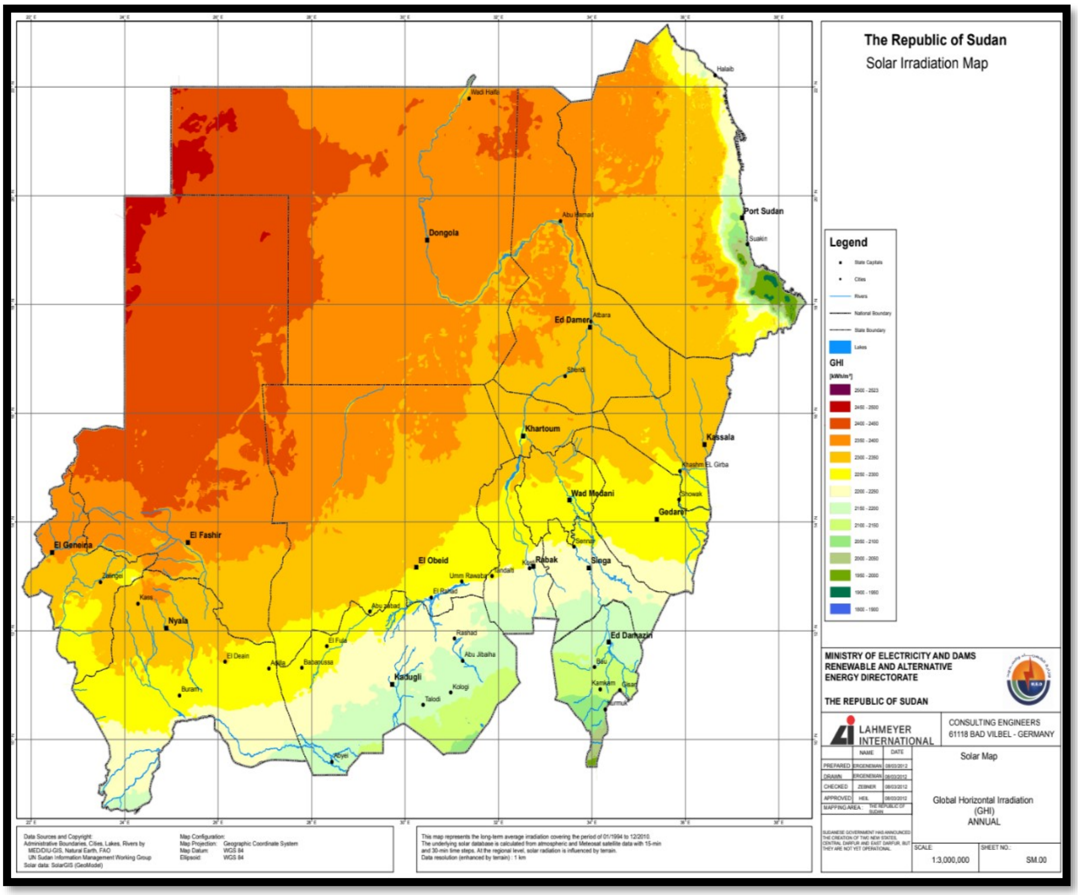


Figure 4.5: Global Horizontal Irradiation (GHI) in Sudan, source: Sudanese Ministry of Electricity and dams.

Table 4.1: Geographic coordinates – Some Cities of Sudan:

No	Name of state	Latitude (°)	Longitude (°)	Altitude(m)
1	Halaib	22^{0} 13'N	36^{0} 39'E	52.00
2	Wadi Halfa	21^{0} 55'N	31^{0} 21'E	190.00
3	Portsudan	19^{0} 35'N	37^{0} 13' E	5.00
4	Abu Hamed	19^{0} 32'N	33^{0} 20' E	315.00
5	Dongola	19^{0} 10'N	30^{0} 29' E	225.00
6	Gebeit	18^{0} 57'N	36^{0} 51'E	795.00
7	karima	18^{0} 33'N	31^{0} 51'E	250.00
8	Toker	18^{0} 26'N	37^{0} 44'E	20.00
9	Atbara	17^{0} 40'N	33^{0} 58'E	345.00
10	Derudeb	17^{0} 35'N	36^{0} 06'E	510.00
11	Hudeiba	17^{0} 34'N	33^{0} 56'E	350.00
12	Shendi	16^{0} 42'N	33^{0} 26'E	360.00
13	Aroma	15^{0} 50'N	33^{0} 09'E	430.00
14	Wadi Seidna	15^{0} 40'N	33^{0} 32'E	385.00
15	shambat	15^{0} 40'N	33^{0} 32'E	380.00
16	khartoum	15^{0} 36'N	32^{0} 33'E	380.00
17	Kassala	15^{0} 28'N	36^{0} 24'E	500.00
18	Jebel Aulia	15^{0} 24'N	32^{0} 30'E	380.00
19	Halfa el Gedida	15^{0} 19'N	35^{0} 36'E	450.00

20	Abu Quta	14^{0} 55'N	35^{0} 44'E	390.00
21	El Showak	14^{0} 24'N	35^{0} 51'E	510.00
22	Wad Madani	14^{0} 23'N	33^{0} 29'E	405.00
23	Medina Block	14^{0} 22'N	33^{0} 19'E	405.00
24	Kutum	14^{0} 12'N	24^{0} 40'E	1160.00
25	El Gadarif	14^{0} 02'N	35^{0} 24'E	600.00
26	Ed Dueim	13^{0} 59'N	32^{0} 20'E	380.00
27	El Fasher	13^{0} 38'N	25^{0} 20'E	733.00
28	Sennar	13^{0} 33'N	25^{0} 37'E	420.00
29	El Geneina	13^{0} 29'N	22^{0} 27'E	805.00
30	Kosti	13^{0} 10'N	32^{0} 40'E	380.00
31	El obeid	13^{0} 10'N	33^{0} 14'E	570.00
32	Dankog	13^{0} 05'N	23^{0} 59'E	965.00
33	Umm Benein	13^{0} 04'N	33^{0} 57'E	435.00
34	Zalingei	12^{0} 54'N	23^{0} 29'E	900.00
35	Abu Naama	12^{0} 44'N	34^{0} 07'E	445.00
36	El Nahud	12^{0} 42'N	28^{0} 26'E	565.00
37	Nyala	12^{0} 04'N	42^{0} 53'E	655.00
38	Rashad	11^{0} 52'N	31^{0} 03'E	885.00
39	Ed Damazin	11^{0} 49'N	34^{0} 24'E	470.00
40	El Renk	11^{0} 45'N	32^{0} 47'E	470.00

Sudan is classified into five climate zones as follows:

1-Hyper Arid.

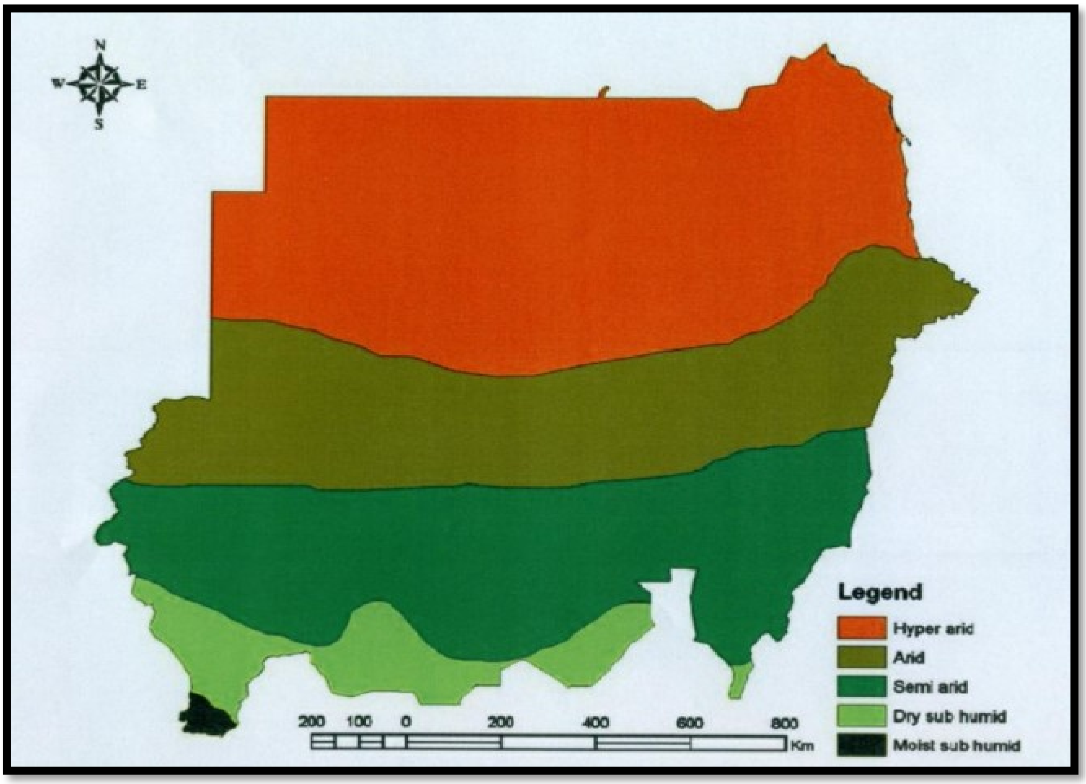
2- Arid.

3-Semi-Arid.

4-Dry Sub Humid.

5- Moist Sub Humid.

Figure 4.7: Climate zones by means of remote sensing.



As shown in the above figure 4.3; in the northern part (zone 1, red one) warm desert climate zone during the summer temperatures exceed till $45C^0$, the desert zones rainfall is negligible except in the center such as the capital Khartoum, and Gezira city where the rainfall is common from June till September. Examples of some cities in this zone (the red one)

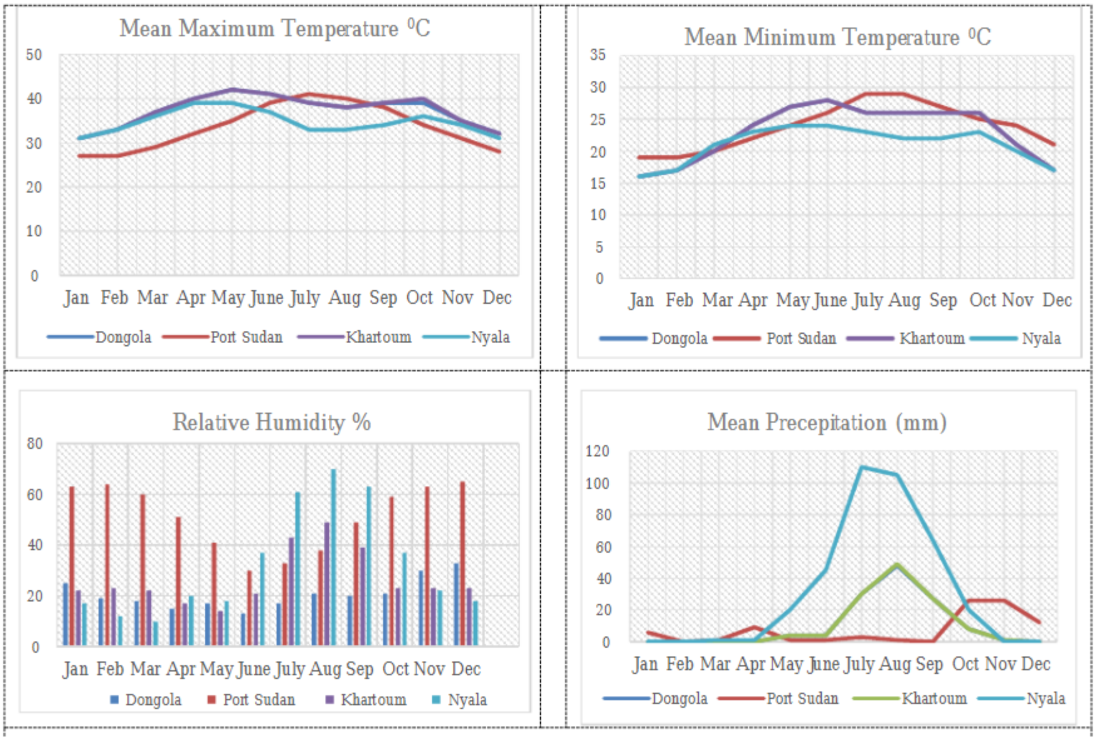


Figure 4.8: Metrological data of Sudan.

are Dongola, Kassal, Port Sudan, and the capital Khartoum, the mean maximum temperature recorded the highest values in Khartoum and Dongola cities, **[31]** while the highest values of humidity are in Port Sudan city because it is a coastal area close to the Red Sea.

In the center for example the capital Khartoum the annual temperature can reach 27 C^0, while the annual rainfall is about 255 mm.

In general, the northern part of Sudan has a harsh climate compared to the other parts of the country.

Darfur is in southwestern warm Semi-arid climate zone area (Zone 3) it has moderate summer and winter temperature and high rainfall and relative humidity; this is because its location is remarkably close to the tropical savannah region.

Kassala, Khartoum, Dongola, and Nyala for the:

(a) mean maximum temperature for 30 years period.

(b) mean minimum temperature for 30 years period.

(c) annual relative humidity in 2009 (CBS).

(d) mean precipitation (mm) for a 30-year period.

4.1 The Types of Soil in Sudan:

The Sudan's soils can be divided geographically into three categories. These are the sandy soils of the northern and west central areas, the clay soils of the central region, and the laterite soils of the south. Less extensive and widely separated, but of major economic importance, is a fourth group consisting of alluvial soils found along the lower reaches of the White Nile and Blue Nile rivers, along the main Nile to Lake Nubia, in the delta of the Qash River in the Kassala area, and in the Baraka Delta around Tawkar near the Red Sea in Ash Sharqi State.

Agriculturally, the most important soils are the clays in central Sudan that extend from west of Kassala through Al Awsat and southern Kurdufan. Known as cracking soils because of the practice of allowing them to dry out and crack during the dry months to restore their permeability, they are used in the areas of Al Jazirah and Khashm al Qirbah for irrigated cultivation. East of the Blue Nile, **[27]** large areas are used for mechanized rainfed crops. West of the White Nile, traditional cultivators use these soils to grow sorghum, sesame, peanuts, and (in the area around the Nuba Mountains) cotton. The southern part of the clay soil zone lies in the broad floodplain of the upper reaches of the White Nile and its tributaries, covering most of Aali and Nil and upper Bahr al Ghazal states. Subject to heavy rainfall during the rainy season, the floodplain proper is inundated for four to six months--a large swampy area, As Sudd, is permanently flooded--and adjacent areas are flooded for one or two months. In general, this area is poorly suited for crop production, but the grasses it supports during dry periods are used for grazing.

The sandy soils in the semiarid areas south of the desert in northern Kurdufan and northern Darfur states support vegetation used for grazing. In the southern part of these states and the western part of southern Darfur there are the so-called qoz sands. Livestock raising is this area's major activity, but a significant amount of crop cultivation, of millet, also occurs. Peanuts and sesame are grown as cash crops. The qoz sands are the principal area from which gum arabic is obtained through tapping of Acacia senegal (known locally as hashab). This tree grows readily in the region, and cultivators occasionally plant hashab trees when land is returned to fallow.

The laterite soils of the south cover most of the western Al Istiwai and Bahr al Ghazal states. They underlie the extensive moist woodlands found in these provinces. Crop production is scattered, and the soil, where cultivated, loses fertility quickly; even the richer soils are usually returned to bush fallow within five years.

4.2 Irrigation in Sudan:

Sudan has the largest irrigated area in sub-Saharan Africa and the second largest in all Africa, after Egypt.

The total estimated area fully equipped for irrigation is 1,764,635 ha and an estimated cropped area of 1,148,665 ha.

There are two categories of irrigation in Sudan, the traditional one and the modern schemes. For the first type of irrigation is practiced on the floodplains of the main Nile downstream of Khartoum and on the substantial areas along the blue and White Nile.

Irrigating by pumping water started at the beginning of the 20th century, substituting traditional water wheel techniques and the traditional flood irrigation.

The Gezira Scheme is Sudan's oldest and largest gravity irrigation system, located between the Blue Nile and the White Nile.

Gezira Scheme is an irrigated scheme with cultivable area of 2.1 million feddan (0.9 million ha). The major crops produced in the scheme are cotton, wheat, sorghum (dura), **[1]** and groundnut (GN). Vegetables, such as tomatoes and onions, are produced as minor crops. During the period 1987–2002, the scheme contributed about 58%, 46%, 12%, and 23% of cotton, wheat, sorghum, **[12]** and groundnut to total production, respectively.

In Sudan, farmers use furrow or drip irrigation, which is a common method for irrigating tomatoes, thanks to its economic advantages in saving water and increasing the yield production.

In general, regularity in watering the plants are important, especially during the summer and winter seasons, On the other hand, the needed water depends on the type of soil and on the weather (temperature, humidity, and the amount of rain).

Tomatoes harvested in Sudan during the summer period are sown in nursery plants during February. In March, the seedlings are transplanted in the fields. Eight to ten weeks after sowing, flowering occurs in the middle of May. At the end of this month and at the beginning of June, fruits ripening occurs. In July, the fruits are ready to be harvested.

In normal rainfall conditions, the irrigation interval can be increased to 3 days. In practice, as April is wet, and the rains are good.

4.3 Solar Energy for Irrigation in Sudan:

Solar energy has been used in water application water pumping, especially in remote agricultural areas especially in western of Sudan.

The need to save water and energy is a critical issue, **[2]** and it has increased over the last few years and will become the most prominent issue soon.

Sudan has been considered as one of the best countries for exploiting solar energy. The sunshine duration ranges from 8.5 to 11 h day^{-1}, with elevated level of solar radiation regime at an average of 20–25 MJ m^{-2} day^{-1} on the horizontal surface. The annual daily mean global radiation ranges from 3.05 to 7.62 kW m^{-2} day^{-1}. However, Sudan has an average of 7–9 GJ m^{-2} year^{-1}, equivalent to 436–639 W m^{-2} year.

The greatest amount of solar radiation in Sudan is found between 15 and 35 latitudes north. The speed and the direction of the wind varies during the seasons of the year. In summer winds are supplemented by sand and dust in the direction of Nort west to southwest, while in winter season the wind speed ranges between 0.54m/s and 1.54m/s in north and northwestern direction **[3]**.

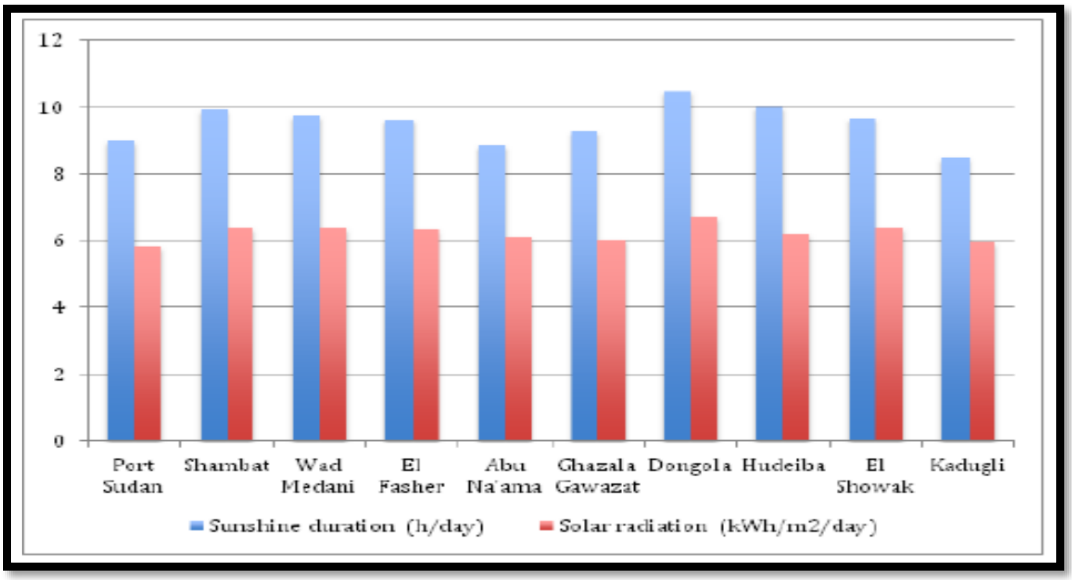


Figure 4.9: Solar Potential of Different cities in Sudan.

The graph shows two sets of data for various locations. The locations listed along the horizontal axis are:

Port Sudan

Shambat

Wad Medani

El Fasher

Abu Na'ama

Ghazala Gawazat

Dongola

Hudeiba

El Showak

Kadugli

For each location, there are two bars representing different datasets:

The blue bars represent "Sunshine duration (h/day)," which indicates the average number of hours of sunshine per day.

The red bars represent "Solar radiation (kWh/m²/day)," which indicates the average solar power received per square meter per day.

The vertical axis goes from 0 to 12, with increments of 2, but it is not clear whether it relates to both sets of data or just one., as the blue bars appear to decrease gradually from left to right, though not strictly monotonically.

The cities with highest solar radiation are in the northern and western parts of the country, namely Dongola, El Fasher

Both sets of data are high, suggesting that these locations receive a significant amount of sunshine and solar radiation, which could be important for solar energy considerations.

Chapter 5

Design The model and its components:

5.1 SYSTEM MODELING AND EVALUATION:

To evaluate the system elements' size and optimize the energy generated, an essential consists of modeling the installation component.

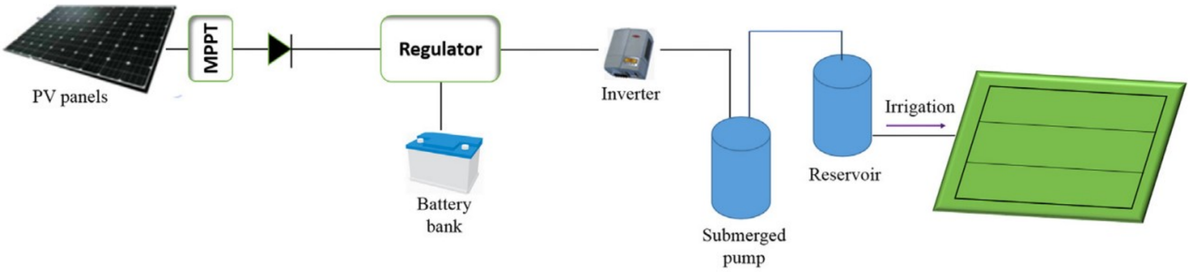


Figure 5.1: Proposed PV Irrigation System.

Figure 1 depicts a schematic diagram of a solar-powered irrigation system. The components are connected in sequence to illustrate the flow of energy and water from the solar panels to the field being irrigated. Here is the breakdown of the system:

1- PV PANELS:

Photovoltaic panels, also known as solar panels, are the first component in the system. They convert sunlight into electrical energy.

2- MPPT:

The stands for Maximum Power Point Tracking, a technology used in solar inverters to maximize the power extraction under all conditions. It is connected directly to the PV panels.

3- Regulator:

This device regulates the electrical energy from the solar panels, ensuring that the batteries are charged correctly and not overcharged.

4- Battery bank:

The regulated power charges a bank of batteries. This stored energy can then be used when sunlight is not available, ensuring a continuous power supply.

5- Inverter:

The inverter converts the direct current (DC) from the solar panels and batteries into alternating current (AC), which can be used to power AC devices.

6- Submersible Pump:

This pump is powered by an inverter and is used to draw water from the reservoir.

7- Reservoir (Storage):

A tank or storage system for water that is to be used for irrigation.

8- Irrigation:

The final step is where water is delivered to the fields or crops to provide them with necessary hydration.

This system models how solar energy can be harnessed to provide a sustainable water supply for irrigation purposes. It is a closed – loop system designed for efficiency, with a renewable energy source and storage capabilities to ensure the pump can operate even when sunlight is not available.

5.1.1 PVs Models:

The panels are the source that generates the electric energy for the rest of the component. To understand the PV panel behavior, an essential step consists of studying the parameters affecting the PV power generation. These parameters are the solar radiation G, the ambient temperature Ta, and the panel characteristics.

5.1.2 Solar Radiation:

solar radiation data are needed for designing, energy, and economic evaluation of solar energy systems.

Solar radiation data provide information on how much of the sun's energy strikes a surface at a location on the Earth during a period.

In this model, the solar radiation depends on the position of the sun, which is determined by using the declination and hour angle of the sun as explained in the following:

Solar declination:

The sun's declination δ, needs to determine its position, which is the angle between the sun's direction at the solar noon and its projection on the equatorial plane. In fact, **[138]** it reaches its maximum (23.45^0) at the summer solstice (21 June), and its minimum (-23.45^0) at the winter solstice (21 December). It is described by Cooper's equation:

$\delta = 23.45\sin(2\pi284+d/365)$.

Where d is the day number in the year.

5.1.3 Hour Angle of The Sun (*ω*):

The hour angle of the sun ω is the sun east to west angular displacement around the polar axis. the value of hour angle is zero at noon, positive in the afternoon, and negative in the morning and it is increased by 15^0 per hour.

the equation of hour angle of the sun ωs at sunset is given by:

$\text{Cos}\ \omega s = -\tau g\varphi\tau g\delta$

where δ is the declination (^{0})

while φ is the latitude (^{0})

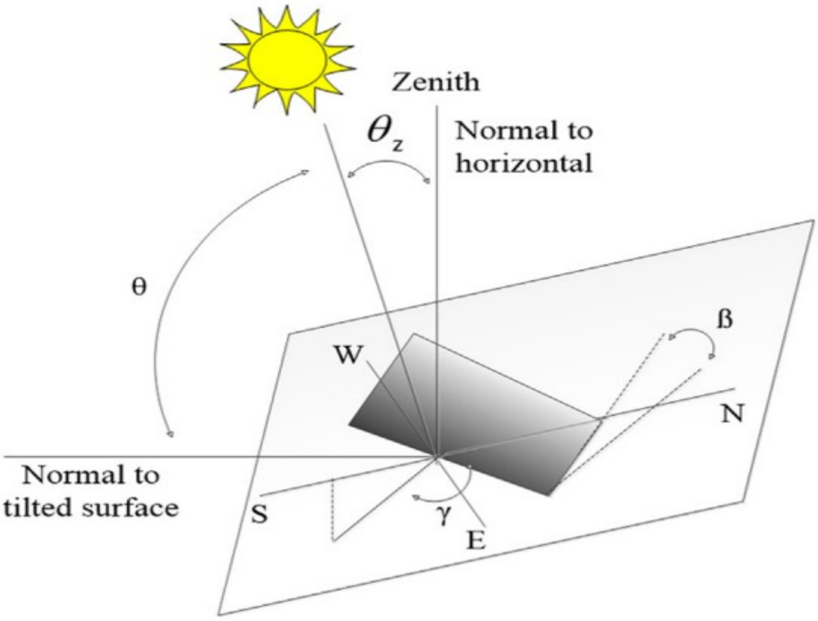


Figure 5.2: Solar radiation angles.

θz: the zenith angle of the sun(^{0}), given by:

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

5.1.4 Sum of the hourly values of the solar radiation:

The evaluation of the solar energy Wpv is performed by summing the solar radiation received during the day. Hence, it is assumed that during the hour, the solar radiation is constant. Hence, the solar energy (Wh) is expressed by:

$$W_{pv} = \sum_{t_{sr}}^{t_{ss}} H_t(t)\mathrm{d}t$$

where:

tsr: the time of sunrise,

tss: the time of sunset.

Position of the sun:

Sin HS =Sin LAT. Sen δ + cos LAT. cos LAT. cos δ . Cos AH

Sin Az =Cos δ . Sin AH /Cos HS

Where:

HS = Latitude (Place)

δ = Declination angle (Day)

AH = hour angle (Time)

HS = sun height angle

AZ = sun azimuth angle

Ambient temperature distribution model:

The distribution model used to forecast the ambient temperature Ta (t, d) of the day d at the hour t depends on the minimum temperature and the maximum temperatures Tmin(d), Tmax (d) of the day. Thus, Ta (t, d) is expressed by below equation:

$$T_a(t,d) = \frac{T_{\max}(d) + T_{\min}(d)}{2} + \frac{T_{\max}(d) - T_{\min}(d)}{2} \cos\left(\pi \frac{t-13}{24}\right)$$

5.2 MPPT Techniques:

MPPT stands for Maximum Power Point Tracking, is algorithm that included in change controllers used for extracting maximum available power from PV module under certain conditions, the voltage at which PV module can produce maximum power is called (maximum power point=peak power voltage).

Maximum power varies with solar radiation, ambient temperature, and the solar cell temperature. The typical PV module produce power voltage of around 17 V when measured at cell temperature of 25°C, it can be drop around 15 V on a very hot day and also arise up to 18v on a very cold day.

5.2.1 How MPPT Works:

The major principle of MPPT is to extract the maximum available power from PV module by making them operate at most efficient voltage (maximum power point), MPPT checks output of PV module, compare it to battery voltage. Then fixes what is the best power that PV module can produce to change the battery and converts it to the best voltage to get the maximum current into battery.

Peak Power and Cell Efficiency:

The reference standard condition (STC) to define peak power cell efficiency:

-Irradiance equal to 1000 W/m2,

-Cell temperature equal to 25°C.

To gain the maximum amount of from the solar cell it should operate at the maximum power voltage. The maximum power voltage is further described by Vmp, the maximum power voltage and Imp, the current at the maximum power point.

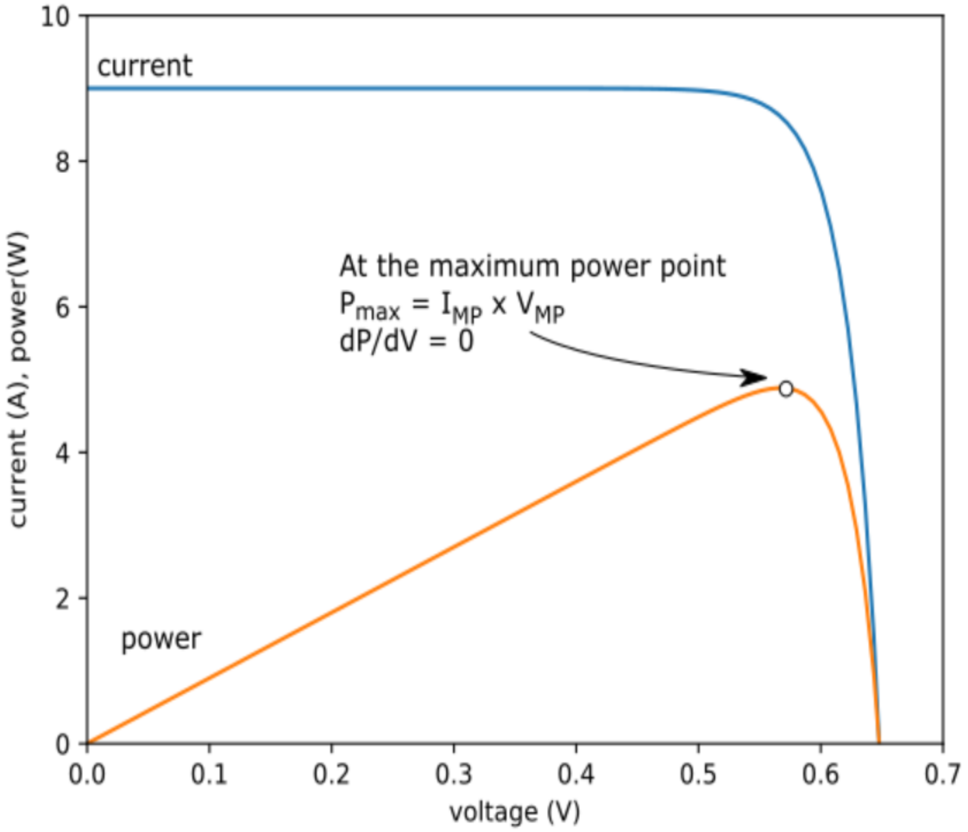


Figure 5.3: The maximum power voltage occurs when the differential of the power produced by the cell is zero**.**

Pmax =Imp*Vmp.

Where:

Pmax = maximum power,

Imax = the current at maximum power point,

Vmp = the voltage at maximum power point.

5.4 Choice of modules and voltage:

The choice of modules includes:

-Identification of the type of material (crystalline or amorphous silicon, CdTe, CIS, etc.)

-Identification of the type of module.

The cost of the modules available on the market affects the choice of the module itself.

Large modules (e.g., 250w) mean fewer anchoring points and fewer cabling, but also imply less flexibility.

The power of the system determines the number of modules needed; the choice of the system voltage identifies the number of modules that make up the single string.

Criteria to choose the voltage:

-Regulatory aspects (may be better low voltage)

-Containment of energy dissipation (better high voltage)

-Adaptation to the electrical characteristics of the other system components

Connection of PV Modules, Series Vs Parallels:

There are two possibles ways we can wire solar panels: series and parallel. Both types of wiring have pros and cons. The main differences in our solar panels in series vs parallel are the output voltage and input voltage. Solar panels that are wired in series have their output voltages added together, while their output current (amperage) remains the same. On the other hand, solar panels that are wired in **parallel have** their output currents added (increased amps), however, their output voltage will be the same .in short for solar panels wired in series, we add voltages together, while for panels wired in parallel, we add the amperages together.

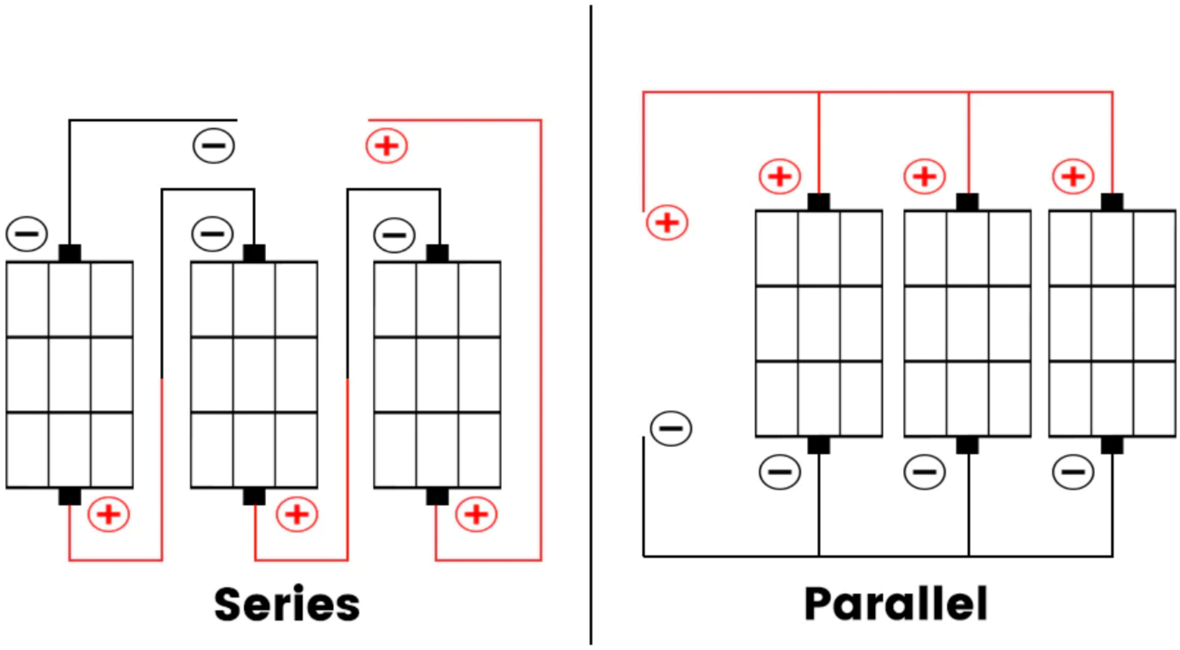


Figure 5.4: Ways of connection to the PV module.

5.3 Inverter:

As in most research related to water pumping, the motor pump adopted is an IM, since it is simple in control and its price is encouraging.

Hence, since the IM needs to be supplied by AC signals, a three -phase is used to convert the signals from DC to AC.

The inverter is composed of six IGBT switches each shunted in antiparallel by a fast-freewheeling diode, to return the negative current to the filter capacitor provided at the input of the converter.

Hence, the is controlled by analog values. Ti and T´ are the ideal switches of the same inverter arm, for switch are associated the logic control signals Si and Si¯, respectively, where Si = 1 if Ti is switched on and Si = 0 if Ti is switched off.

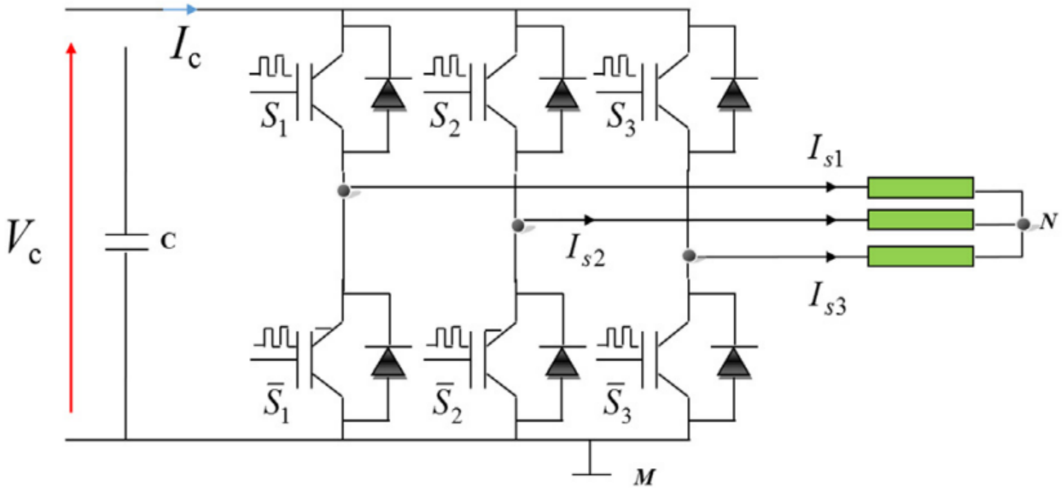


Figure 5.5: Schema of the three-phase inverter.

5.4 Pump:

In general, the pump uses electric power to provide mechanical energy to the water.

In fact, the pumps are either positive displacement or dynamic pumps. The positive displacement pumps are used in applications characterized by a constant discharge speed, or at high heads and low flow rates, since this type of pump delivers periodic flows, dynamic pumps are used, as they are adequate when the application needs a variable discharge speed, or at high flow rate and low or moderate heads.

Centrifugal pumps are commonly used, since they require less torque to start, and produce more head than other dynamic pumps at variables speed.

Moreover, in addition to their simplicity and low cost, they are characterized by their limited maintenance; moreover, centrifugal pumps are available for different flow rates and heads.

Hence, for this application, a centrifugal submerged pump is selected.

5.6.1 Performance parameters of solar pump:

The performance of a PV water pump depends on the water flow rate which is influenced by weather conditions in the location, especially solar radiance, and air temperature variations. the performance of solar pump dependence on the water requirements, size of storage tank, head (m) by which water must be filled, water to be pumped (m3), PV array virtually (kWh), pump efficiency (%), and system efficiency (%)

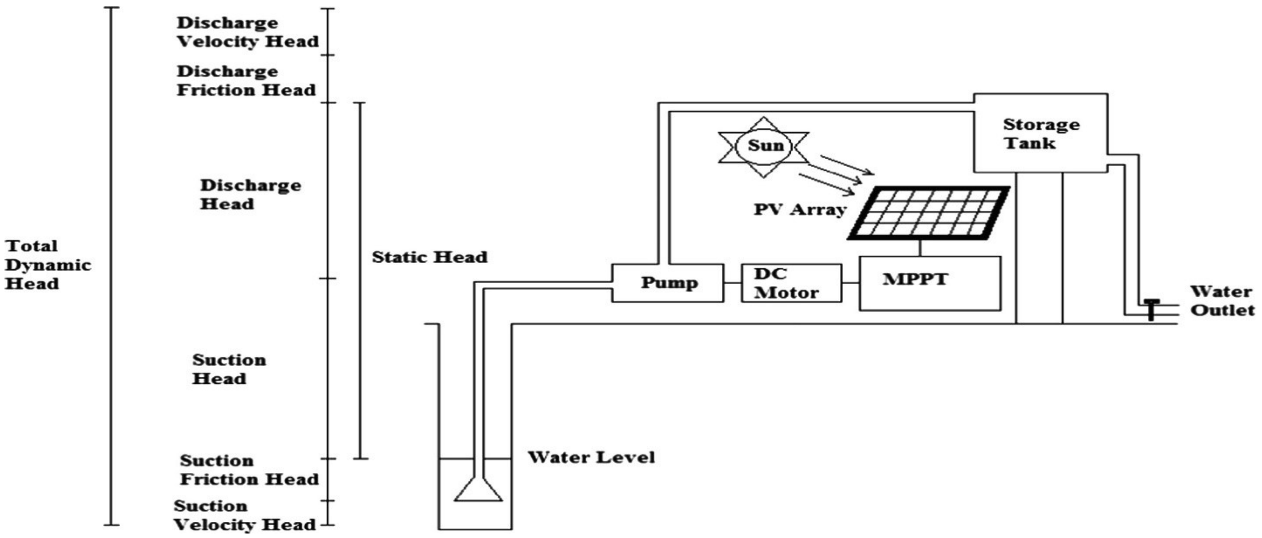


Figure 5.5: A schematic of a typical direct-coupled DC solar photovoltaic water pumping system with MPPT.

The efficiency of PV technology used in PV generator has also a great influence on the performance. Besides the degradation of PV panels is one of the important parameters which affect the performance of a solar pump.

The performance of solar water pumping system depends on the following parameters:

- Solar radiation availability at the location.

- Total Dynamic Head (TDH): Sum of suction head (height from suction point till pump), discharge head (height from pump to storage inlet) and frictional losses.

- Flow rate of water.

- Total quantity of water requirement; and

- Hydraulic energy: potential energy required in raising the water to discharge level.

Hydraulic energy *h* (kWh/d) required per day to supply a volume of water (m^3) at TDH is given by:

$E = \rho_x g_x V_x THD$

where:II

ρ = is the water density.

g = the acceleration due to the gravity (9.81 m/s2)

TDH = is the total dynamic head (m), is the sum of static head(m) and friction losses (m).

Solar photovoltaic array power Ppv required is given by:

$$P_{pv} = E_w/(I_T \times \eta_{mp} \times F)$$

where:

It = is the average daily solar irradiation (kWh/m^{2}day) incident on the plane of array.

F = is the array mismatch factor.

ηmp = is the daily subsystem efficiency.

The amount of water pumped V (m^3) is given by.

$$V = (P_{pv} \times I_T \times \eta_{mp} \times F)/(\rho \times g \times TDH)$$

The efficiency of the motor-pump system ηmp is given as follows:

Efficiency = hydraulic energy output/input energy input

Efficiency of PV array (%) is given by.

$$\eta_{pv} = \frac{P_{pv}(W)}{I_T(W/m^2) \times A_c(m^2)} \times 100$$

The overall solar water pump system efficiency is obtained as

$$\eta_{total} = (\eta_{pv} \times \eta_{mp}).$$

In this chapter we described the components model of an autonomous PV installation for pumping water to irrigate an agriculture land.

As general conclusion, the efficiency of the components model will be assessed and proved by PVsyst software. Hence, the components models will be used to determine the optimum components size in the calculation chapter.

Chapter 6

6.1 PVsyst Software:

PVsyst stands for Solar Design Software and is designed for the solar industry. It includes a detailed contextual help menu that explains the procedures and models that are used and offers a user-friendly approach with a guide to develop a project.

PVsyst can import meteo data, as well as data from many different sources.

Two main reasons make PVsyst famous, accurate and flexible:

1-The PVsyst software allows users to input specific data about their solar systems.

2-The Pvsyst software can simulate the performance of an energy system under various conditions.

For Instance:

With the solar panels' orientation, site location, and climate, PVsyst offers advanced customization options for PV system design. This includes modeling different panel technologies, incorporating shading and other site-specific factors, and optimizing system performance based on various criteria.

Some features of PVsyst:

Accuracy:

PVsyst uses advanced algorithms and databases to simulate solar energy systems' performance. Thus, users design optimized systems for their locations, meteorological data, and electrical load.

Flexibility:

PVsyst allows users to input a wide range of data and customize their simulations to their needs. Optimizing system performance based on various circumstances saves the user money.

Ease-of-Operation:

PVsyst makes it easy for solar energy professionals to input data, run simulations, and analyze results. The software also comes with comprehensive documentation and support resources to help users get the most out of the software.

6.2 The procedure of PVsyst consists of two main tips:

1-Data Input:

Users input specific data about their solar energy system, for example, weather data, panel type, system size, and equipment specifications. The software uses this data to simulate the system's performance under different conditions. PVsyst runs simulations to predict energy production and consumption over time. The software bases the data on hourly, daily, or monthly data. They can consider factors such as solar irradiance, temperature, and shading.

2-Analysis:

PVsyst provides a range of analysis tools to help users understand and optimize the performance of their system. For example, the software provides graphs and tables that display key performance metrics. Ex. Energy production, efficiency, and cost.

Pvsyst provides four central project design systems:

3-Standalone system:

The standalone system is best for small, self-contained solar energy systems that are not connected to the grid. It is suitable for applications such as remote cabins, boats, or off-grid homes. The standalone system produces the most significant energy production and self-sufficiency.

Grid-connected system:

The Grid-connected system is best for grid-connected energy systems and systems selling excess energy. It is suitable for applications such as residential or commercial buildings. The Grid-connected system optimizes for the largest energy production and cost savings.

Hybrid system:

A hybrid system is for solar energy systems that combine different technologies. Ex. PV panels, solar water heaters, and energy storage systems. The Hybrid system is best for homes or businesses that want to be energy efficient and reduce carbon emissions. Users can perfect their approach using various criteria. Ex. Energy production, cost, or CO2 emissions.

Solar thermal system:

Solar thermal system is for systems that use solar energy to generate heat. Ex. Solar water heaters or solar thermal power plants. The solar thermal system has two common users. Industrial hot water systems or large-scale power generation applications. The solar thermal system perfects strategy using factors such as temperature, flow rate, and efficiency.

Basic Approach-Khartoum-Sudan Project

6.3 First Connect with PVsyst:

6.3.1 Isolated Pumping System:

THE "Pumping System" in PVsyst only concerns "isolated" pumping systems that work according to the availability of the sun. such as it has neither electrical storage nor a grid, and consists of a (or several) pump, a Photovoltaic array, and a controller/power conditioning unit.

The implementation of such a system involves a detailed definition of the hydraulic circuit (type of the system like depth of the well, pumping from the lake, or equivalent, or even pressurizing system), water needs, the pressure gage height (as a function of the flowrate and other parameters) and tank storage. Some other constraints may be considered (maximum drawdown in a deep well, tank full, etc.)

The running mode according to the sun’s availability implies that the pump will operate at a power imposed by the maximum power of the PV array at a given time. As the head is imposed by external conditions (head losses in the pipes, level differences, the drawdown in a deep well, etc.), the resulting flow rate will be related to the instantaneous power availability.

Therefore, the simulation needs a complete model of pump behavior giving the resulting flow rate in any conditions of power and head. The operating point, depending on the total head variation according to

the flow rate (pipes head losses), drawdown level)) will be evaluated by successive approximations.

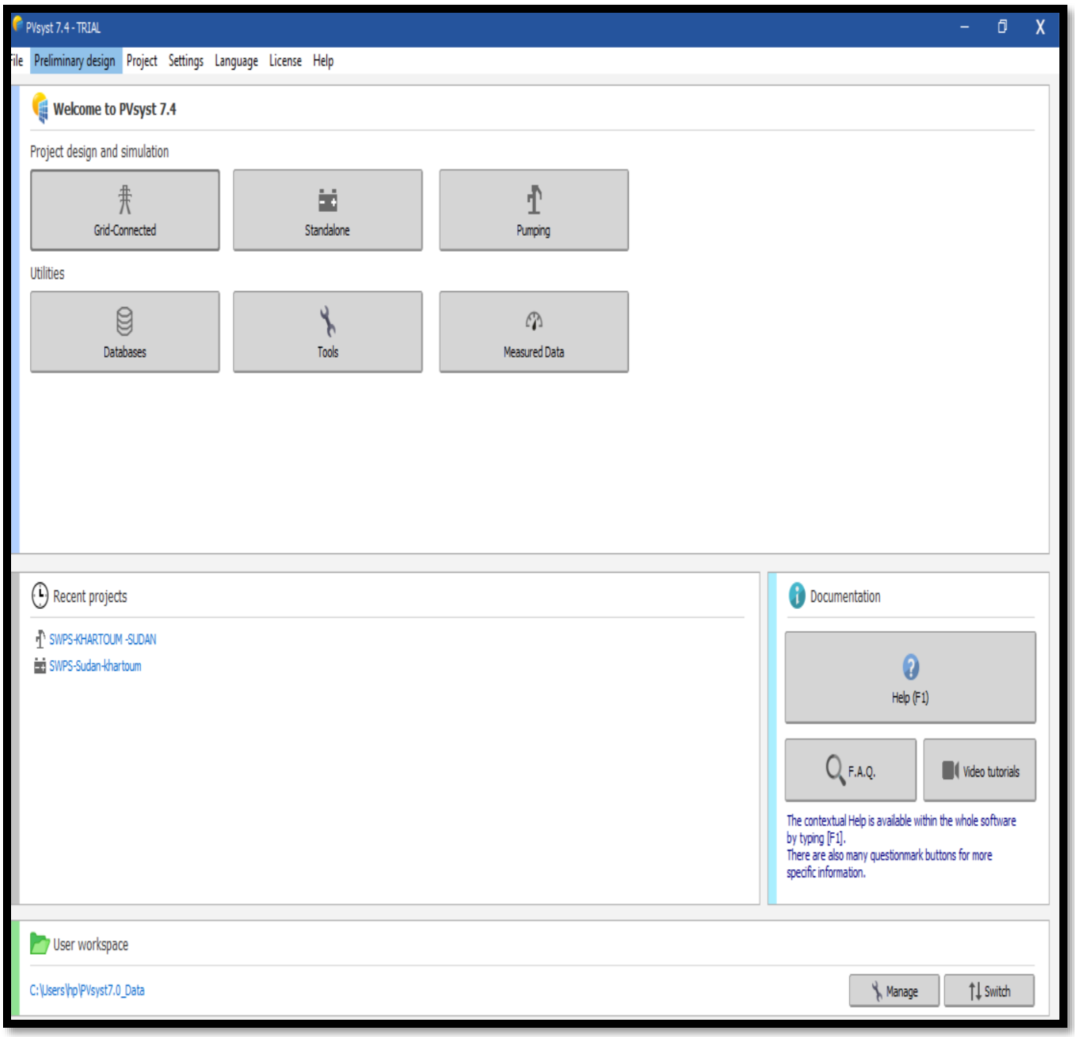
The main advantages of isolated pumping systems are the absence of battery. Consequently, the associated maintained costs (replacement.) is lower. The storage is given by the accumulation of water in the tank. However, this requires a pump that can operate a wide range of powers.

6.3.2 conventional pumping system:

The conventional pumping systems fed by a grid electrical system (or eventually a big stand-alone system like a village mini grid) operate at the specified voltage of the grid. The operating power is fixed, it is supposed to be available at any time. The system operates in "ON/OFF" mode, according to the water needs and control system.

Such systems are not implemented explicitly in PVsyst. The pumping system should be considered as a load in the same way as any other load.

Therefore, a pumping system as defined in PVsyst cannot be associated to any other PV system, even stand – alone system. It should really stay independent of any other power system.



The contextual Help is available within the whole software by typing [F1].
There are also many questionmark buttons for more specific information.

Figure 6.1: Pumping button in the main dialog.

This page gives full procedure for the development of a pumping system in PVsyst.

First step:

As for any variant calculation in PVsyst, we should begin by defining the collector array orientation.

Second step:

We must define the pumping circuit, i.e., choose among one of the three available systems:

-pumping from a deep well, to tank storage,
-pumping form a lake or river, to tank storage,
-pumping into a pressurized tank, for water distribution.

and define the Hydraulic circuit configuration (Storage Tank and Pipes)

Third Step:
Go to the "Water needs and hand definitions " page.
define the water needs in m3/day (yearly, seasonal or in monthly values).

define the pumping static depth if it varies according to the year (seasonal or monthly). the value defined here corresponds to the "level depth ״or "static depth."

Fourth step:

Choose the" system " button, observe and play with the "Pre-sizing Suggestions."

The pre-sizing suggestions on the top of the dialog pre-evaluate some parameters (tank volume, pump, and PV array power) required for meeting your Pref-defined water needs requirements. We can play with parameters for getting orders of magnitude. However, this pre-evaluation is difficult and may be inaccurate, as performances are quite different from one to another pump.

Fifth step:

In the "System" dialog at the "pump definition" page.
choose a pump model, taking the nominal Head into account (pumps are colored in green for suitable, orange for not optimal, or red for not suited devices.
This dialog also provides a little tool for the calculation of the hydraulic power corresponding to a given Head x flowrate product.

Sixth step:

In the "system" dialog at the "Sub Array design " page.
choose a PV module (also Green/Orange/Red) and a suitable PV array configuration (proposed PVsyst).

Seventh step:

Here we choose the control mode.

Again, the Green/Orange/Red colors indicate the stability of the choices, according to the system type, pump model and pumps number chosen previously. A collection of specific warning messages explains the reasons for incompatibilities or poor design.

The chosen regulation strategy fixes the available set of control devices.

Eighth Step:

We can open the controller device and check its parameters.

All systems running specificities are defined in the controller/regulations device. This includes namely the boundary operating conditions (Tank full, dry running, power, voltage, current limits.)

Nineth Step:

PV array design, number of modules in series/parallel.

For MPPT converter devices, the procedure is analogous to the design of grid connected systems :you can specify a planner power and PVsyst will propose a configuration(use the button “Resize " for a complete resizing).We have to choose a number modules in series for which the Voc(T min) doesn’t exceed the VmaxAbs of the converter ,and the

Vmpp(TO per) should not be under the vmppMin of the converter.

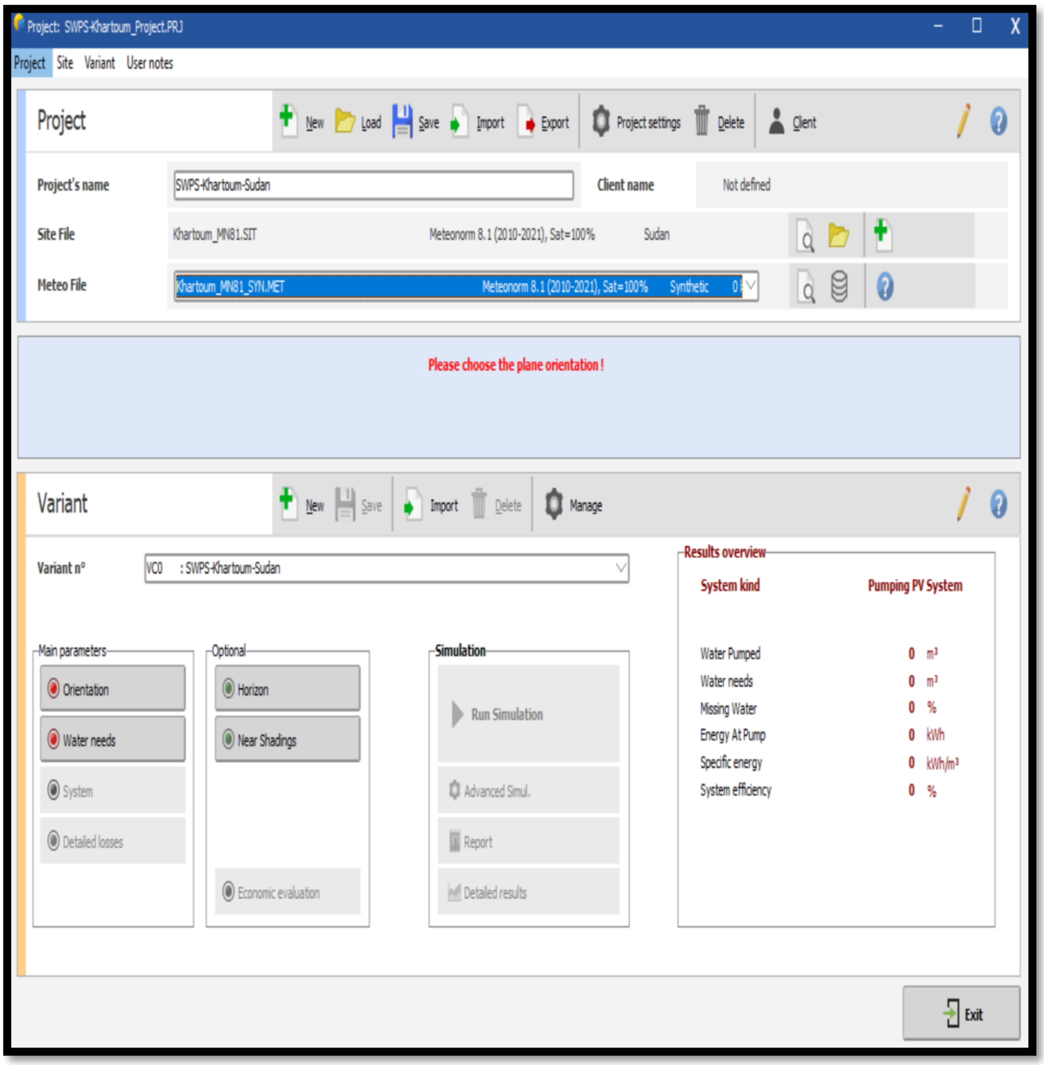
The number of strings is adjusted according to the power requirements of the pump in operating conditions. This is not always easy to obtain, due to the constraints on the MPPT inputs of the real controllers.

Tenth Step:

If no error appears in red, you are ready for the first simulation of your system.

6.4 creating the basic variant for the project:

After defining the site and the meteorological input of the project, we can proceed to create the first variant. We will notice that in the beginning of there are two buttons marked in red: "Orientation" and "water needs." The red color means this variant of the project is not yet ready for simulation: additional input is required. Basic parameters that need to be defined for any of the variant, and not yet specified are the orientation of solar panels, water needs, type and number of PV modules, type and number of pumps that will be used.



Project's name: SWPS-Khartoum-Sudan
Client name: Not defined
Site File: Khartoum_MN81.SIT Meteonorm 8.1 (2010-2021), Sat=100% Sudan
Meteo File: Khartoum_MN81_SYN.MET Meteonorm 8.1 (2010-2021), Sat=100% Synthetic 0

Please choose the plane orientation !

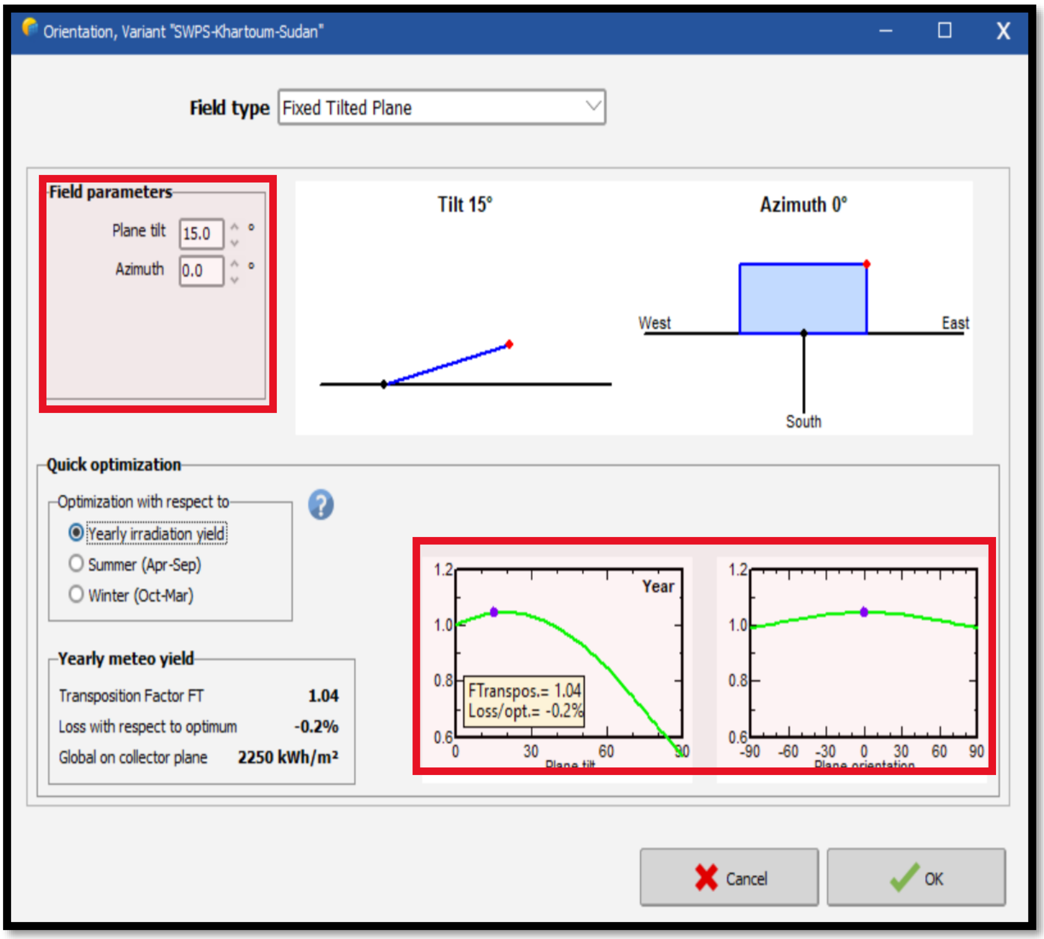
Variant n° VC0 : SWPS-Khartoum-Sudan

Results overview

System kind	Pumping PV System	
Water Pumped	0	m³
Water needs	0	m³
Missing Water	0	%
Energy At Pump	0	kWh
Specific energy	0	kWh/m³
System efficiency	0	%

Figure 6.2: Variants to be defined.

Firstly, click on the “Orientation Button”:



Orientation, Variant "SWPS-Khartoum-Sudan"

Field type: Fixed Tilted Plane

Field parameters

Plane tilt 15.0 °

Azimuth 0.0 °

Quick optimization

Optimization with respect to

● Yearly irradiation yield

○ Summer (Apr-Sep)

○ Winter (Oct-Mar)

Yearly meteo yield

Transposition Factor FT 1.04

Loss with respect to optimum -0.2%

Global on collector plane 2250 kWh/m²

Figure 6.3: Orientation dialog.

These tools aim to show the best suited orientation for a PV system, or what we lose when not optimally oriented.

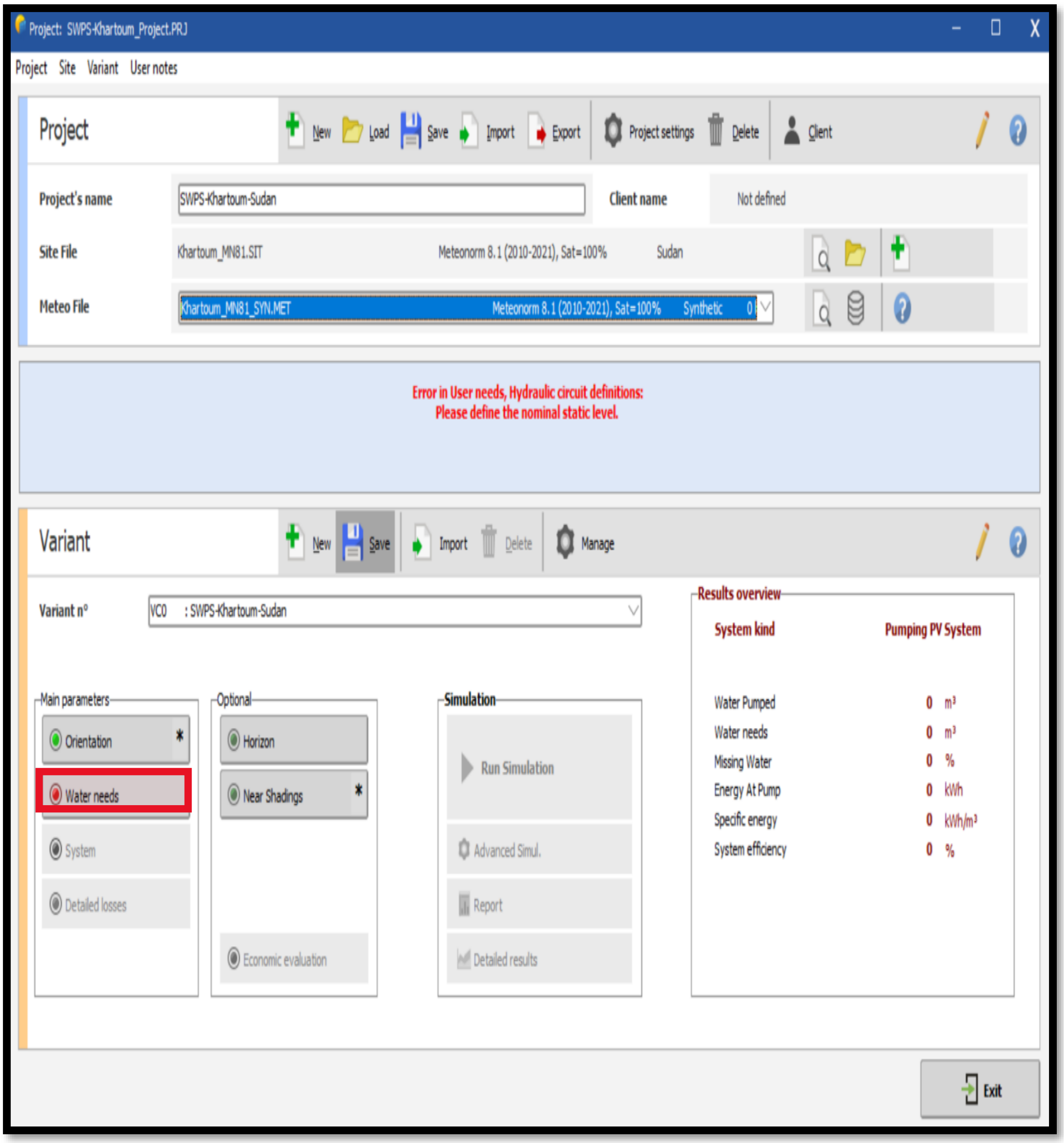
The transposition factor is the ratio of the incident irradiation on the plane, to the horizontal irradiation. i.e., what you gain (or lose) when tilting collector plane.

We observe that the optimization of the orientation depends on the planned use of the PV energy. Therefore, this tool gives the possibility to the optimizing period: Year, Winter, Summer, or chosen months.

Moreover, the optimization may depend on specific far-shading conditions (mountains): We can define a horizon line, and this will usually result in an azimuth displacement.

6.4.1 Basic definition of Water Needs:

TO complete the water needs, click on the "Water needs."



Project's name: SWPS-Khartoum-Sudan

Client name: Not defined

Site File: Khartoum_MN81.SIT Meteonorm 8.1 (2010-2021), Sat=100% Sudan

Meteo File: Khartoum_MN81_SYN.MET Meteonorm 8.1 (2010-2021), Sat=100% Synthetic 0

Error in User needs, Hydraulic circuit definitions:
Please define the nominal static level.

Variant n°: VC0 : SWPS-Khartoum-Sudan

Results overview

System kind	Pumping PV System
Water Pumped	0 m³
Water needs	0 m³
Missing Water	0 %
Energy At Pump	0 kWh
Specific energy	0 kWh/m³
System efficiency	0 %

Figure 6.4: Water needs button in the main dialog.

Once "water needs" menu is open, we must define:

-Pumping system type:

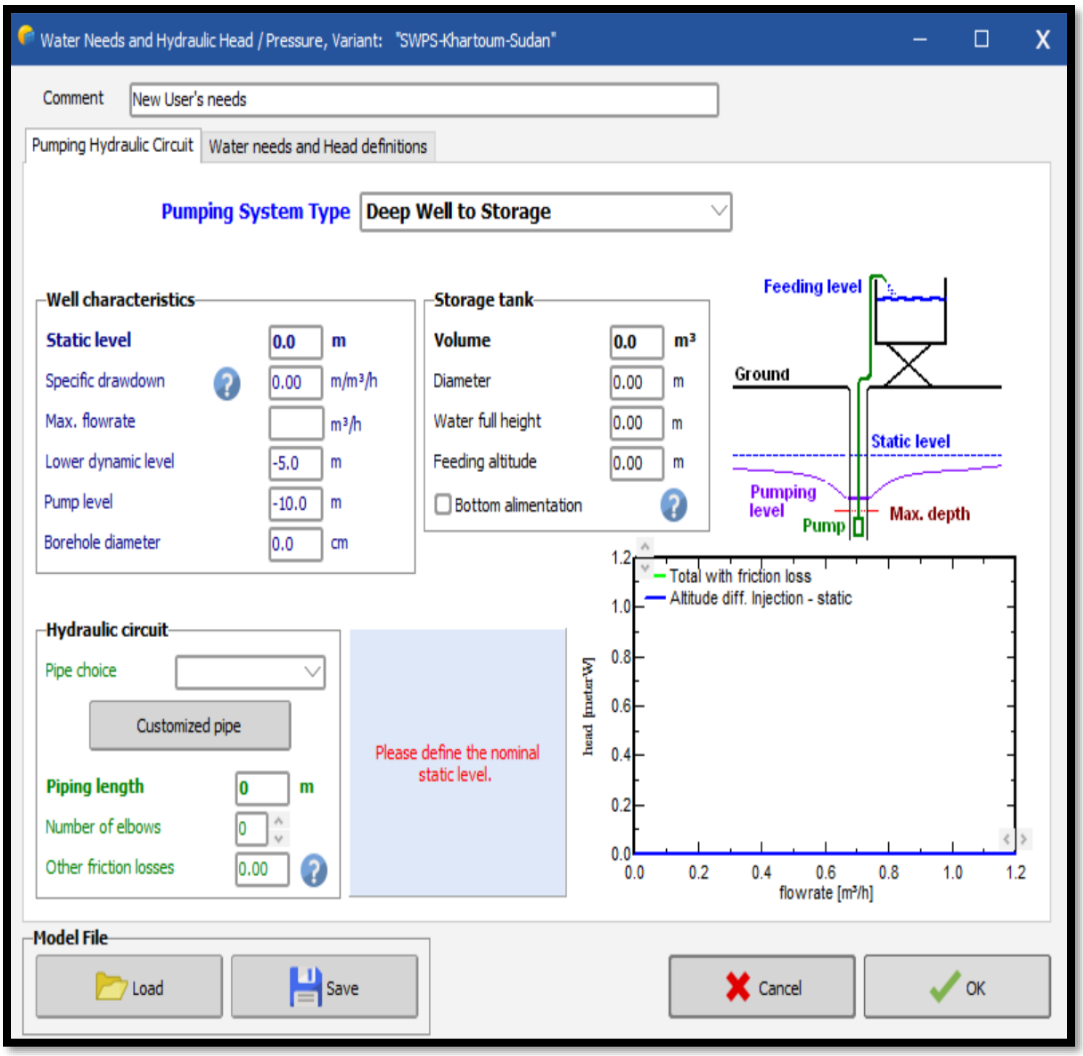
- Deep well to storage,
- Lake or river to storage,
- Pressurization.

-Characteristics of Well.

-Storage tank.

-Hydraulic circuit.

-Water needs.



Water Needs and Hydraulic Head / Pressure, Variant: "SWPS-Khartoum-Sudan"

Comment: New User's needs

Pumping System Type: Deep Well to Storage

Well characteristics

Static level: 0.0 m

Specific drawdown: 0.00 $m/m^3/h$

Max. flowrate: m^3/h

Lower dynamic level: -5.0 m

Pump level: -10.0 m

Borehole diameter: 0.0 cm

Storage tank

Volume: 0.0 m^3

Diameter: 0.00 m

Water full height: 0.00 m

Feeding altitude: 0.00 m

☐ Bottom alimentation

Hydraulic circuit

Pipe choice:

Piping length: 0 m

Number of elbows: 0

Other friction losses: 0.00

Please define the nominal static level.

Figure 6.5: List of parameters to be completed.

Here is the list of elements that we must fill in to continue the simulation.

-**Well Characteristics**

- Static level.
- Drawdown or Max flowrate.

One of the two values is enough, the other value will be automatically calculated by the software according to the following formula: Drawdown = (Lower Dynamic Level - static Level)/ Max. Flowrate.

- Lower Dynamic level (will be calculated by software, if we modify the value, this will modify the value of Drawdown or Max Flowrate. The value of the lower dynamic level must always be greater than the value of the static level.
- Pump level.
- Borehole diameter (not used in calculation or simulation)

Level or distances in PVsyst are always relative are always relative to natural ground (TG).

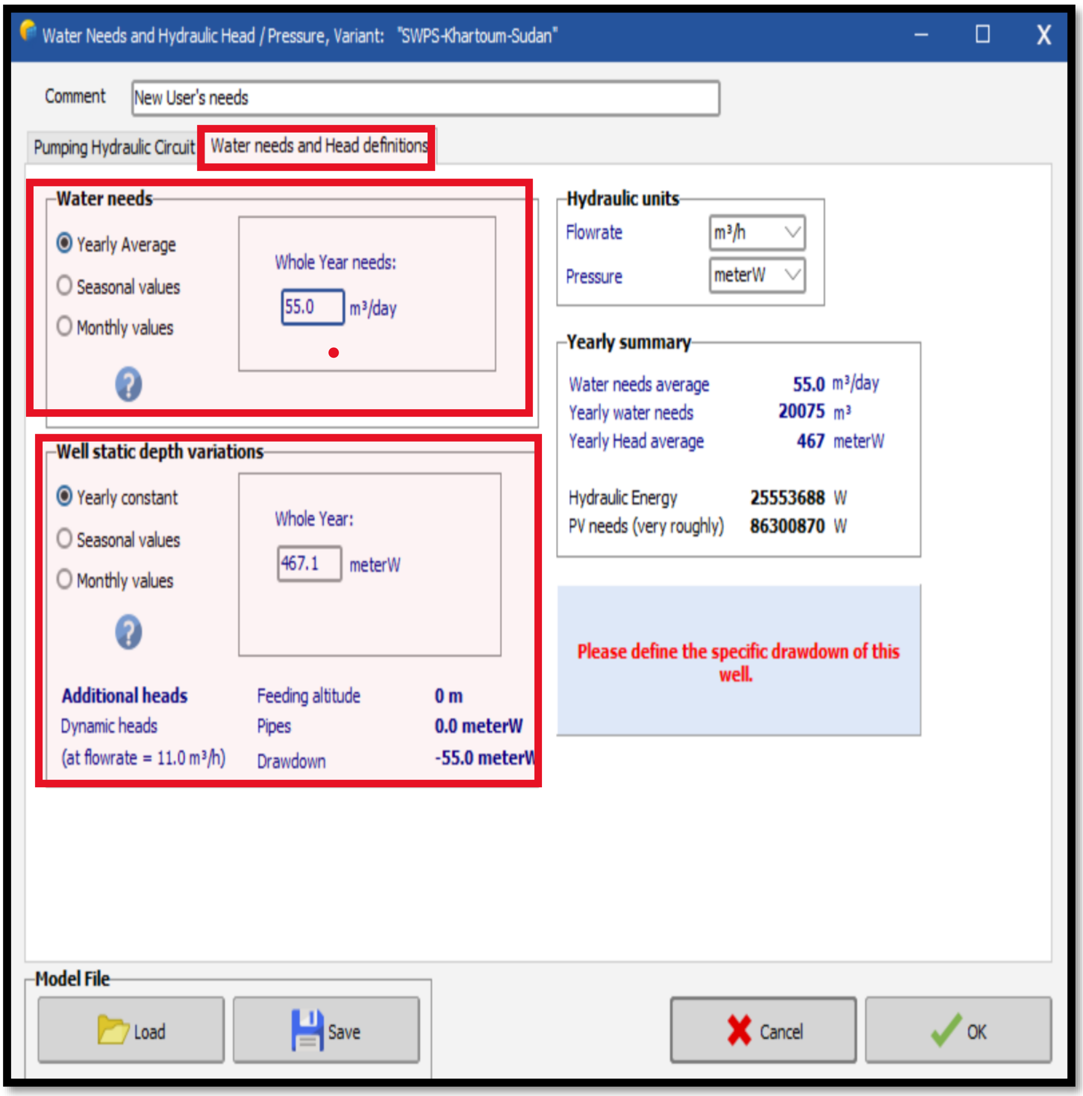
-**Storage Tank:**

- Volume.
- Diameter.
- Water full height (this value has for reference the bottom of the tank and not the natural ground)
- Feeding Altitude (the injection height is important, especially if our tank is high. This will allow more pressure at the outlet of the tank)

-**Hydraulic Circuit:**

- Pipe choice.

- Piping length.
- Number of elbows (can stay at “0” for the simulation).
- Other friction losses (can stay “0” for the simulation.
- Now, we need to define the water needs. To do so, click on the “water needs and head definitions” tab.



Water Needs and Hydraulic Head / Pressure, Variant: "SWPS-Khartoum-Sudan"

Comment: New User's needs

Water needs

● Yearly Average
○ Seasonal values
○ Monthly values

Whole Year needs: 55.0 m³/day

Hydraulic units

Flowrate: m³/h
Pressure: meterW

Yearly summary

Water needs average	**55.0**	m³/day
Yearly water needs	**20075**	m³
Yearly Head average	**467**	meterW
Hydraulic Energy	**25553688**	W
PV needs (very roughly)	**86300870**	W

Well static depth variations

● Yearly constant
○ Seasonal values
○ Monthly values

Whole Year: 467.1 meterW

Additional heads	Feeding altitude	**0 m**
Dynamic heads	Pipes	**0.0 meterW**
(at flowrate = 11.0 m³/h)	Drawdown	**-55.0 meterW**

Please define the specific drawdown of this well.

Figure 6.6: water needs and head parameters.

The water needs (volume of pumped water) may be specified yearly (constant value), or in monthly / seasonal values.

Specifying needs in terms of hourly values (daily distribution) does not make sense, as most of the time the pumping system includes storage for at least one day of consumption.

The detailed simulation will rely on these specified values (monthly or seasonally) at each time step. We do not need to change the value of "well static depth variations," this value is the same as the static level in the "Pumping Hydraulic Circuit" tab.

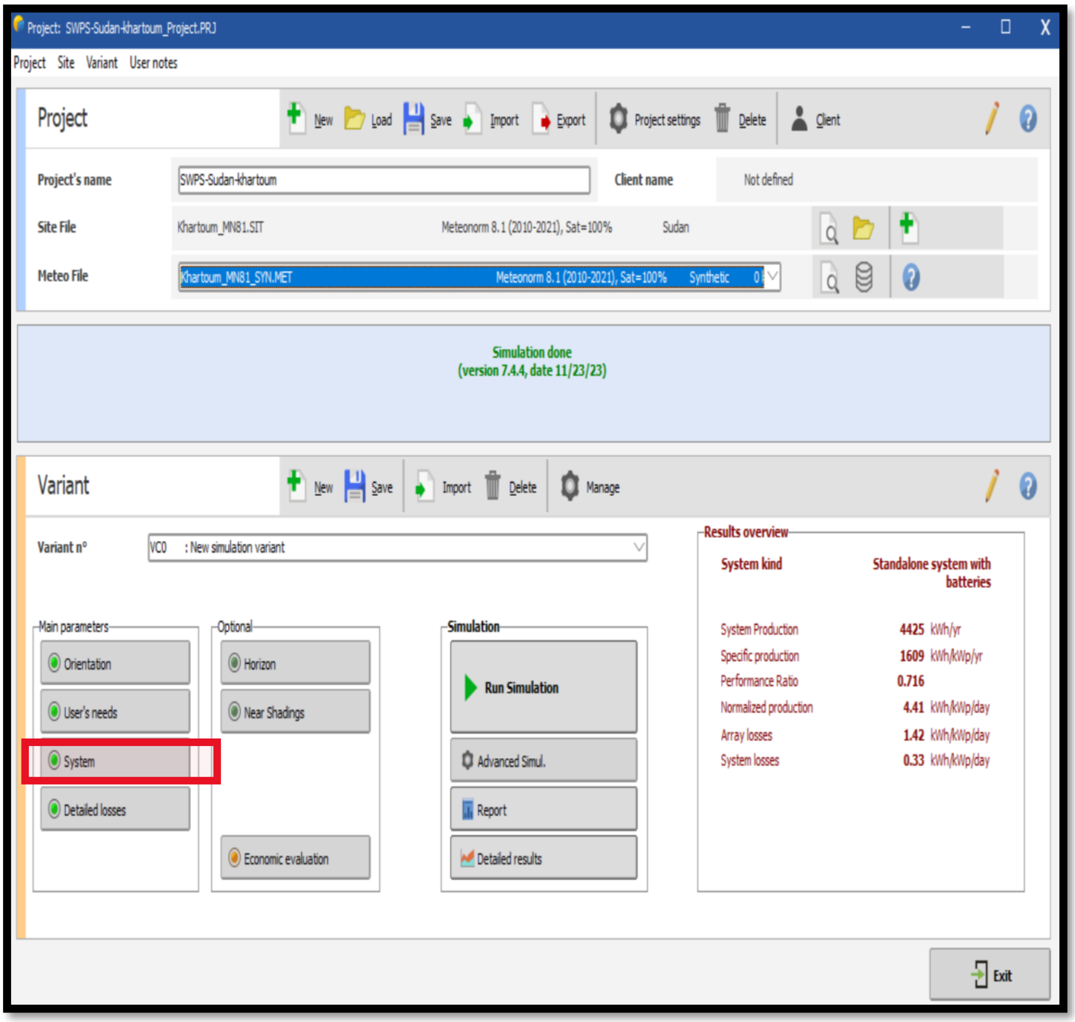
6.4.2 Definition of System:

We can click on "System " to define:

-Pump technology / brand and reference.

-Technology / brand and reference of the photovoltaic field.

-Technology / brand and reference of the pumping regulation system.



Project's name: SWPS-Sudan-Khartoum

Client name: Not defined

Site File: Khartoum_MN81.SIT Meteonorm 8.1 (2010-2021), Sat=100% Sudan

Meteo File: Khartoum_MN81_SYN.MET Meteonorm 8.1 (2010-2021), Sat=100% Synthetic

Simulation done
(version 7.4.4, date 11/23/23)

Variant n°: VC0 : New simulation variant

Results overview

System kind	Standalone system with batteries
System Production	4425 kWh/yr
Specific production	1609 kWh/kWp/yr
Performance Ratio	0.716
Normalized production	4.41 kWh/kWp/day
Array losses	1.42 kWh/kWp/day
System losses	0.33 kWh/kWp/day

Figure 6.7: System definition.

In this first window, we will have to define the model and the number of pumps in our circuit.

We have the choice between several pump manufactures, where we can choose between:

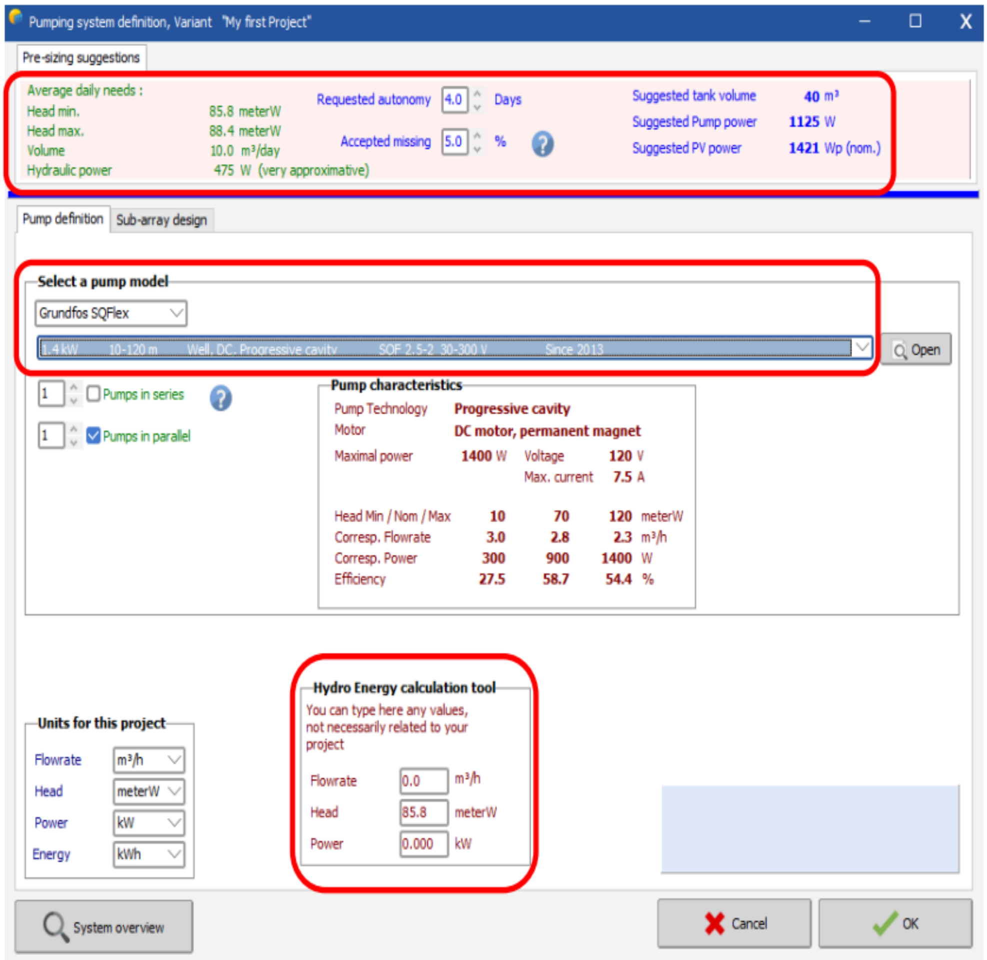
-Surface pump,

-Immersed pump,

-AC Pump,

-DC Pump,

-ETC.



Average daily needs :
Head min. 85.8 meterW
Head max. 88.4 meterW
Volume 10.0 m³/day
Hydraulic power 475 W (very approximative)

Requested autonomy 4.0 Days
Accepted missing 5.0 %

Suggested tank volume 40 m³
Suggested Pump power 1125 W
Suggested PV power 1421 Wp (nom.)

Select a pump model
Grundfos SQFlex
1.4 kW 10-120 m Well, DC, Progressive cavity SQF 2.5-2 30-300 V Since 2013

1 ☐ Pumps in series
1 ☑ Pumps in parallel

Pump characteristics
Pump Technology: Progressive cavity
Motor: DC motor, permanent magnet
Maximal power 1400 W
Voltage 120 V
Max. current 7.5 A

Head Min / Nom / Max	10	70	120	meterW
Corresp. Flowrate	3.0	2.8	2.3	m³/h
Corresp. Power	300	900	1400	W
Efficiency	27.5	58.7	54.4	%

Units for this project
Flowrate m³/h
Head meterW
Power kW
Energy kWh

Hydro Energy calculation tool
You can type here any values, not necessarily related to your project
Flowrate 0.0 m³/h
Head 85.8 meterW
Power 0.000 kW

Figure 6.8: Pre-sizing a pump.

The Pre-Sizing Tool Calculate three pieces of information:

-Suggest tank volume (calculated with the expected consumption and the requested again),

-Suggested pump power,

-Suggested PV power.

Select a Pump model:

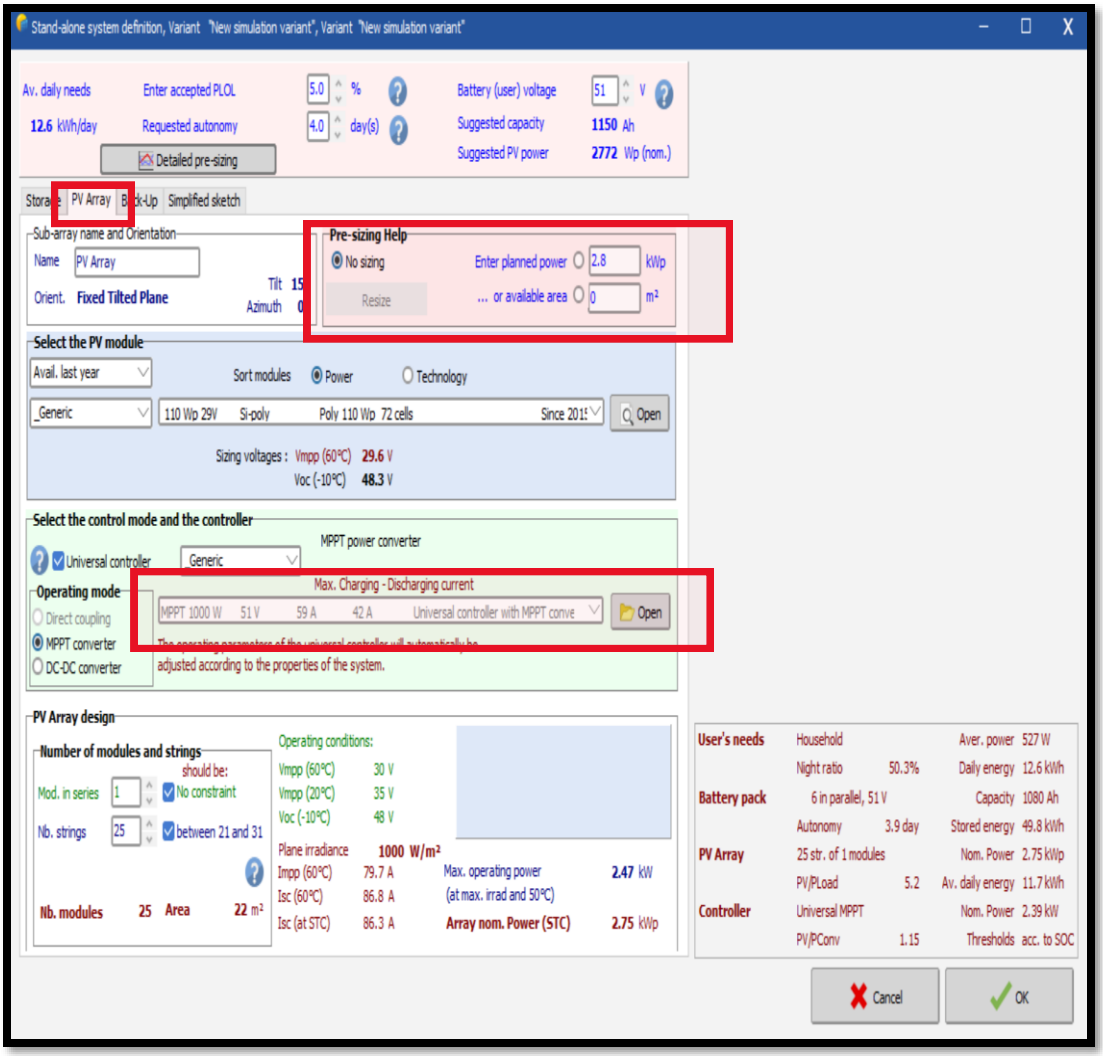
To choose the most suitable pump for the characteristics of our system, the software will make a pre- selection. This selection is made according to following characteristics:

-Total HMT (minimum and maximum),

- Flowrate,

-Drawdown.

In the second window, we will have to define the model and number of PV module and controller.



Av. daily needs 12.6 kWh/day
Enter accepted PLOL 5.0 %
Requested autonomy 4.0 day(s)
Battery (user) voltage 51 V
Suggested capacity 1150 Ah
Suggested PV power 2772 Wp (nom.)

Sub-array name and Orientation
Name PV Array
Orient. Fixed Tilted Plane
Tilt 15
Azimuth 0

Pre-sizing Help
● No sizing
Enter planned power ○ 2.8 kWp
... or available area ○ 0 m²

Select the PV module
Avail. last year
Sort modules ● Power ○ Technology
_Generic
110 Wp 29V Si-poly Poly 110 Wp 72 cells Since 2015
Sizing voltages : Vmpp (60°C) 29.6 V
Voc (-10°C) 48.3 V

Select the control mode and the controller
☑ Universal controller
_Generic
MPPT power converter
Operating mode
○ Direct coupling
● MPPT converter
○ DC-DC converter
Max. Charging - Discharging current
MPPT 1000 W 51 V 59 A 42 A Universal controller with MPPT conve
The operating parameters of the universal controller will automatically be adjusted according to the properties of the system.

PV Array design
Number of modules and strings
should be:
Mod. in series 1 ☑ No constraint
Nb. strings 25 ☑ between 21 and 31
Nb. modules 25 Area 22 m²

Operating conditions:
Vmpp (60°C) 30 V
Vmpp (20°C) 35 V
Voc (-10°C) 48 V
Plane irradiance 1000 W/m²
Impp (60°C) 79.7 A
Isc (60°C) 86.8 A
Isc (at STC) 86.3 A
Max. operating power (at max. irrad and 50°C) 2.47 kW
Array nom. Power (STC) 2.75 kWp

User's needs	Household		Aver. power	527 W
	Night ratio	50.3%	Daily energy	12.6 kWh
Battery pack	6 in parallel, 51 V		Capacity	1080 Ah
	Autonomy	3.9 day	Stored energy	49.8 kWh
PV Array	25 str. of 1 modules		Nom. Power	2.75 kWp
	PV/PLoad	5.2	Av. daily energy	11.7 kWh
Controller	Universal MPPT		Nom. Power	2.39 kW
	PV/PConv	1.15	Thresholds	acc. to SOC

Figure 6.9: Sub- array design pumping system definition.

PV array sizing tool:

With this tool, we can define a maximum surface or power that we want to install.

When a value is defined in one of the two boxes, the software will make a wiring suggestion via the PV array design tool.

Controller and Power Conditions:

In fact, even these simplest configurations (direct coupling) require the presence of a control device, which should at least assume the following functions:

-Manual Power ON/OFF,

-Pump off when tank is full,

-Pump off when aspiration level is below the pump inlet (preventing dry running).

-Eventually motor temperature protection,

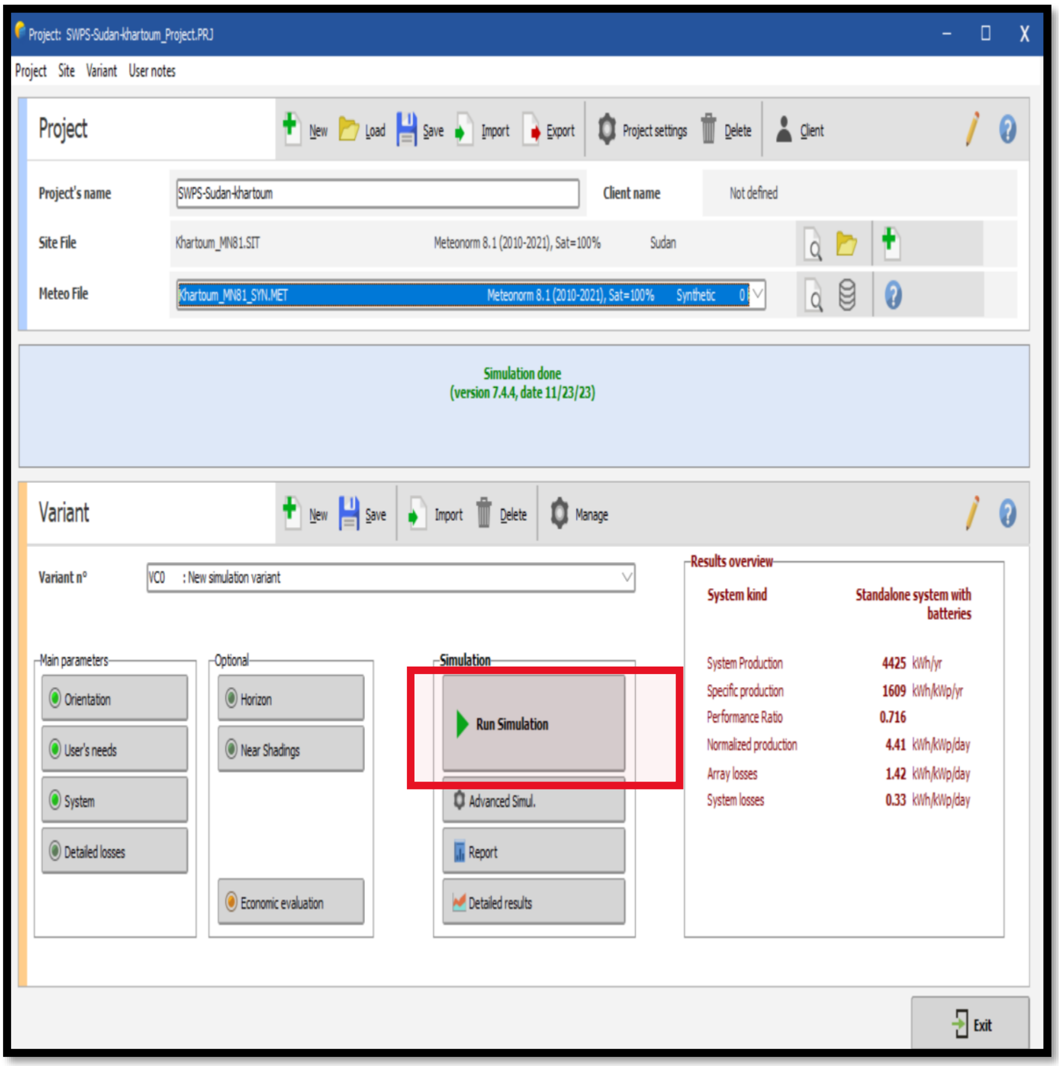
-Protection against powers, currents or voltages which exceed the maximum specified for the pumps.

The sizing constraints depend on the system layout.

6.5 Executing the Simulation:

On the project' dashboard, all buttons are now green (eventually orange) or off.

The "Simulation " button is activated, and we can click on it.



Project's name: SWPS-Sudan-khartoum

Client name: Not defined

Site File: Khartoum_MN81.SIT Meteonorm 8.1 (2010-2021), Sat=100% Sudan

Meteo File: Khartoum_MN81_SYN.MET Meteonorm 8.1 (2010-2021), Sat=100% Synthetic 0

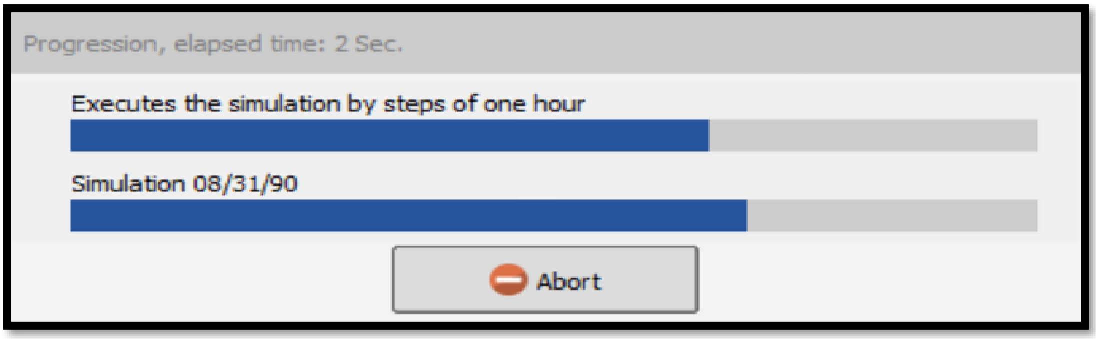
Simulation done
(version 7.4.4, date 11/23/23)

Variant n°: VC0 : New simulation variant

Results overview

System kind	Standalone system with batteries
System Production	4425 kWh/yr
Specific production	1609 kWh/kWp/yr
Performance Ratio	0.716
Normalized production	4.41 kWh/kWp/day
Array losses	1.42 kWh/kWp/day
System losses	0.33 kWh/kWp/day

Figure 6.10: Project page when ready to run simulation.



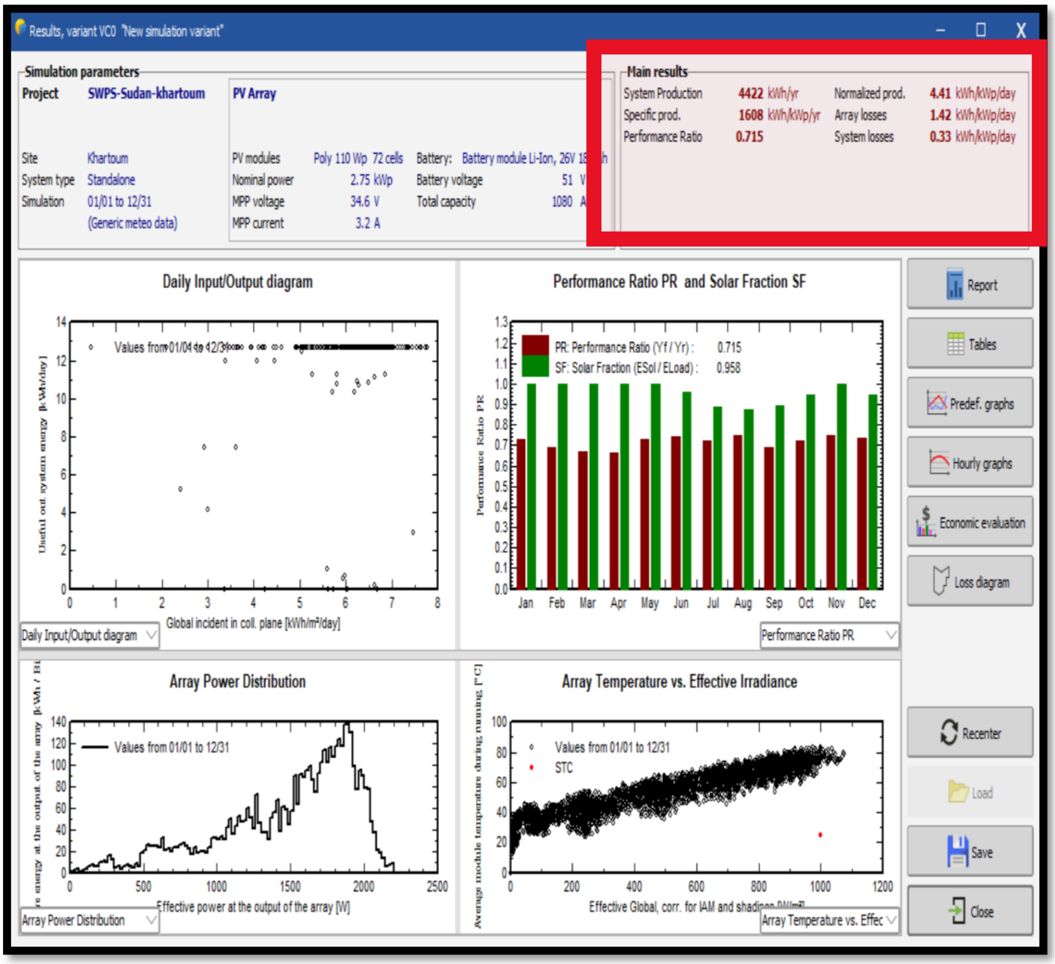
Progression, elapsed time: 2 Sec.

Executes the simulation by steps of one hour

Simulation 08/31/90

Figure 6.11: Progress bar.

A progress bar will appear, indicating how much of the simulation is still to be performed. Upon completion, the "OK" button will be active. When we click on it, we will get directly to the "Results" dialog.



Results, variant VC0 "New simulation variant"

Simulation parameters

Project SWPS-Sudan-khartoum

PV Array

Site Khartoum

System type Standalone

Simulation 01/01 to 12/31 (Generic meteo data)

PV modules Poly 110 Wp 72 cells

Nominal power 2.75 kWp

MPP voltage 34.6 V

MPP current 3.2 A

Battery: Battery module Li-Ion, 26V 18

Battery voltage 51 V

Total capacity 1080 A

Main results

System Production 4422 kWh/yr

Specific prod. 1608 kWh/kWp/yr

Performance Ratio 0.715

Normalized prod. 4.41 kWh/kWp/day

Array losses 1.42 kWh/kWp/day

System losses 0.33 kWh/kWp/day

Figure 6.12: The results dialog.

This dialog shows a small summary of the simulation parameters on the top. Check quickly to make sure that we did not make an obvious mistake in the input parameters.

On the bottom is a frame with nine values that summarizes the main results of the simulation at one glance. This only gives a very rough picture of the results and is there to quickly spot obvious mistakes or to get a first impression of a change or a comparison between variants of the project.

The simulation report will give a complete description of our system, with all the parameters used and the results.

The "loss diagram" at the end of the report allows a detailed analysis of the actual operation of the system throughout the year and a thorough check of its sizing. Here are some examples the loss diagram:

Example 1:

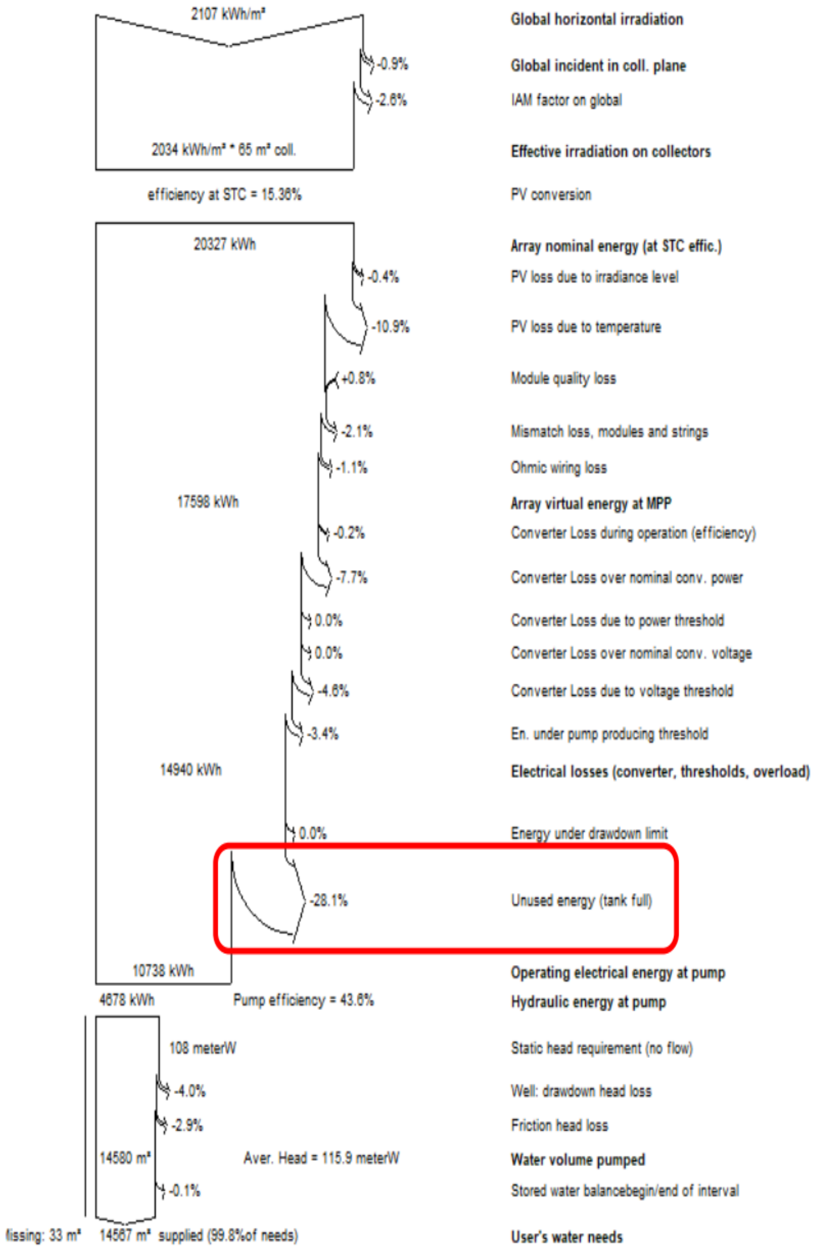


Figure 6.13: Loss diagram.

In this loss diagram, we can see an energy loss of 28.1% with the label "unused energy (tank full)".

This loss is present when:

-The water tank is undersized,

-Or the PV field is oversized,

-Or the water demand is low compared to simulated system.

This loss is normal, Sunshine conditions and water requirements can change throughout the year. To satisfy the user, it is necessary to size the system with conditions less favorable than a full sun. There will inevitably be times during the year when the production will be more than sufficient.

Example 2:

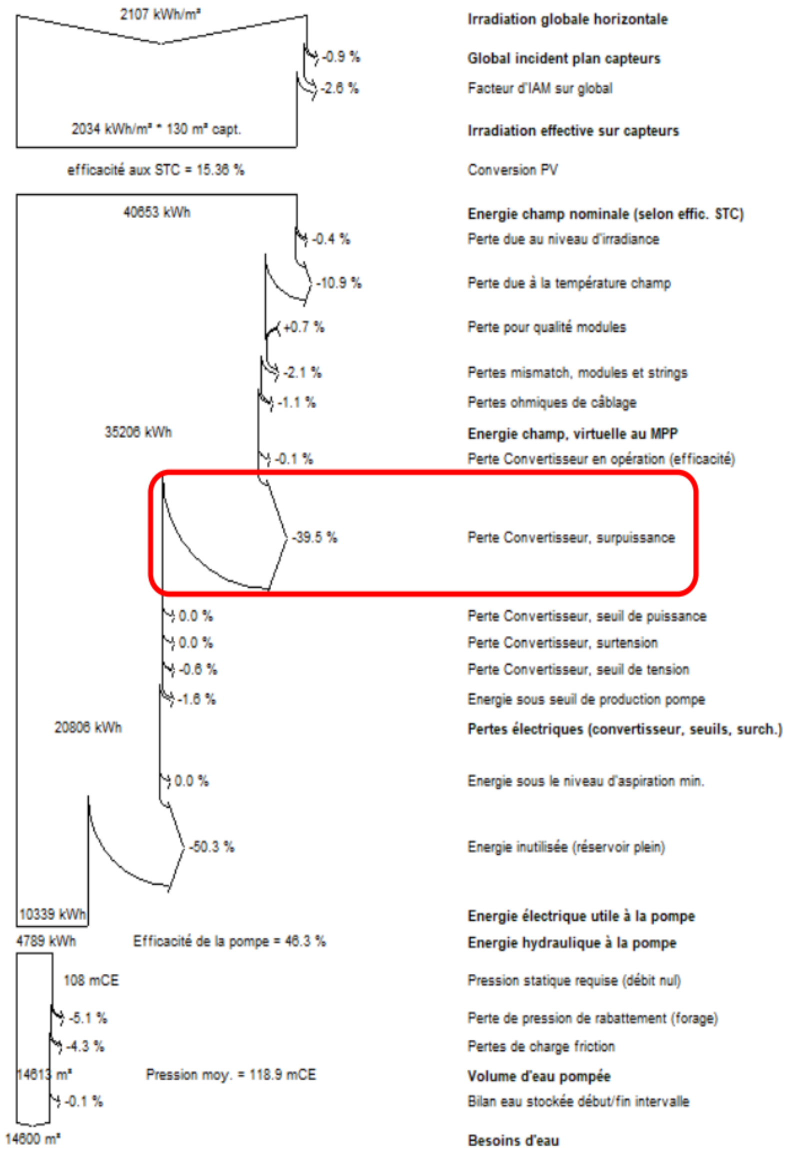


Figure 6.14: loss diagram.

In this loss diagram, we can see an energy loss of 39.5% with the name "Converter loss, overpower".

This loss is present when:

-The power of the PV array at certain times of the day is higher than the max power of the pump controller (characteristic of an oversized PV array).

Example 3:

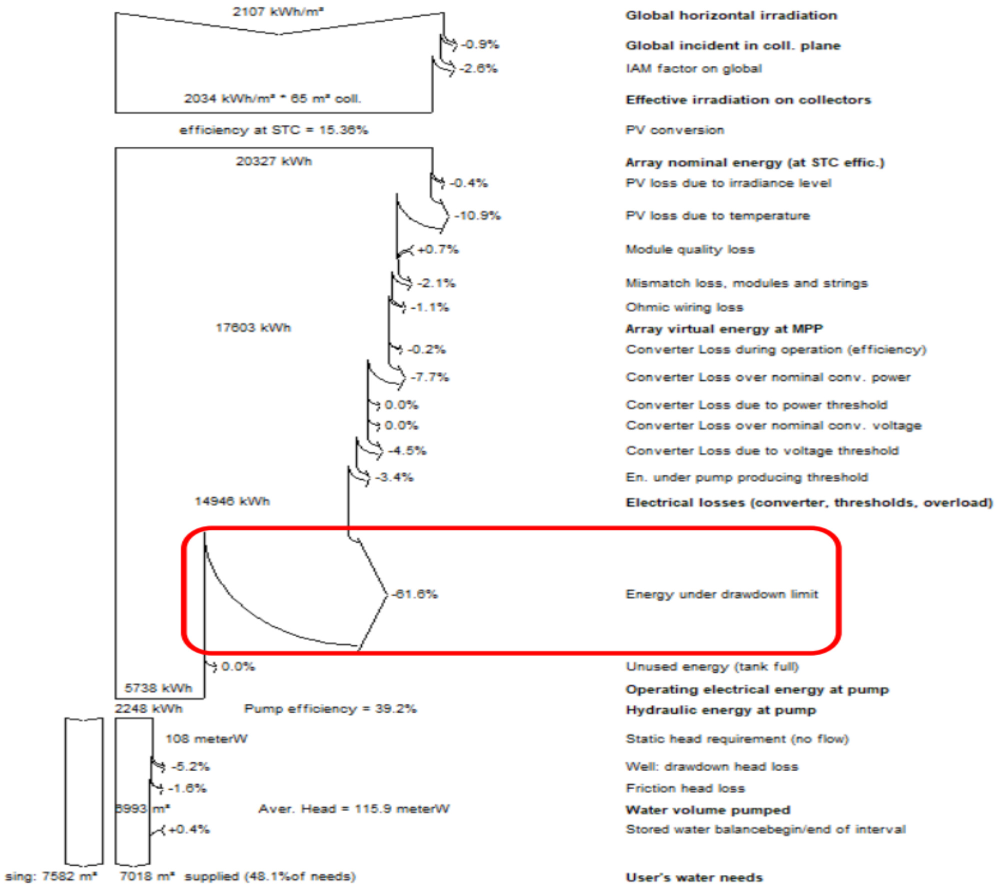


Figure 6.15: Loss diagram.

In this loss diagram, we can see an energy loss of 61.6% with the label "Energy below min. suction level".

This loss is present when:

-The pump has a flow rate that is too high compared to the drawdown of our well. The dynamic level

is therefore below the suction strainer. The pump stops for safety thanks to the lack of water sensor in the well.

To analyze the loss diagrams in more detail, we can view them in monthly values.

In this chapter, we demonstrated how to create our project on pumping system starting by describing the isolated and conventional pumping systems, followed by a step-by guide on creating variants to the project, defining the water needs and the system, executing the simulation and rounding it up with analyzing the results with a few examples given.

Chapter 7

7.1 Validation and Results Using PVsyst:

The installation size has been evaluated using PVsyst, since the solar radiation, the ambient temperature and load requirements of the target cite.

7.1.2 Design factors Considered:

- **Environmental data**: Explain the significance of irradiation and ambient temperature in determining the system's performance.
- **System Specification**: Detail the PV and battery technologies considered, along the array geometry used in the design.
- **Load information:** Discuss the monthly daily demand for the well pumping system and how it relates to the water needs of crops.

7.2 Evaluation:

- **Manual Configuration:** Highlight the ability to manually set solar radiation, ambient temperature, and load requirements within PVsyst for testing different scenarios.
- **component Size Determination:** Emphasize how PVsyst aids in determining and validating the sizes of installation components considering

various losses related to components or climatic parameters.

- **Solar Fraction (SF):** Explain how SF determines the panel surface's ability to meet the load's energy needs. Mentions that a high SF indicates efficient utilization of solar energy for meeting the load requirements.

7.3 The main results:

7.3.1 System Production:

water pumped 131894 m^3

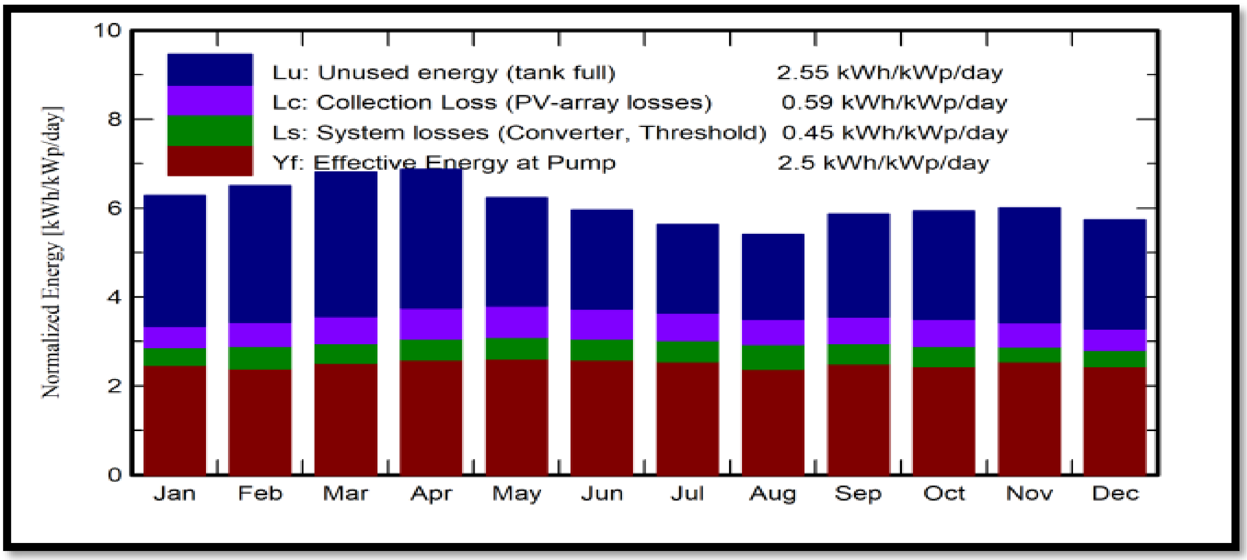


Figure7.1: Normalized Production Using PVsyst.

The chart is a stacked bar graph that displays normalized energy (in kWh/kWp/day) for month of the year. It is color – coded to show several types of energy:

- The blue represents unused energy (when the tank is full).
- The purple represents collection losses, which are due to PV – array losses.
- The green represents system losses, which include convert losses and threshold losses.
- The red represents effective energy at the pump.

The total height of each bar represents the total normalized energy for that month, and the assorted colors show how this total is divided into four categories mentioned above. The side panel provides specific values for each type of loss and effective energy:

- Unused energy (tank full): 2.55kWh/kWp/day.
- Collection loss (PV – array losses):0.59 kWh/kWp/day.
- System losses (converters, Threshold): 0.45kWh/kWp/day.
- Effective energy at the pump:2.5 kWh/kWp/day

The graph shows variability in energy distribution throughout the year, with January and December having the highest total normalized energy values and the summer months showing lower values. The effective energy at the pump remains constant across the months, as indicated by the red section's consistent size.

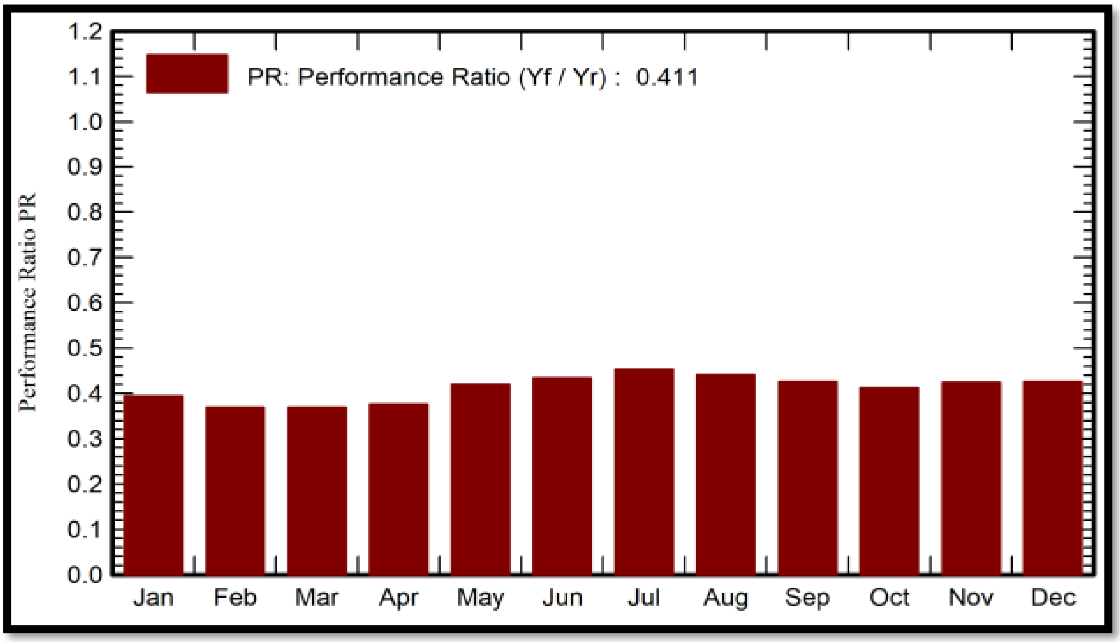


Figure 7.2: Performance Ration and Solar Fraction Using PVsyst.

This chart is a simple bar graph that displays the performance ratio (PR) for each month of the year.

Performance Ratio (**PR**):

Is a measure of the quality of a photovoltaic (PV) system and is defined as the ratio of the actual energy output from the PV system (Yf) to the theoretical possible energy output (Yr) under ideal condition.

A label indicates the PR value: "PR: Performance Ratio (Yf/Yr):0.41 ".

This suggests that the average PR over the year is 0.411, indicating that the PV system is producing just over 40% of the energy it could potentially generate under ideal conditions.

The highest PR value is in January, starting the year at just over 1.0, which would indicate exceptional performance.

From February to December, the PR values are consistent and significantly lower than January staying below 0.5, which indicates less than half of the ideal output is being realized each month.

Key PVsyst Results:

- Performance Ratio (PR):

Is the ratio of actual energy produced to theoretical available energy under standard conditions.

- Solar Fraction (SF):

The percentage of the load's energy met by solar power determines system efficiency.

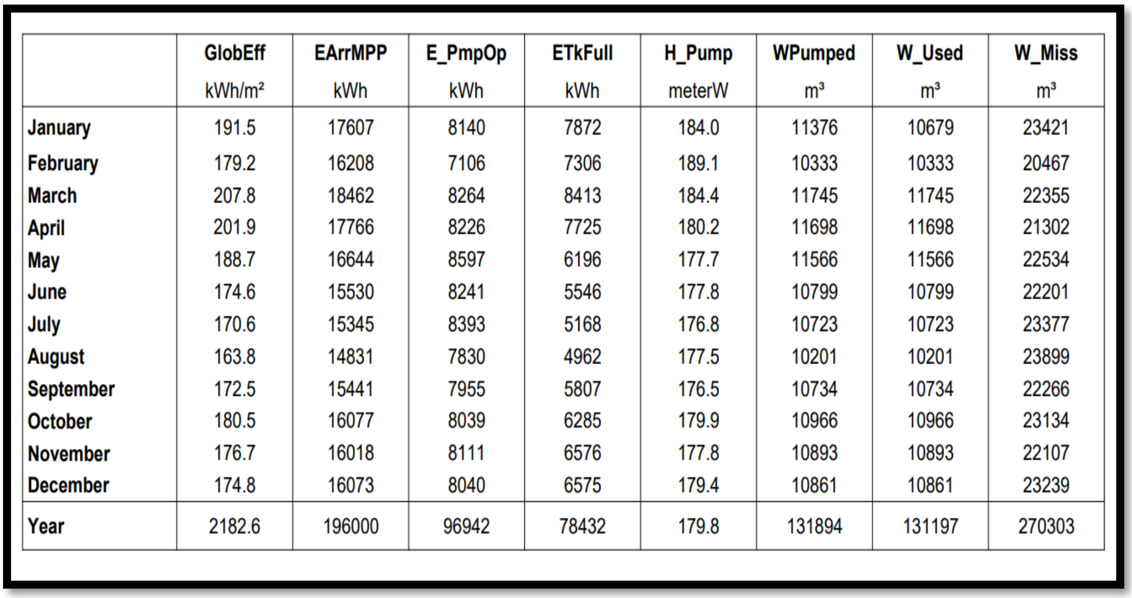
- System losses (Ls):

Evaluation of losses within the system affecting overall performance.

Comparing PR and SF using PV syst assets gauge both the efficiency of energy conversion and the system's ability to fulfill the load demand using solar power alone system.

By examining these metrics over different periods, we can gain insight into the system’s performance and its reliance on solar energy across varying conditions.

Energy balances and main PVsyst Results:



	GlobEff kWh/m²	EArrMPP kWh	E_PmpOp kWh	ETkFull kWh	H_Pump meterW	WPumped m³	W_Used m³	W_Miss m³
January	191.5	17607	8140	7872	184.0	11376	10679	23421
February	179.2	16208	7106	7306	189.1	10333	10333	20467
March	207.8	18462	8264	8413	184.4	11745	11745	22355
April	201.9	17766	8226	7725	180.2	11698	11698	21302
May	188.7	16644	8597	6196	177.7	11566	11566	22534
June	174.6	15530	8241	5546	177.8	10799	10799	22201
July	170.6	15345	8393	5168	176.8	10723	10723	23377
August	163.8	14831	7830	4962	177.5	10201	10201	23899
September	172.5	15441	7955	5807	176.5	10734	10734	22266
October	180.5	16077	8039	6285	179.9	10966	10966	23134
November	176.7	16018	8111	6576	177.8	10893	10893	22107
December	174.8	16073	8040	6575	179.4	10861	10861	23239
Year	2182.6	196000	96942	78432	179.8	131894	131197	270303

This table presents data related to a photovoltaic system’s performance and water pumping metrics over months of the year. Each column represents a different aspect of the system’s performance or output:

- GlobEff(kWh/m^2):

Global efficiency, indicating the amount of solar energy received per square meter.

- EArrMPP(kWh):

Energy at the maximum power point, which is the point where the product of current and voltage of the solar cell is maximized.

- E_pmpop(kWh):

Energy during pump operation, representing the amount of energy used by the pump when operational.

- TkFull(kWh):

Tank fullness in kilowatt-hours potentially indicates the energy content of the storage system when full.

- H_Pump(meterW):

This represents the hydraulic head in meters for water pumped or the height to which the pump is able to lift water.

- WPumped(m^3):

Volume of water pumped, measured in cubic meters.

- W_Used(m^3):

Volume of water used, also in cubic meters.

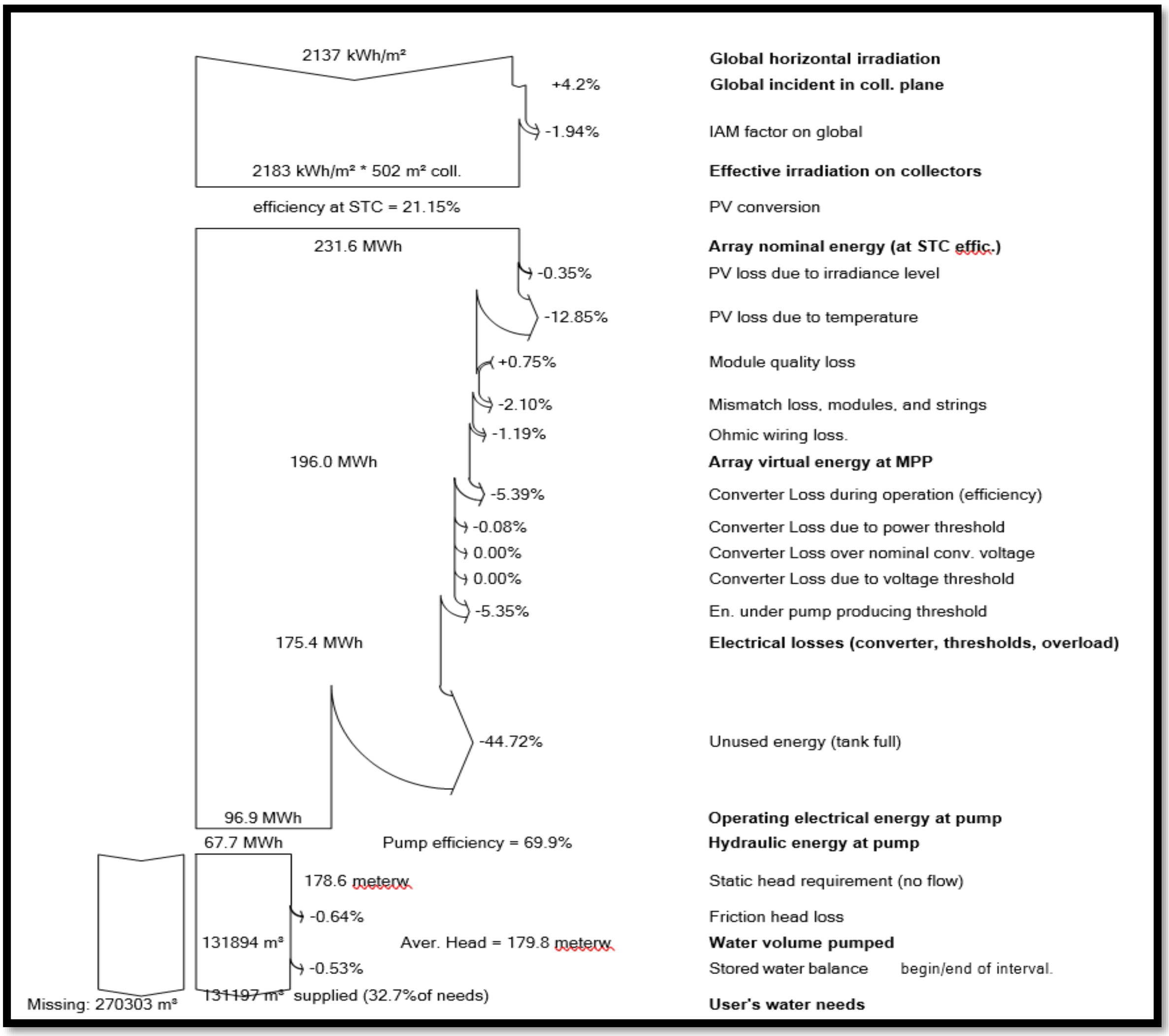
- W_Miss(m^3):

Volume of water missed or not utilized, in cubic meters.

The rows display monthly data from January to December, with the last row giving the annual totals. For instance, in January, the system received 191.5 kW/m^2 of solar energy, had an energy production at the maximum power point of 17,607 kWh, used 8,140 kWh during pump operation, etc.

March had the highest GlobEff value and August the lowest. The H_Pump value is stable across the year. The volume of water pumped and used fluctuates during May and June, showing higher values. The W_Miss column indicates that there is a significant amount of water that was pumped but not used every month. The total row at the bottom sums up the data for the entire year.

The loss diagram.



The diagram represents the flow of energy; it shows the distribution of energy from solar irradiation to the final needs covered by a pumping system. The widths of the lines are proportional to the flow rate they represent.

Here is the flow as depicted in the diagram:

1-Global horizontal irradiation:

The initial energy input is 2137 kW/m^2, which then adjusts for the global incident in the collector plane (+4.2%) and IAM factor on global (-1.94%).

2-PV Conversion losses:

There are several losses in photovoltaic (PV) conversion process, including losses due to irradiance level (-0.35%), temperature (-12.85%), module quality (-0.75%), mismatch between modules and strings (-2.10%), and ohmic wiring loss (-1.19%). The energy then goes through the array virtual energy at Maximum Power Point (MPP).

3-Converter losses:

There are further losses in the converter operation due to efficiency (-5.39%), power threshold (-0.08%), nominal converter voltage (0.00%), and voltage threshold (0.00%). There is also energy under the pump producing threshold (-5.35%).

4-Elecritcal losses:

This includes losses due to the converter, threshold, and overload, after which 175.4 MWh of energy is left.

5-Pump Efficiency:

The pump has an efficiency of 69.9%, which results in hydraulic energy at the pump.

6-Water Pumping and Storage:

There is a static head requirement and friction head loss that needs to be considered, and the diagram shows the water volume pumped (131894 m^3) and stored water balance at the beginning of/end of the interval.

7-User's Water needs:

The system covers 67.7 MWh of the user's water needs, which corresponds to 131,917 m^3 of water supplied, meeting 32.7% of the needs. It is noted that there is a missing amount of 27,033 m^3 to meet the total needs.

The diagram is especially useful for identifying major losses in the system and can be utilized for optimizing system performance by focusing on the largest inefficiencies.

Chapter 8

Calculations and discussion

8.1 Calculations:

The design will focus on how we can fulfil the demand for water to irrigate the agricultural piece the proper way throughout the year. Therefore, it is necessary to calculate the power and select components of the system.

The case study is a farm that is in eastern Khartoum in Soba. After many studies on this area, we have obtained the important design elements or requirements which are contained in table8.1.

Table (8.1): The farm requirements

Requires	Amount	Key
Total farm ‘area	Ten acres (40468.6m2)	A
Daily output of water	550m^3/day	Qr
Daily production of well	600 m^3/day	Qw
Depth of well	18 m	H
High of tank	3 m	Ht
Length of pipe	25 m	L
Diameter of pipe	11mm	Dp
Fitting 90 (degree)	6	-
None return valve	2	-

The kinematic viscosity of water	1.336*10^-6 m²/s	Kv
Kind of pipe material	Stain steel	k=0.015

These elements are crucial for various calculations involved in the design of the irrigation system, including determining the pumping power required, considering losses due to friction in the pipes, ensuring the appropriate diameter for the pipes, and selecting fittings and values for the system.

The Area land:

Although the metric system is commonly used for measurements like area (in square meters, hectares, etc.), in some regions, especially in agriculture, may still refer to lad area in acres. An acre is a unit of measurement commonly used in Sudan for land area.

One acre is equivalent to approximately 4047 square meters. So, if we are dealing with farmland prefer to use acres instead of square meters. We can make conversions accordingly:

-To convert from acres to square meters: multiply the number of acres by 4047 and vice versa.

Farmers often use acres for their familiarity and ease of understanding when it comes to estimating land area, planning crops yields, or determining the sizes plots.

Every 1 acre of farm 'area' needs approximately 55 m3/day of water, so 10 acres need approximately 550 m3/day (to irrigate all this area we need maximum of 1 week ,because we cannot use the maximum capacity of power, maybe we can use the 70% of the pump capacity).So; we divide the irrigation period into two parts(the first takes 3 days, and the other part takes 4 days more or less).

To irrigate our farm which is ten acre (40468.6 m^2), we need pump 5.5hp (so we choose PS4000 C-SJ8-15), the number four thousand indicates for the power in kilowatts means 4000kW.

One horsepower (hp) is equal to 0.746 kilowatts (kW). so, for our project.

So, Power in kW = Power in hp*0.746,

Then, 4000 ≈ 4103(5.5*0.746)

8.1.1 Velocity calculations (v):

The flow rate 13*8(H) = 104 m3/day

The flow rate 13*8(h) = 104 m3/day,

104*30(days) = 3120 m3/month,

Velocity in the pipe can be determined as flow:

$v = \frac{q}{a}$

Our daily required amount of water q= (104m^3/day)

Flow rate of water per hour q = (104(m^3/day)/(8(hr.))

=13m^3/hr.

Flow rate per second=(13(m^3/hr.)) /(3600(sec))

q =3.611*10^-3(m/sec)

Area of the pipe can be calculation as flow:

$$a = \frac{\pi d^2}{4} = \frac{\pi(0.011)^2}{4} = \underline{9.5033*10\text{^}{-5}(m\text{^}2)}$$

So that the velocity can be determined:

$$v = \frac{q}{a} = \frac{3.611*10\text{^}{-3}(m/sec)}{9.503*10\text{^}{-5}(m\text{^}2)} = \underline{37.998(m/sec)}$$

8.2 The dynamic head calculations (Hd):

$$Hd = \frac{K*V^2}{2G}$$

$$K = K(pipes) + nK(fittings)$$

Where K is the losses coefficient, and it is two kind losses in pipe (friction) and fitting losses.

Losses of friction in pipe:

K (pipes) = f*L/d

f= (1/ (-1.8*log10 ((6.9/Re+ (k*0.001/(d*3.7)) ^1.11)))) ^2

Where (k) is roughness factor of a material and it is standard value obtained from standard tables and is based upon the material of the pipe, including any internal coating, and the internal condition of the pipeline.

According to pipe material type, which is stain steel, k=0.012

Re ≡ is the Renold number and can be determined as flow:

$$Re = \frac{vd}{\upsilon} = \frac{37.998\left(\frac{m}{sec}\right)*0.01}{1.336*10^{\wedge}-6} = \underline{2.645*10^{\wedge}5}$$

f= (1/ (-1.8*log10 ((6.9/2.645*10^5 + (0.012*0.001/ (0.01*3.7)) ^1.11)))) ^2

f = 0.021

K (pipes)=0.021*25/0.01 =52.5

8.2.1 Losses of fittings:

K (fittings) =∑n*K

Where (K) is the losses coefficient of fittings and can be obtained from table, and (n) is the number of fittings.

K 90°bend fitting) =6*0.75=4.5

K (none return valve) =2*1=2

So, summation of fittings losses coefficient is:

K (fittings) =2+4.5=6.5

Lastly, we can obtain the total losses coefficient:

K=K (pipes) +∑nK (fittings)=52.5+6.5=59

Then the dynamic head can be determined:

$$Hd = \frac{K*v^2}{2G} = \frac{59*(37.998)^2(m/sec)}{2*9.81(m^2/sec)} = \underline{4341.8466m}$$

8.2.2 Static head calculation (Hs):

The static head is the sum of any vertical high in a system.

Hs=h (depth of well) + ht (high of tank) =15+3=18m

4.4Total head calculations (Ht):

Ht= Hd +Hs=4341.8466m +18m=4359.8466m

8.3 Pump selection:

Pump selection depends on amount of a required water per hour and the static head for that by knowing those two variables we can select the suitable pump. In our system the required amount of water is 13 m^3/hr. and the static head Ht=18

m, we will choose the suitable pump from authenticated table from LORENTZ COMPANY for solar pumping.

Note:

All pumps in this table are DC pumps; that mean is no need to use invertors

Table (8.2): DC pump types

Pump type	Max q(m^3/hr.)	Max static head Hs(m)
PS150 C-5J5-8	4	20
PS1800 C-SJ1-25	3	100

PS1800 C-SJ1-12	7.5	70
PS4000 C-SJ8-15	13	80
PS4000 C-SJ5-25	7	140
PS4000 C-SJ3-32	5	160

The table includes various pumps models with their corresponding flow rates and maximum head capacities.

Then the suitable pump to this amount of water to be pumped safely is PS4000 C-SJ8-15

8.3.1 System Overview of PS4000 C-SJ8-15:

Technical Data

8.3.2 System Overview:

Head	max. 80 m
Flow rate	max. 13m3/h.

8.3.3 Controller selection:

The choice of the controller for the DC pump, in this case, the PS2-4000, is a critical aspect of the solar – powered irrigation system. The controller serves as the brain of the system, managing the operation and optimizing the performance of the pump, particularly in conjunction with the solar power supply.

Technical Data:

Controller PS2 – 4000:

-Integrated MPPT (Maximum Power Point Tracking)

-Integrated Sun Sensor.

Power	max. 4,0 kW
Input Voltage	max. 375 V
Optimum Vmp	> 238V
Motor current	max. 14 A
Efficiency	max. 98 %
Ambient temperature	-40 ….50°C

8.4 Power calculations:

$$P = \frac{q*Ht*G*\rho}{\eta p}$$

Where (ηp) is the pump efficiency and it is (%)

$$P = \frac{q*Ht*G*\rho}{\eta p}$$

$$= \frac{2.778*10\text{^}-3(m^3/sec)*9.81(m/sec\ \text{^}2)*1000(kg/m\text{^}3)}{0.98} = 27.80W$$

P=27.80 W

8.4.1 PV panels selection:

The Selection of the appropriate Photovoltaic panels is crucial to harness the sufficient solar power to operate the irrigation system effectively. To determine the number and type of PV panels needed, it is essential to consider the power requirements calculated for the system.

Given that the system involves a pump, controller, and potentially other components, the power calculations should account for the total power consumption. Once we have the total power requirements, we can refer to the authenticated table from the **LORENTZ COMPANY**, which includes several types of PV panels with their specifications such as wattage, efficiency, size, and other relevant details.

There are some factors to consider when selecting PV panels:

- Wattage:

The power output of the panel. Ensure that the combined power output of the selected panels meets or exceeds the total power requirement of the system.

- Efficiency:
  Higher efficiency panels can generate more power in the same amount of space.
- Size and Dimensions:
  Consider available space for installation when selecting panel sizes.
- Durability and Warranty:
  Look for panels with a good track record of durability and a manufacturer's warranty.
- Compatibility with Controller:
  Ensure compatibility between the selected PV panels and the PS2-4000 controller and the overall system design.

According to power that we have calculated we can determine the number of suitable (PV) panels, selecting them suitable (PV) panel will be from an authenticated table which contains many types of popular (PV) panels used by LORENTZ COMPANY for solar pumping operations.

Table (8.3): Popular types of (PV) panels

(PV) panels type	power (watt)
LC50-12M	50
LC120-12P	120
LC150-P36	150
LC200-P60	200

8.4.2 Specifying tilt angle of PV panels:

Specifying tilt angle depends on many variables such as the location of fixing the PV panels such as the latitude of this area where the PV panels will be fixed and the many solar angles this is overly complicated to understand by the simple farmer. But we have tried to do this as simple as we can.

The tilt angle for stable or fixing system will be selected from this table:

Table (8.4): Tilt angle selection table

Site latitude (degree)	Tilt angle (degree)
0 to 15	15
15 to 25	Same as latitude
25 to 30	Latitude +5
30 to 35	Latitude +10
35 to 40	Latitude +15
Above 40	Latitude +20

From the requirements table the Soba latitude is 15°then our tilt angle will be 15°

The angle affects the direct sunlight exposure of the panels, which affects their energy production throughout the year. For a fixed installation, the optimal tilt angle is often close to the location's latitude to capture maximum sunlight.

Here is a simplified approach:

1-Latitude -base Tilt:

Set the tilt angle of the panels equal to the latitude of the area where the panels will be installed.

for the instance, if the location's latitude is 15°, tilting the panels at around 15 ° can be a good starting point.

2-Seasonal Adjustment:

If possible, consider adjustment mounting systems that allow seasonal adjustments. In some cases, optimizing for winter or summer sun might be beneficial. Adjusting the angle a few times a year can significantly improve energy capture.

3-General Guidelines:

For fixed installation without adjustment capability, using a tilting angle within a range of 5-10°of the location's latitude can still yield efficient energy capture without the need for frequent adjustments.

While this simplified approach may not be as precise as more intricate calculations, it offers a practical and straightforward method for setting the tilt angle that can work well for many installations.

Chapter 9

Conclusion and recommendations

9.1 Conclusion:

With a lot of efforts, prayers and supports from The Prof, I have completed this project, and I can say that all the project objectives are being achieved, designing a solar water pumping system and evaluating a system by using PVsyst Software. The system requires:

- Demand of daily water was 550m^3/day
- Depth of well or source of water was 18 m.
- High of tank or water reservoir 3 m
- Location of the project was Khartoum state Soba.

Therefore, the results of the designing were as follow:

- Power needed to pump a required amount of water is 4 kW.
- A suitable kind of PV panels to cover this power is LC200-200P.
- Number of PV panels needed is twenty-four.
- A suitable submersible pump to the system hourly flow and head is PS4000 C-SJ8-15
- Controller type controller PS4000
- Tilt angle of PV panels 15^0 on horizontal axis.
- Total static head is 45m.
- Total dynamic head is 45.3472 m.
- The efficiency of the system 38.89 %

- The total losses in head ratio 0.7716% of total static head
- Accuracy of a system is +20.8 watt.
- The ratio of accuracy 0.727% of the actual power needed.

For the portability of the system the tilt angle of PV panel will change every season and determined as follow:

- In winter season tilt angle is 42 degrees south (on the vertical plane)
- In summer season tilt angle is 10 degrees north (on the vertical plane)
- In autumn and spring season is 12.5 degree south (on the vertical plane)

9.2 Recommendations:

1. Taking the quantity of irradiance, depth of water and the surrounding condition carefully make pump works better.
2. We do not recommend using the sun tracer technique in Sudan because it is costly and not so benefit according to the unique location to the equator.
3. Cleaning the PV panels surfaces from by using smooth piece of cloth all periods make PV panels operate at a maximum efficiency.
4. The pump power designed at maximum so we can benefit from the power at the peak time.

References:

[1] Abdeen Mustafa Omer, (2015), Evaluation of sustainable development and environmentally friendly energy systems: case of Sudan" E3 Journal of Environmental Research and Management Vol. 6(3). pp. 0237-0261.

[2] Asim Osman Elzubeir (2016), "Solar Energy in Northern State (Sudan): Current State&Prospects", Science PG, American Journal of modern Energy.

[3] Eisa EI. Renewable energy potential and applications in Sudan. In: Proceedings of the round table on renewable energy, 1016 King Street, Virginia, USA.

[4] National Energy Administration (NEA) (1983), Renewable energy assessment for the Sudan. Sudan: Khartoum.

[5] Energy Research Institute (ERI), (1997). Renewable energy resources potential in Sudan. Khartoum, Sudan.

[6] Franz Trieb, Joachim Nitsch, Stefan Kronshage, Christoph Schillings, Lars-ArvidBrischke, Gerhard Kniesb, G. Czisch)2002(," Combined solar power and desalination plants for the Mediterranean region - sustainable energy supply using large-scale solar thermal power plants", ELSEVIER

[6] Jorgenson, J., P. Denholm, and M. Mehos (2014), Estimating the Value of Utility-Scale Solar Technologies in California under a 40% Renewable Portfolio Standard, NREL/TP-6A20- 61695.

[7] Lenzen, F. (2014), Overview of Parabolic Troughs and Linear Fresnel Receivers, presentation at the IEA workshop on solar electricity roadmaps, Paris, 3.

[8] Nelson, D., and G. Shrimali (2014), Finance Mechanisms for Lowering the Costs of Clean Energy in Rapidly Developing Countries, Climate Policy Initiative.

[9] R. Faranda, S. Leva, and V. Maugeri MPPT techniques for PV System; energetic & cost comparison, WSEAS Transactions on Power System, Issue 6, volume 3, June 2008, Italy.

[10] LILIT V. MELIKYAN, "Outcome Evaluation in the Practice of Environment and Energy Outcome Evaluation", UNDP Sudan Under CPD 2013- 2017 –Final Report, Ministry of Water Resources Irrigation and Electricity, January 30, 2018

[11] Zuhairuse Md. Darus, Nor Atikah Hashim Siti Nurhidayah, Abdul Manan MohdAzhar, Abdul Rahman Khairul Nizam, Abdul Maulud, Othman Abdul Karim. (2009), "The Development of Hybrid Integrated Renewable Energy System (Wind and Solar) for Sustainable Living at Perhentian Island, Malaysia", European Journal of Social Sciences, Vol. 9, Number 4.

[12] University of Khartoum Consultancy Corporation (UKCC) (2016), Feasibility Study of Developing Solar PV Projects in Khartoum State: An Economic Analysis.

[13] International Finance Corporation (2015), UtilityScale Solar Photovoltaic Power Plants A Project Developer’s Guide.

[14] Global Warming of 1.5°C, An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, IPCC, 2018.

[15] Stern N. The economics of climate change, The Stern review, Cambridge University, 2007.

[16] Race G. How to manage overheating in buildings: a practical guide to improving summertime comfort in buildings. The Chartered Institution of Building Services Engineers, London, 2010.

[17] Lomas K. J., Porritt S.M. Overheating in buildings: Lessons from research, Building Research & Information, Vol. 45, No. 1-2, 2017, pp. 1–18.

[18] Rapp D. Assessing climate change temperatures, solar radiation, and heat balance, Praxis Publishing, Chichester, UK, 2013.

[19] TM52: The limits of thermal comfort: avoiding overheating in European buildings, The Chartered Institution of Building Services Engineers, London, 2013.

[20] Robertson G. Passive design toolkit, City of Vancouver, 2009.

[21] Albdour M. S., Baranyai B. Numerical evaluation of outdoor thermal comfort and weather parameters in summertime at Széchenyi square, Pollack Periodica, Vol. 14, No. 2, 2019, pp. 131–142.

[22] Indoor environment: Health aspects of air quality, thermal environment, light, and noise, WHO, 1990

[23] Dengel A., Swainson M., Ormandy D., Ezratty V. Overheating in dwellings guidance document, The BRE Centre for Resilience, 2011.

[24] ASHRAE Standard 55-2010, Thermal environmental conditions for human occupancy, 2010.

[25] Osman M. M., Sevinc H. Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan, Sustainable Cities and Society, Vol. 47, 2019, Paper No. 101429.

[26] Szkordilisz F, Kiss M. Passive cooling potential of alley trees and their impact on indoor comfort, Pollack Periodica, Vol. 11, No. 1, 2016, pp. 101–112.

[27] Ali S. I. A., Szalay Zs. Towards developing a building typology for Sudan, IOP Conference Series: Earth and Environmental Science, Vol. 323, Paper No. 012012.

[28] Sudan Meteorological Authority, Maximum Temperature Forcast, Sudan, 2018.

[29] Köppen Climate Classification, Sudan map of Köppen climate classification, 2019.

[30] World Weather and Climate, Sudan Metrological Authority World Weather Information Service, 2019.

[31] Meteonorm v7.1, weather data of Khartoum, 2019.

[32] Design Builder, https://designbuilder.co.uk/helpv6.0, (last visited 2 March 2020).

[33] Ahmed M. H. A. Solutions to low-income urban housing problems in the Sudan, PhD Thesis, University of Sheffield, England, 1978.

[34] Central Bureau of Statistics Census, Sudan, 2008.

[35] Taha, Abdelmoneim; Thomas, Timothy S. and Waithaka, Micheal.2013. Sudan in East African agriculture and climate change: A comprehensive analysis. Eds.Waithaka

[36] Michael; Nelson, Gerald C.; Thomas, Timothy S. and Kyotalimye, Miriam. Chapter 10. Pp. 279-311

[37] Allen, R. G., Pruitt, W. O., Wright, J. L., Howell, T. A., Ventura, F., Snyder, R., et al. (2006).

[38] A recommendation on standardized surface resistance for hourly calculation of reference ET by the FAO56 Penman-Monteith method. Agricultural Water Management, 81(1), 1−22.

[39] Belakhal, S. (2010). Conception & Commande des Machines a` Aimants Permanents De´die´es aux Energies Renouvelables (thesis). Algeria: University of Constantine.

[40] Ben Ammar, M. (2011). Contribution a` l’optimisation de la gestion des syste`mes multi-sources d’e´nergies renouvelables (thesis). Tunisia: National Engineering School of Sfax.

[41] Bernal-Agustı´n, J. L., & Dufo-Lo´pez, R. (2009). Simulation and optimization of stand-alone hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 13(8), 2111−2118.

[42] Cavallo, A. (2007). Controllable and affordable utility-scale electricity from intermittent wind resources and compressed air energy storage (CAES). Energy, 32(2), 120−127.

[43] Chaabene, M. (2009). Gestion e´nerge´tique des syste`mes photovoltaı¨ques (Master course). Tunisia: National School for Engineers of Sfax.

[44] Chanson, H. (1994). Comparison of energy dissipation between nape and skimming flow regimes on stepped chutes. Journal of Hydraulic Research, 32(2), 213−218.

[45] Chapman, N. A., & Mc Kinley, I. G. (1987). The geological disposal of nuclear waste. New York, NY: John Wiley & Sons, Inc., ISBN 0-471-91249-2.

[46] Chenni, R., Messaoud Makhlouf, M., Kerbache, T., & Bouzid, A. (2007). A detailed modelling method for photovoltaic cells. Energy, 32(9), 1724−1730.

[47] Specifications of Photovoltaic Pumping Systems in Agriculture Cle´ment, A., McCullen, P., Falca, A., Fiorentino, A., Gardner, F., Hammarlund, K., et al. (2002).

[48] Wave energy in Europe: current status and perspectives. Renewable and Sustainable Energy Reviews, 6(5), 405−431.

[49] de Brito, M. A. G., Galotto, L., Sampaio, L. P., de Azevedo Melo, G., & Canesin, C. A. (2013). Evaluation of the main MPPT techniques for photovoltaic applications. IEEE Transactions on Industrial Electronics, 60(3), 1156−1167.

[50] Demirbas, A. (2005). Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Progress in Energy and Combustion Science, 31(2), 171−192.

[51] Deshmukh, M. K., & Deshmukh, S. S. (2008). Modeling of hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 12(1), 235−249.

[52] EPIA (2014). Global market outlook for photovoltaic 2014−2018. European Photovoltaic Industry Association. <www.epia.org>.

[53] Fridleifsson, I. B. (2001). Geothermal energy for the benefit of the people. Renewable and Sustainable Energy Reviews, 5(3), 299−312.

[54] Fridleifsson, I. B. (2003). Status of geothermal energy amongst the world’s energy sources. Geothermics, 32(4), 379−388.

[55] Goswami, D. Y., Kreith, F., & Kreider, J. F. (2000). Principles of solar engineering. CRC Press, ISBN 1-56032-714-6.

[56] Green, M. A. (1982). Solar cells: operating principles, technology, and system applications. Englewood Cliffs, NJ: Prentice-Hall, Inc.

[57] Gules, R., De Pellegrin Pacheco, J., Hey, H. L., & Imhoff, J. (2008). A maximum power point tracking system with parallel connection for PV stand-alone applications. IEEE Transactions on Industrial Electronics, 55(7), 2674−2683.

[58] GWEC (2013). Global wind statistics. Global Wind Energy Council. Henrik, L. (2007). Renewable energy strategies for sustainable development. Energy, 32, 912−919.

[59] Ibrahim, D. (2000). Renewable energy and sustainable development: a crucial review. Renewable and Sustainable Energy Reviews, 4, 157−175.

[60] IEA-AIE (2013). Key world energy statistics 2013. International Energy Agency. www.iea.org.

[61] SM Ismail; K Ozawa; & NA Khondaker. (2007). Effect of irrigation frequency and timing on tomato yield, soil water dynamics and water use efficiency under drip irrigation. Proceedings of the eleventh international water technology conference (pp. 15−18).

[62] Johansson, T. B., Kelly, H., Amulya, R. K. N., & Williams, R. H. (1992). Renewable energy: sources for fuels and electricity. Island Press, ISBN 1-55963-139-2.

[63] Kumar, A., & Kandpal, T. C. (2007). Renewable energy technologies for irrigation water pumping in India: a preliminary attempt towards potential estimation. Energy, 32(5), 861−870.

[64] Lutze, W., & Ewing, R. C. (1988). Radioactive waste forms for the future. Amsterdam, Netherlands: North Holland, ISBN 0 444 87104 7.

[65] Naika, S., van Lidt de Jeude, J., de Goffau, M., Hilmi, M., & van Dam, B. (2005). Cultivation of tomato. Wageningen: Agromisa Foundation.

[66] Nema, P., Nema, R. K., & Rangnekar, S. (2009). A current and future state of art development of hybrid energy system using wind and PV-solar: a review. Renewable and Sustainable Energy Reviews, 13(8), 2096−2103.

[67] Pelc, R., & Fujita, R. M. (2002). Renewable energy from the ocean. Marine Policy, 26(6), 471−479.

[68] Price, S. C., Stuart, A. C., Yang, L., Zhou, H., & You, W. (2011). Fluorine substituted conjugated polymer of medium band gap yields 7% efficiency in polymer 2 fullerene solar cells. Journal of the American Chemical Society, 133(12), 4625−4631.

[69] Purohit, P., & Kandpal, T. C. (2005). Renewable energy technologies for irrigation water pumping in India: projected levels of dissemination, energy delivery, and investment requirements using available diffusion models. Renewable and Sustainable Energy Reviews, 9(6), 592−607.

[70] Raes, D., Sahli, A., Van Looij, J., Ben Mechlia, N., & Persoons, E. (2000). Chart for guiding irrigation in real time. Irrigation and Drainage Systems, 14, 343−352.

[71] Saidur, R., Abdulaziz, E. A., Demirbas, A. H., Hossain, M. S., & Mekhilef, S. (2011). A review on biomass as a fuel for boilers. Renewable and Sustainable Energy Reviews, 15(5), 2262−2289.

[72] Renewable Energies and Irrigation 13 Siegfried, H. (2014). Grid integration of wind energy. John Wiley & Sons.

[73] Sumaila, U. R., Teh, L., Watson, R., Tyedmers, P., & Pauly, D. (2008). Fuel price increase, subsidies, overcapacity, and resource sustainability. ICES Journal of Marine Science, 65(6), 832−840.

[74] Wang, H. & Zhang, D. (2010). The stand-alone PV generation system with parallel battery charger. Proceedings of the IEEE conference on electrical and control engineering (ICECE) (pp. 4450−4453)

[75] W Xiao & Dunford W.G. (2004). A modified adaptive hill climbing MPPT method for photovoltaic power systems. Proceedings of the IEEE conference on power electronics specialists (pp. 1957−1963).

[76] Yahyaoui, I., Tadeo, F., & Segatto, M. E. V. (2016). Energy and water management for drip-irrigation of tomatoes in a semi-arid district. Agricultural Water Management.

[77] Yotaka, H., Kazuo, Y., & Hitomi, S. (1984). Spectral sensitization in an organic P-N junction photovoltaic cell. Applied Physics Letters, 45(10), 1144−1145.

[78] Adamo, F., Attivissimo, F., Di Nisio, A., & Spadavecchia, M. (2011). Characterization and testing of a tool for photovoltaic panel modeling. IEEE Transactions on Instrumentation and Measurement, 60(5), 1613−1622.

[79] Altin, N., & Ozdemir, S. (2013). Three-phase three-level grid interactive inverter with fuzzy logic based maximum power point tracking controller. Energy Conversion and Management, 69, 17−26.

[80] Arunkumar, T., Jayaprakash, R., Denkenberger, D., Ahsan, A., Okundamiya, M. S., Tanaka, H., et al. (2012). An experimental study on a hemispherical solar still. Desalination, 286, 342−348.

[81] Balghouthi, M., Chahbani, M. H., & Guizani, A. (2012). Investigation of a solar cooling installation in Tunisia. Applied Energy, 98, 138−148.

[82] Ben Ammar, M. (2011). Contribution a` l'optimisation de la gestion des syste`mes multi-sources d'e´nergies renouvelables (Thesis). Tunisia: National Engineering School of Sfax (ENIS).

[83] Ben Salah, C., & Ouali, M. (2012). Energy management of a hybrid photovoltaic system. International Journal of Energy Research, 36(1), 130–138.

[84] Bernal-Agustı´n, J. L., & Dufo-Lo´pez, R. (2009). Simulation and optimization of stand-alone hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 13(8), 2111–2118.

[85] Bernstein, L., & Francois, L. E. (1973). Comparison of drip, furrow, and sprinkler irrigation. Soil Science, 115(1), 73–86.

[86] Bouadila, S., Lazaar, M., Skouri, S., Kooli, S., & Farhat, A. (2014). Assessment of the greenhouse climate with a new packed-bed solar air heater at night, in Tunisia. Renewable and Sustainable Energy Reviews, 35, 31–41.

[87] Casoli, P., & Anthony, A. (2013). Gray box modeling of an excavator's variable displacement hydraulic pump for fast simulation of excavation cycles. Control Engineering Practice, 21(4), 483–494.

[88] Chaabene, M. (2009). "Gestion e´nerge´tique des syste`mes photovoltaı¨ques" (Master course). Tunisia: National School of Engineering of Sfax.

[89] Charfi, S., &Chaabene, M. (2014). A comparative study of MPPT techniques for PV systems. IEEE proceedings of the international renewable energy congress (IREC) (pp. 22−28).

[90] Chenni, R., Makhlouf, M., Kerbache, T., & Bouzid, A. (2007). A detailed modeling method for photovoltaic cells. Energy, 32(9), 1724−1730.

[91] Clean Energy Decision Support Centre (2001−2004). "Photovoltaic project analysis, Chapter," Catalogue no: M39-99/2003E. RETScreen International, ISBN 0-662-35672-1.

[92] Collares-Pereira, M., & Rabl, A. (1979). The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values. Solar Energy, 22(2), 155−164.

[93] Collins, J., Kear, G., Li, X., Low, J. C. T., Pletcher, D., Tangirala, R., et al. (2010). A novel flow battery: A lead acid battery based on an electrolyte with soluble lead (II) Part VIII. The cycling of a 10 cm 3 10 cm flow cell. Journal of Power Sources, 195(6), 1731−1738.

[94] De Blas, M. A., Torres, J. L., Prieto, E., & Garcia, A. M. M. (2002). Selecting a suitable model for characterizing photovoltaic devices. Renewable Energy, 25(3), 371−380

[95] Desai, H.P., & Patel, H.K. (2007). Maximum power point algorithm in PV generation: An overview. Proceedings of the IEEE conference on power electronics and drive systems (PEDS'07) (pp. 624−630).

[96] Duffie, J. A., & Beckman, W. A. (2013). Solar engineering of thermal processes. John Wiley & Sons, ISBN 978-1-118-43348-5.

[97] El-Sebaii, A. A., Al-Hazmi, F. S., Al-Ghamdi, A. A., & Yaghmour, S. J. (2010).

[98] Erbs, D. G., Klein, S. A., & Duffie, J. A. (1982). Estimation of the diffuse radiation fraction for hourly, daily, and monthly-average global radiation. Solar Energy, 28(4), 293−302.

[99] Esram, T., & Chapman, P. L. (2007). Comparison of photovoltaic array maximum power point tracking techniques. IEEE Transactions on Energy Conversion, 22(2), 439−449.

[100] Faranda, R., & Leva, S. (2008). Energy comparison of MPPT techniques for PV systems. WSEAS Transactions on Power Systems, 3(6), 446−455

[101] Femia, N., Petrone, G., Spagnuolo, G., & Vitelli, M. (2005). Optimization of perturb and observe maximum power point tracking method. IEEE Transactions on Power Electronics, 20(4), 963−973.

[102] Fendri, D., & Chaabene, M. (2012). Dynamic model to follow the state of charge of a lead-acid battery connected to photovoltaic panel. Energy Conversion and Management, 64, 587−593.

[103] Ghaisari, J., Habibi, M., & Bakhshai, A. R. (2007). An MPPT controller design for photovoltaic (PV) systems based on the optimal voltage factor tracking. Proceedings of the IEEE conference on electrical power (EPC) (pp. 359−362).

[104] Gonza´lez-Longatt, F.M. (2005). Model of photovoltaic module in Matlab. Proceedings of the second Iberoamerican conference of electrical, electronics and computation students (pp. 1−5).

[105] Guasch, D., & Silvestre, S. (2003). Dynamic battery model for photovoltaic applications. Progress in Photovoltaics: Research and Applications, 11(3), 193−206.

[106] Hohm D.P., & Ropp M.E. (2000a). Comparative study of maximum power point tracking algorithms using an experimental, **[107]** programmable, maximum power point tracking test bed. IEEE proceedings of the photovoltaic specialist's conference (pp. 1699).

[108] Hohm, D. P., & Ropp, M. E. (2000b). Compar

ative study of maximum power point tracking algorithms. Progress in Photovoltaics: Research and Applications, 11, 47−62.

[109] Hussein, K. H., Muta, I., Hoshino, T., & Osakada, M. (1995). Maximum photovoltaic power tracking: An algorithm for rapidly changing atmospheric conditions. Proceedings of the IEE Conference on Generation, Transmission and Distribution, 142(1), 59−64.

[110] Global, direct, and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. Applied Energy, 87(2), 568−576.

[111] Kenny, R.P., Friesen, G., Chianese, D., Bernasconi, A., & Dunlop, E.D. (2003). Energy rating of PV modules: Comparison of methods

and approach. Proceedings of the 3rd IEEE world conference on photovoltaic energy conversion (pp. 2015−2018).

[112] Khatib, T., Mohamed, A., & Sopian, K. B. (2012). A review of solar energy modeling techniques. Renewable and Sustainable Energy Reviews, 16(5), 2864−2869.

[113] Kurella, A., & Suresh, R. (2013). Simulation of incremental conductance MPPT with direct control methods using cuck converter. IJRET, 2(9), 557−566.

[114] M. R., Rahmat, M. F., Ghadimi, A. A., & Mustafa, M. W. (2016). Control techniques for three−phase four-leg voltage source inverters in autonomous microgrids: A review. Renewable and Sustainable Energy Reviews, 54, 1592−1610.

[115] Moghadam, H., Tabrizi, F. F., & Sharak, A. Z. (2011). Optimization of solar flat collector inclination. Desalination, 265(1), 107−111.

[116] Oi, A. (2005a). Design and simulation of photovoltaic water pumping system (Doctoral dissertation). San Luis Obispo, CA: California Polytechnic State University.

[117] Oi, A. (2005b). Design and simulation of photovoltaic and IC water pumping system (Master course). San Luis Obispo, CA: University of Faculty of California Polytechnic State University.

[118] Orgill, J. F., & Hollands, K. G. T. (1977). Correlation equation for hourly diffuse radiation on a horizontal surface. Solar Energy, 19(4), 357−359.

[119] Posadillo, R., & Lo´pez Luque, R. (2009). Hourly distributions of the diffuse fraction of global solar irradiation in Co´rdoba (Spain). Energy Conversion and Management, 50(2), 223−231.

[120] Rana, G., Katerji, N., Lazzara, P., & Ferrara, R. M. (2012). Operational determination of daily actual evapotranspiration of irrigated tomato crops under Mediterranean conditions by one-step and two-step models: Multiannual and local evaluations. Agricultural Water Management, 115, 285−296.

[121] Reis, J.H., Miranda, A.C., Lemes, L.J., Viajante, G.P., & Chaves, E.N. (2015). Analysis of IMC method applied to output current control on DC/DC buck converter—a power led switching on aapplication IEEE 13th Brazilian power electronics conference and 1st southern power electronics conference (COBEP/ SPEC) (pp. 1−6).

[122] IEEE. Riggio, C., & Houghton, B. (2014). U.S. Patent No. 8,896,263. Washington, DC: U.S. Patent and Trademark Office.

[123] Roger, J.A.; Perez, A.; Campana, D., Castiel, A.; & Dupuy, C.H.S. (1978). Calculations and in situ experimental data on a water pumping system directly connected to a 1/2 kW photovoltaic conver−tors array. Proceedings of the photovoltaic solar energy conference (pp. 1211−1220).

[124] Salas, V., Olias, E., Barrado, A., & Lazaro, A. (2006). Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. Solar Energy Materials and Solar Cells, 90(11), 1555−1578.

[125] Salimi, M., Soltani, J., Markadeh, G. A., & Abjadi, N. R. (2013). Indirect output voltage regulation of DC-DC buck/boost converter operating in continuous and discontinuous conduction modes using adaptive backstepping approach. Power Electronics, IET, 6(4), 732−741.

[126] Sallem, S., Chaabene, M., & Kamoun, M. B. A. (2009a). Energy management algorithm for optimum control of a photovoltaic water pumping system. Applied Energy, 86(12), 2671−2680.

[127] Sallem, S., Chaabene, M., & Kamoun, M. B. A. (2009b). Optimum energy management of a pphotovoltaicwater pumping system. Energy Conversion and Management, 50(11), 2728−2731

[128] Sen, Z. (2008). ¸ Solar energy fundamentals and modeling techniques: Atmosphere, environment, climate change and renewable energy (Vol. 276Springer.

[129] Soussi, M., Balghouthi, M., & Guizani, A. (2013). Energy performance analysis of a solar-cooled building in Tunisia: Passive strategies impact and improvement techniques. Energy and Buildings, 67, 374−386.

[130] Sweeeney, D. W., Graett, D. A., Bottcher, A. B., Lacario, S. J., & Camphll, K. L. (1987). Tomato yield and nitrogen recover as influenced by irrigation method, nitrogen source and mulches. HortScience, 22, 27−29.

[131] Taufik EE410 Power Electronics I—Lecture note. (2004). SanLuis Obispo, CA: Cal Poly State University.

[132] Veerachary, M., & Yadaiah, N. (2000). ANN based peak power tracking for PV supplied DC motors. Solar Energy, 69(4), 343−350.

[133] Xiao, W., Dunford, W.G., & Capel, A. (2004, June). A novel modeling method for photovoltaic cells. Proceedings of the 35th IEEE annual conference on power electronics specialists (pp. 1950−1956).

[134] Yahyaoui, I., Chaabene, M., & Tadeo, F. (2013). An algorithm for sizing photovoltaic pumping systems for tomato irrigation. Proceedings of the IEEE conference on renewable energy research and applications (ICRERA) (pp. 1089−1095).

[135] Yahyaoui, I., Chaabene, M., & Tadeo, F. (2016). Evaluation of maximum power point tracking algorithm for off-grid photovoltaic pumping. Sustainable Cities and Society, 25, 65−73.

[136] Yahyaoui, I., Sallem, S., Chaabene, M., & Tadeo, F. (2012). Vector control of an induction motor for photovoltaic pumping. Proceedings of the international renewable energy conference (IREC) (pp. 877−883).

[137] Yin, X. X., Lin, Y. G., Li, W., Liu, H. W., & Gu, Y. J. (2015). Adaptive sliding mode back-stepping pitch angle control of a variable-displacement pump-controlled pitch system for wind turbines. ISA Transactions, 58, 629−634.

[138] Zhang, C. P., Sharkh, S. M., Li, X., Walsh, F. C., Zhang, C. N., & Jiang, J. C. (2011). The performance of a soluble lead-acid flow battery and its comparison to a static lead-acid battery. Energy Conversion and Management, 52(12), 3391−3398.