Master Level Thesis

European Solar Engineering School

No. 257, May 2019

Conjunctive Operation of Hydro and Solar PV Power with Pumped Storage at Kafue Gorge Power Station (Zambia)

Master thesis 30 credits, 2019
Solar Energy Engineering

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Course Code: EG4001

Examination date: 2019-05-27

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MASTER THESIS

Dalarna University
Solar Energy Engineering

Abstract

This report covers the work carried out to redesign the two existing conventional hydro power stations in Zambia on the Kafue river into the pumped storage facility with solar photovoltaic power so that security of supply and water conservation is achieved to reduce the power deficits during the dry and drought periods. The two stations are Kafue gorge upper power station (KGUPS) and Kafue gorge lower power station (KGLPS) with an installed capacity of 990 MW and 750 MW respectively. These two stations are dammed hydro power station with the reservoirs size of $785 \ 10^6$ m^3 and $80 \ 10^6$ m^3 respectively and situated on the 9000 hectares of land with the net head of 400 m. The two plants are situated 15 kilometres apart and the water inflow in the KGUPS is dependent on the water release from the holding dam Ithezi- thezi (ITT dam) situated 220 kilometres from the KGUPS dam. The work covered the sizing of the storage dams and determining the autonomy days needed in order to keep the station (KGUPS) running with minimal impact on power blackouts which were calculated at 5 days considering the size of the dam and the available energy. The financial calculation for the PV system was also carried out in this study except for the hydro system which was not carried out due to the time allocated to conduct this study. The proposed operation scheme for the two hydro stations and the solar PV system is also carried out in order to increase solar power penetration in the Zambian grid, reduce power deficit and conserve water during the days/times with enough solar power.

Designing of the system was carried out using Homer Pro software on which the hydro power station was modelled using the water influx into the turbines at KGUPS, the plant net head of 400 meters was also used with the calculated head losses of 7 % for the 4 meter diameter penstock between KGUPS dam, KGUPS machine hall to the KGLPS dam. The KGUPS dam was modelled as a natural battery so that charging is done using the water from the KGLPS dam, the battery with a total annual capacity of 428 GWh was modelled. PVsyst and PVGIS software tools were also used to simulate the production from the optimised PV system so that the accuracy of tools can be compared.

To cover the load of 777 MW/day (18.6 GWh/day), the available power to provide the necessary energy for the pumps was 270 MW as surplus power from the hydro power machines at KGUPS .The available power from solar PV plant of 236 MW maximum was achieved from the optimized 300 MW PV plant in the dry period of the day which occurs in the month of October, with 300 MW converter , 8 % penetration of solar into the Zambian grid and the pumping scheme was able to provide 589 hours of autonomy with 80 % average state of charge. The total maximum power of 390 MW was good enough to provide power to the two pumps of each 165 MW. From the simulations carried out in the increment of solar PV system from 50 MW to 350 MW, the reliance on hydro power can be reduced drastically and power deficits due to the drought situation as the case for the year 2016 can be alleviated. 300 MW PV plant was selected in order to match with the available land, machines to work as pumps and the initial investment cost to be closely monitored. The optimized 300 MW PV system with the life of 30 years had a project capital cost of $113 million united states dollars with the levelized cost of electricity 0.0487 $/kWh. The solar PV plant has a payback period of 9 years considering the yearly production from solar PV of 534 GWh as simulated from Homer, PVGIS interactive tool gave an output of 491 GWh. Pumped hydro systems has the capability of utilizing the already existing structures like dams and turbines. They also have the capability of stabilizing the grid network and allow easy penetration of renewable energy technologies like wind and solar. With the government of Zambia pushing for more renewables in the grid by 2030, a pumped hydro project at KGUPS will certainly be able to stabilize the grid and provide a scheme that will be able to push thermal plants to run at full capacity and the efficiency can be improved. In accordance with the IEC TC (technical committee) [30] pumped hydro energy storage is a mature bulk energy technology offering stability and allowing the penetration of intermittent renewables like wind and solar.

Acknowledgment

Let me take this opportunity to thank the almighty God for granting me an opportunity to pursue my master's degree in Sweden at Darlana University. I want to thank my dear wife Janet Nsama Mkanda Nyirenda for the love and dedication given to me and the family during the time I have been away for studies.

My dedication of this work goes to my Late Grandmother Doris Mkandawire and my Mother Maybe Kunda for raising me up and giving me a life with a lot of meaning. My gratitude goes to my project supervisor PhD Martin Andersen for the academic support and encouragement during this study and Engineer Abiya Simwinga for the encouragement on this wonderful study and my love goes to my two sons Elton and Elvis Waliko Nyirenda that endured the absence of a Father.

Contents

Abbreviations

Abbreviation	Description
AC	Alternating current
ACOM	Annual cost of operations and maintenance
CRF	Capital recovery factor
DC	Direct current
EMF	Electromagnetic Field
ETAP	Electrical transient analyser program
ITT	Ithezi -Thezhi
KGLPS	Kafue Gorge Lower Power Station
KGUPS	Kafue Gorge Upper Power Station
KNBPS	Kariba North Bank Power Station
LHPS	Lunsemfwa Hydro Power Station
LCOE	Levelized Cost of Electricity
NAE	Net annual electricity produced
NHA	National Hydro Power Association
PHES	Pumped Hydro Electric Scheme
PS	Power Station
PV	Photovoltaic
PVSyst	Photovoltaic system simulation software
VFPS	Victoria Falls Power Station

Nomenclature

Symbol	Description	Unit
A	Surface area of the penstock	m^2
d	Discounted rate	%
D	Penstock diameter	m
ε	Pipe roughness	m
E_c	Energy stored in the upper reservoir	MWh
E	Evaporation	mm
E_{Load}	Load supported by the system	MWh
f_C	Churchill friction factor	
f_D	Darcy friction factor	
f_h	Friction head losses	%
h_l	Circular pipe losses	%
H_u	Overall plant head	m
I	Inflation rate	%
L	Length of the penstock	m
L_v	Latent heat of vaporization	kJ/kg
μ	Dynamic viscosity of the fluid	Pa.s
η	System efficiency	%
N_{day}	Number of autonomy days	
$n_{\emptyset}$	Doubly fed induction machine rotor speed	rpm
n_r	Rotor speed	rpm
n_s	Synchronous speed	rpm
P	Installed capacity of power plant	MW
ρ_w	Density of water	kg/m^3
$Q_p(t)$	Volume flux rate of pumped water to dam	L/s
Q_t	Volume flux input to the turbine	L/s
$Q_{UR}(t)$	Volume flux rate of water in the upper dam	L/s
R	Interest rate	
R_e	Reynolds number	%
SC_{PV}	Self-Consumption for a PV system	%
SS_{PV}	Self-Sufficiency for a PV system	%
u	Water volumetric flow rate	m^3/s
V	Volume of the reservoir	m^3
$\dot{V}$	Water mass flowrate	kg/s
$\dot{V}_{wat}$	measured volume flow rate of water	m^3/s
γ	Overall plant efficiency	%
μ	Kinematic viscosity of water	m^2/s

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1 Introduction

Kafue Gorge Lower Power Station (KGLPS) is situated in Zambia along the Kafue River and the geographic location is latitude 15.916 under the equator and longitude 28.676 on the east of the prime meridian. The station is located near the tailrace of the Kafue Gorge Upper Power station (KGUPS). The map below on Figure 1.1 Location of Kafue Gorge Lower Power Station [1].

Figure 1.1 Location of Kafue Gorge Lower Power Station [1]

The KGLPS is located at 55 kilometres from the confluence of the Kafue river with the Zambezi river and about 5 kilometres from the main tailrace of the KGUPS.

Zambia has a total installed capacity of 2739 MW of which 2339 MW is hydro (about 90% of the generation), composed of 1080 MW (KNBPS), 990 MW(KGUPS), 120 MW(ITTPS), 108 MW (VFPS) and 30 MW of small hydro power stations. Besides the hydro power stations, Zambia has 50 MW (LHPS), 300 MW (Maamba coal fired plant and 50 MW (Ndola heavy fuel power plant). The power utility grid is state owned and managed by the parastatal company ZESCO limited. The Zambian government is developing the KFGLPS with the planned installed capacity of 750 MW and investing in 1000 MW of solar power systems mainly photovoltaic power (PV).

The investment in energy projects is due to the increase in demand of electricity especially the mines in North Western Province, the Copperbelt Province, creation of new districts and expansion of current cities such as Lusaka, the capital, which alone has the power demand close to 800 MW. The plan by the government to invest in solar projects has since commenced with the initial investment in the 50 MW of solar power in Lusaka province. Figure 2 below shows the energy demand focus for Zambia projected up to year 2030.

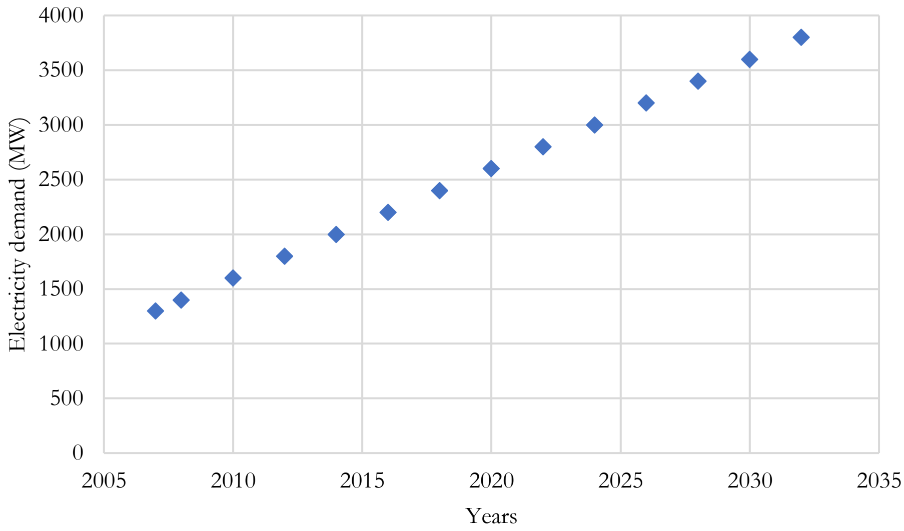

Figure 1.2 Electricity demand for Zambia [2]

Figure 1.2 shows the past and future projected electricity demand for Zambia; the electricity demand is increasing rapidly with time and this is the main reason why the government is investing in energy projects. The future projects which include solar and wind however are intermittent in nature and this project focuses on sustainable energy solution to effectively use the renewable energy resources. Unlike hydro, thermal and nuclear energy, solar energy is not always available on demand, meaning that controlling of the primary energy is a major challenge. In this project a pumped storage on the existing KGUPS and KGLPS is to be undertaken. The operation of the storage facility is to be responding to the intermittence nature of the solar power system and the fluctuations in the power quality of the electricity grid.

Besides, due to climate change; the country was heavily affected by poor rainfall from the late 2014 to early 2017 due to drought periods which are predominant and projected to continue in the southern hemisphere and other parts of the world as outlined by M. Bhattarai et al [2]. These droughts forced prolonged power outages since the water reservoirs decreased in storage dams and there was not enough water to be used for power generation. Some mines like Konkola copper mines, Kansanshi gold and copper mines and Mopani copper mines closed sections of their plants and so many jobs were lost. This project if implemented will be able to alleviate similar problems from occurring and the economy of the country can be more easily sustained.

This project falls within the area of sustainable energy development in that the existing structures of the KGUPS and the KGLPS should be used. As a matter of fact, hydro pumped storage facilities are site specific [3] and the marked site is suitable for the development of the project.

1.1 Background

The current status of the Kafue gorge upper power station (KGUPS) is that it is dammed hydro power station which was constructed in Lusaka province 28 km from Kafue town. The installed capacity of the power station is 990 MW. Water supply for this power station comes from the Kafue river which is the tributary of the Zambezi river as shown on Figure 1.1. Water storage for power generation is first stored on the (Ithezi-Thezhi dam) ITT dam located 220 km from the KGUPS dam, this means that on the upstream of the KGUPS two dams are in existence. After the KGUPS water is discharged in the new Kafue gorge lower (KGLPS) dam, this water in the KGLPS dam will be used to generate electricity by the 750 MW KGLPS which is scheduled for completion in the year 2021. The next section describes the configuration of the current KGUPS and the proposed plant in relation to civil design and power evacuation. The seasonal water usage depends on the water release from the ITT dam and precipitation which is very variable depending on the season. The primary situation is that the average daily load for KGUPS is 860 MW and the peak load is 920 MW recorded during the month of June due to the increased demand for heating. Most of the times, the hydro power plant does not run at full load, however in times of drought like the case for the year 2016, generation reduced considerably to below 500 MW due to the reduced water influx into the ITT dam and KGUPS dam. In order to offer the security of supply and cover the deficit power recorded in the year 2016 and similar years form much of the scope of the project. The study covers the contribution of solar energy from the solar PV plant, the grid and the power consumption from the pumps which are proposed to be installed at KGUPS for the conservation of water from the KGLPS dam to KGUPS dam. In order to supply power to the pumps, the surplus power of 130 MW from the KGUPS should be used and the contribution from solar as well as the grid. However, this power is variable depending on the load, the water in the KGUPS dam and the available solar energy resource. A comparison of the worst years (2016) in terms of power generation, consumption and water utilization from the KGUPS and one of the best years (2012) is the basis of this study.

1.2 System description of current and proposed KGUPS with PHES

The current design of KGUPS is such that, water is abstracted from the KGUPS dam to the turbine through one common tunnel called the headrace tunnel, from the headless tunnel which is 10 km long, the tunnel is subdivided into six penstocks with surge chambers and isolating valves before water goes into the main draft tubes on each turbine. The draft tube of each machine is linked to the spiral casing, in the spiral casing it where the Francis turbine runner is housed. The runner has supporting structures which include, stay rings, upper and lower guide bearings, generator lower and upper guide bearings, the turbine shaft which is a vertical arrangement. The overall effective head for KGUPS is 400 meters with a station discharge of 276 m^3/s. At KGUPS there are six identical generating units with each machine installed capacity of 165 MW with the rated speed of 375 revolutions per minute. The generation voltage for these machines is 17.5 kV which is later stepped up using power transformers to 330 kV.

The water which comes from the power station after electricity has been generated goes to the KGLPS dam. The tunnels marked existing are the current ones linking the penstock/turbines of each machine, KGUPS dam and the KGLPS dam. The electricity generated from the power station is evacuated using single phase transformers rated at 165 MVA, the setup is that two machines use three shared transformers. The arrangement of the system incorporating the proposed tunnels and the solar PV system is as shown on Figure 1.3. The existing 330 kV substation will be expanded to accommodate power evacuation. The deep blue penstocks will be constructed to allow water to flow from the KGLPS dam to the KGUPS dam using the machines at KGUPS.

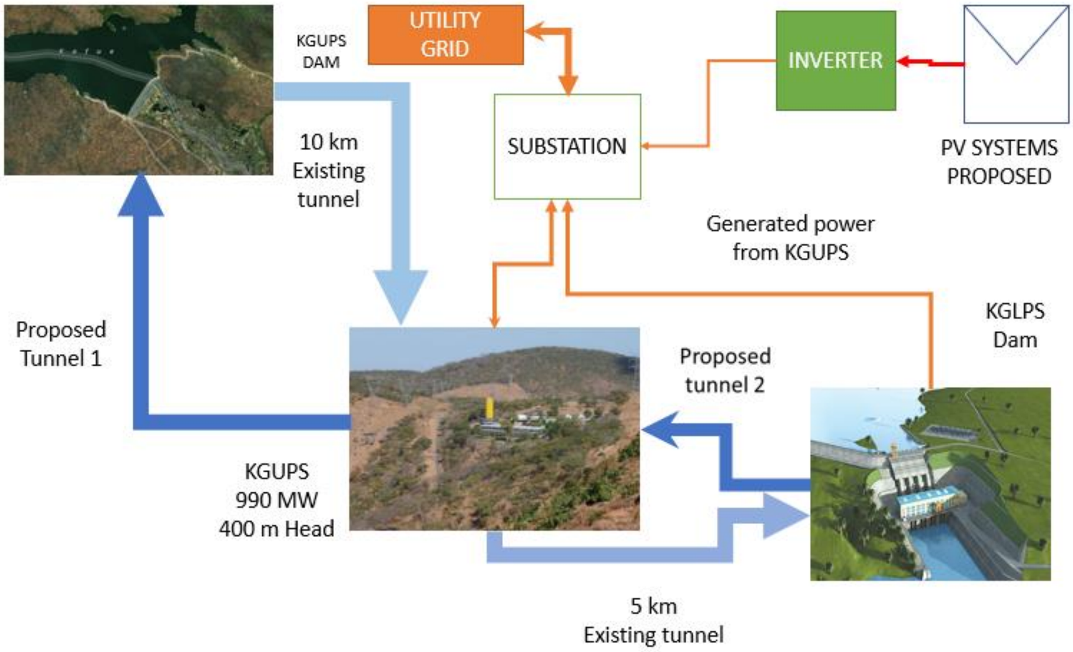

Figure 1.3 Existing and proposed system layout

The scheme is proposed to work in such way that, during the period of enough solar, the power plant will work either in the pumping mode or reduced generation from the generators to allow power from solar into the grid and in this way, water will be conserved to be used later. This cycle repeats itself in accordance with the chosen operation strategy. In most cases, the power plant runs in generation mode during peak periods of electricity demand. During these peaks, electricity prices on the market are generally high and as such the huge investment cost associated with PHES is mitigated and the net payback period on investment is reduced considerably. In this project, the implementation of the PHES for Kafue Gorge lower power plant will help to cushion the impact of having huge penetration of renewables in the Zambian electricity grid and be able to mitigate carbon dioxide emissions from the heavy fuel oil plant in Ndola and Maamba coal fired plant in southern province of Zambia.

1.3 Aims

The major aims of the project are the following:

1.3.1 To design the pumping scheme, sizing the load of pumps to be supported by PV and grid

In pumped storage systems the pumps play a major role in determining the efficiency of the scheme. In this project, the pumping scheme will be clearly defined and sized such that it becomes technologically viable to implement the project.

1.3.2 To carry out the sizing of the water storage dams and autonomy days in which the store can support the load in case of severe black outs

The dams that are existing i.e. KGUPS dam and KGLPS dam should be utilised for this project but however, a clear sizing in terms of water storage and autonomy days is one of the objectives of this project. As it is stated during the introduction stage, the pumped storage should be able to respond to fluctuations in terms of power demand and supply in the electricity grid.

1.3.3 To carry out the economic analysis model of the system, PV and hydro schemes

The parametric study of the PV system and the pumping power needed will be analysed in terms of costs and benefits and the results will be used to calculate the cost of investing in such a project and a comparison to other storage technologies will be done.

1.3.4 Propose a detailed operation scheme for the system

The operation scheme of the system is very important in this project and a such a detailed operation scheme will be provided in this report. As a matter of fact, solar power systems are not dispatchable and the load profile of the system will be clearly defined so that losses are minimised to a larger extent. Most of the solar production normally occurs during the afternoon peak and the non-peak periods and as such a scheme to carry out load matching with generation will be established in this project. The aims above are a benchmark for this project, renewable energy technologies penetration in Zambia will be increased if the above aims are realised in that most projects are commercial in nature and the utility grid can be able to profit from the benefits which comes with investing in renewable energy projects which will be discussed later in this project.

Pumped hydroelectric systems (PHES) design in this context will be used to accommodate solar power systems which have faced various challenges in penetrating the already congested electricity grid. The major challenge facing most electrical grids is that, renewables are mostly being injected into the grid system on the distribution network. However, most of the transformers in the distribution systems are already overloaded. This project will try to enhance the penetration of renewables in the Zambian electricity mix by incorporating PHES system at the KGUPS and KGLPS.

1.4 Method

In order to carry out this work, some of the tools that are utilized include, PVSyst, Homer Energy and Digi silent Power factory. In this chapter, these systems are explained in detail including the limitations encountered. Therefore, it is very important to outline the setup of the pumping system strategy. The sections following discusses the strategy behind the pumping scheme, the system description, the available resources of energy needed for the scheme to function which include water energy and solar energy resource. The site chosen for the erection of the project is also discussed in relation to project suitability and the impact the project will bring on the social economic and environmental aspect.

On the other hand, this project falls under the sustainable energy development goals in the sense that, the feasibility studies that where undertaken for the development of the KGLPS still applies. The details of some of the studies that where done will also be discussed in this report.

1.4.1 Hydro pumping system design strategy and working principle

This strategy works by employing two separate dams having different elevations. The Kafue Gorge Upper dam (KGUPS) has an effective head of 400 meters and that of Kafue gorge lower dam (KGLP) is 5 kilometres from the tailrace of KGUPS, this difference in elevation is within the technical boundaries for pumped hydro systems. However, the physical horizontal distance between the KGUPS dam and the KGLPS dam is less 20 kilometres, utilizing this distance by building penstocks to connect the two dams will be the only costly item unlike building another storage dam. In this project, I am proposing to construct a new penstock between the KGLPS and the KGUPS all the way to the KGUPS dam. The overall head should be 400 meters maximum and the horizontal distance should be within the acceptable range to avoid losses. This will reduce the effective pipe head losses and reduce the overall electricity energy needed to drive the turbine in the pumping mode.

The working principle of the pumping system is such that water will be pumped from the KGLPS dam (the dam located 15 km from the main KGUPS) to the KGUPS dam. The machines at KGUPS will be redesigned to accommodate the working either in generating/motoring mode and turbine/pumping mode.

1.4.2 System design in Homer energy software

The design of the scheme will be accomplished using the software HOMER PRO v3.12.4 [3] energy systems and PVSyst v6.7.8 software. Homer energy software will be the core for performing optimization of the scheme and the least cost project will be recommended for the undertaking. PVSyst software is used to carry out the simulation of the optimised PV system and its output compared with Homer. The load profile for KGUPS will be inputted in homer energy software and the Kafue river annual water flow profile will be used as in input for the project. PVSyst software will be used to design a grid connected PV system. The size of the system will be incremental from 50 MW to 300 MW. The target by the Zambian government is to increase solar capacity to over 1000 MW by the year 2030 [2]. Homer pro software will be used to carry out the dynamic study of the system with the addition of PV system in order to determine the generation output from both the solar PV power plant and the hydro station. Different scenarios will be compared to the base case, the base case will be a system without storage and the project case is that with pumped storage facility. The layout of the system in Homer software will be as shown below on Figure 1.4.

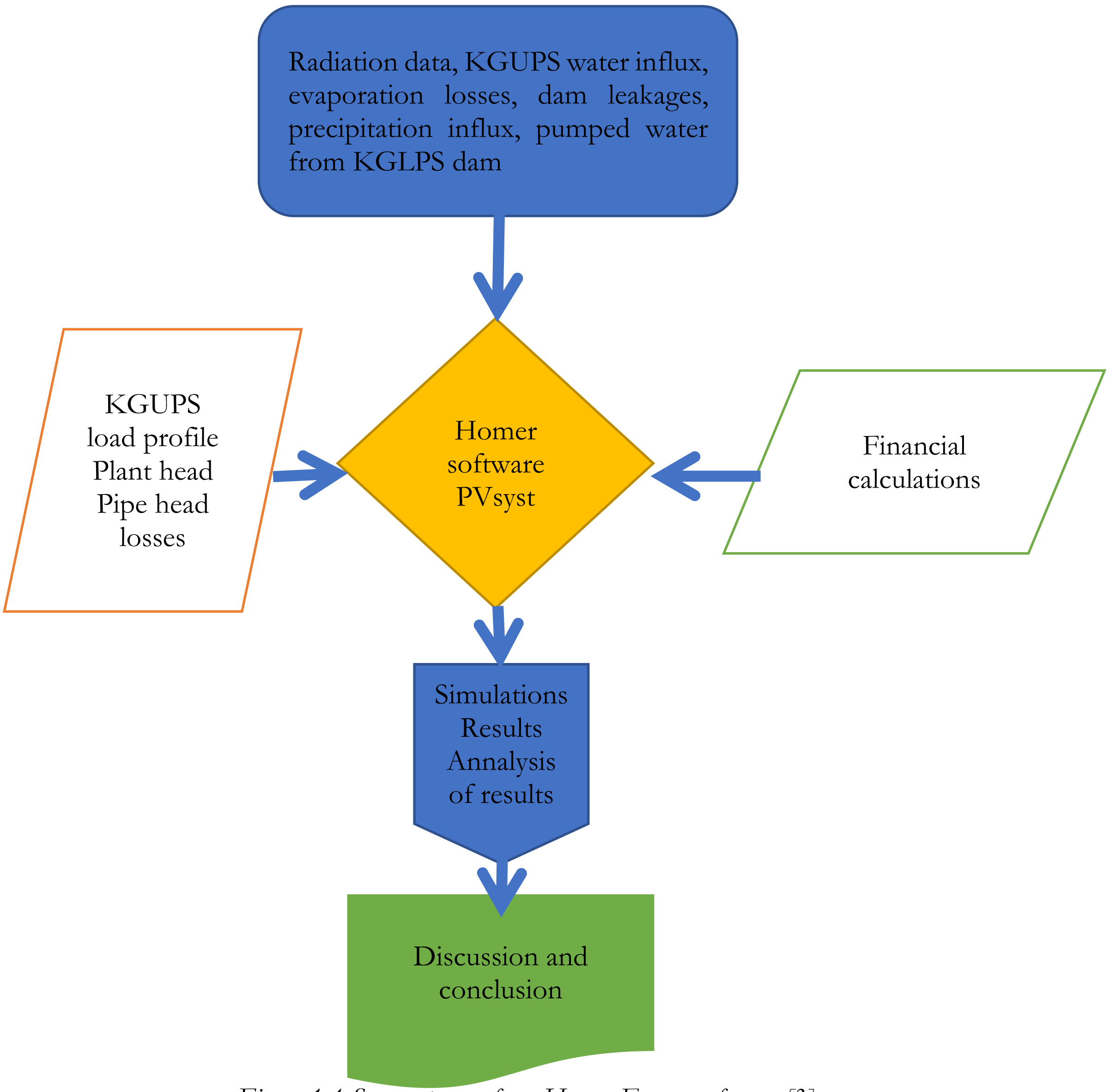

Figure 1.4 System layout from Homer Energy software [3]

From Figure 1.4 above, the hydro power station for Kafue gorge upper will be used with some of the machines operating in generation and pumping modes depending on the available load at the time. The loadings of the system will be represented by the industrial loads and commercial loads as input values in Homer. Th values of the loads will be extracted from the generation figures for the power plant from the 2012 to the year 2018. The converter in this case is the inverter which will be operated as a grid tied equipment. The grid voltage and frequency will be treated as the reference to ease in synchronization. The storage facility in homer software is modelled as a battery with the following characteristics for a single battery, nominal voltage of 240 V, capacity 1 059 Ah and maximum charging current of 91.6 A and discharge current of 91.6 A. This can be configured in any model and connected into several strings depending on the size of the storage capacity.

1.4.3 Scheme configuration for the KGLPS Hydro/ solar project

The key parameters needed for the scheme include dams as stated above, the head of the two dams, the flow rate, the power output and the autonomy days needed for the scheme. This section outlines the method used to alive at these parameters that are useful for the design of the pumping scheme. The power output of the pumping scheme is given by the formula on Equation 1.1,

$$P = \gamma \cdot u \cdot H_u \cdot \eta$$ *Equation 1.1*

The overall efficiency constitutes the efficiency of the turbine and the generator. The parameters being used in this project originated from the onsite data collection and the feasibility study that was undertaken by the international finance corporation of the world bank group [4] on the Kafue gorge lower project. These key components are as outlined in Table 1.1 below.

Table 1.1 Kafue river storage dams configuration

Station	Installed Capacity (MW)	Dam storage volume (M m^3)	Effective head (m)	Overall efficiency
KFGU	990	785	400	91
KFGL	750	80	200	88
ITT	120	6 008		88

Legend: MW – Megawatt, M m^3 – million cubic meters

The inflows to the KGUPS power plant are regulated by the ITT Dam which is located 220 kilometres away from the KGU dam. The other key parameter that need to be taken note is the overall loss due to horizontal distance from the main KGUPS dam to the KGL dam, the overall horizontal distance is 16 kilometres. This however is one of the uncertainties on the viability of the project. The proposed penstock diameter to connect the two dams is 4 meters. To calculate the losses needed, the formula on Equation 1.2 is utilized, the losses calculated under this equation are what is referred to as pipe head losses. This value is calculated as a percentage and is depicted by Equation 1.2.

$$f_h = 100 \cdot \frac{H_l}{H_u}$$ *Equation 1.2*

Where, f_h: is the overall pipe head loss
H_l: is the loss in circular pipe in accordance with the Darcy- Welsbach equation outlined below on Equation 1.3.

$$H_l = f \cdot \left(\frac{L}{D}\right) \cdot \left(\frac{V^2}{2g}\right)$$ *Equation 1.3*

Where,
f: is the friction factor, L is the length of the pipe, D is the pipe diameter, V is the flow velocity and g is the acceleration due to gravity. The Reynolds number is given by Equation 1.4.

$$R_e = \frac{\rho \cdot V_D}{\mu}$$ *Equation 1.4*

These equations are being used in this project to carry out the calculations for the pipe head losses. These parameters will be an input to Homer software and simulations will be done on given scenarios in relation to hydro power capacity in the generating mode, pumping mode and the variable energy resource from the solar power plant.

1.4.4 Location of the solar PV plants

The location of the solar PV power plant should be within 10 kilometres from the main KGLPS substation. The solar PV system modelling will depend on the size on the scenario chosen and this will be discussed under the discussion and results section. The location chosen has the available solar irradiation as shown below on Figure 1.5.

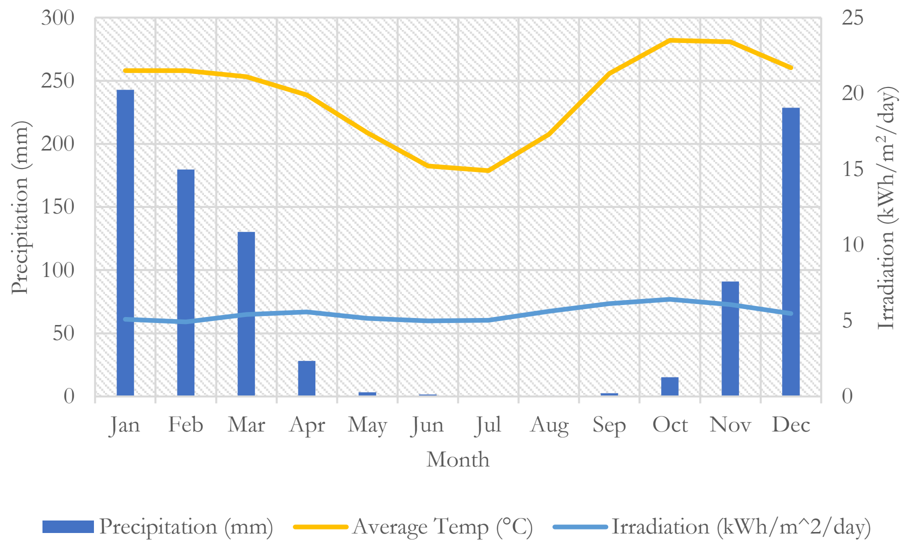

Figure 1.5 Yearly irradiation and precipitation for KGLPS [5]

From Figure 1.5 above, it is seen that the average annual irradiation is 5.5 kWh/day for the period 2000 to the year 2018 [5]. The site has the geographic coordinates of -15.4 degrees latitude, 28.5 degrees longitude and an elevation of 1154 meters above sea level. These conditions and the available solar resource are enough for electricity production using solar energy. The peak irradiation occurs during the month of October at 6.5 kWh/day. Precipitation on the other hand is very variable and of late the country has received very less rainfall due to climate change [5]. Peak precipitation is normally supposed to be in January at 250 mm, but the climate pattern has shifted such that, the average precipitation has reduced significantly. This reduced precipitation has an adverse effect on the electricity production from hydro power plants. In accordance with the IFA report [5], the projected annual rainfall for Zambia is as stated on Figure 1.6. The maximum rainfall occurs in the months January and February and the minimum is recorded in October and April. The solar irradiation however is almost linear with maximum in October and lowest in June. The available solar resource is ideal for electrical production using photovoltaic cells. And the fact that the peak solar resource is in the period when precipitation is almost zero.

Figure 1.6 Estimated annual rainfall for Zambia [5]

From Figure 1.6, the annual rainfall is expected to reduce considerably in the year 2022 and this will have significance impart on the electricity production in Zambia. This is like the drought situation that was experienced during the year 2012 to the late 2016. This drought leads to the loss of jobs and the shutting down of some copper mines in Zambia [6].

1.4.5 Sustainable energy development application to KGLPS

The application of sustainable energy development goals forms a great benchmark in this project in that the development of this project should not affect the future generations and aquatic life which includes flora. Meaning that the natural state of the Kafue river should be preserved and the local people that depend on the river be well taken care off. A review of the feasibility studies that where undertaken before the development of the KFGL power station shows that the area in question has not been utilized for farming as it falls in the mountainous area called the Kafue escarpments.

The existing structures of the KGUPS and the KGLPS will remain unchanged, the construction of the dam on the tailrace of the KGLPS will not impact any inhabitants as the inhabitants where already evacuated during the construction of the KFGPS and the KGLPS. These inhabitants where mainly camping from this area only during the times of fishing and it was mainly illegal fishing. The 25 families where compensated in accordance with the regulations which applied at that time. The villages where some of them originated from where also upgraded with decent housing, schools, access roads and provision of clean water which this area lacked at the time before the development of the KGLPS.

The next sections following discusses the previous works within the area of hydro pumping schemes. The significance of this scheme mainly is that the intermittence nature of renewables is compensated by the application of energy storage facilities like hydro pumping schemes.

1.5 Previous work

The global energy demand has increased in recent years although the world is shifting towards low carbon emitting energy sources like wind and solar. Climate change and the increased cost of depleting fossil fuels has made many sectors to invest in renewable energy technologies. In this section, a review of the studies undertaken in the implementation of PHES and solar PV power plants is reviewed.

1.5.1 History of pumped hydro power stations (PHES)

The development of PHES is a mature technology ranging from the early 19th century as outlined by E. Barnes, Frank S., and Jonah G. Levine [7]. This technology was somewhat abandoned after some time due to its high initial capital investments. PHES are very site specific in that a need for a considerable head is needed and the flow of water in the river should not be disturbed in order to support agricultural needs, aquatic life and preserving the natural outlook of the environment. Some of the sites are within what is termed as the UNESCO heritage sites like the Victoria falls power station in Zambia [8]. The setup of the PHES is like a conventional hydro power station except the PHES has the capability to draw electricity from the system and use it again to pump up water from the lower reservoir to the upper reservoir. The configuration of these systems where mainly applied to smaller systems.

The first stations where built mainly on run off the river systems which had seasonal precipitation and to avoid prolonged power outages in some sections of the power system, it was vital that some of the energy was recycled back. PHES uses the principle of energy conversion, which states that energy can never be stored but be transformed from one form to the other. In this case, hydraulic energy in water is converted to potential energy in the upper storage dam. Using the difference in height (head) between the upper dam and the mechanical turbine, potential energy is converted to kinetic energy in the water, the turbine converts the kinetic energy in the water into mechanical and rotational energy. The mechanical turbine is connected to the same shaft as the generator. The rotational energy causes the generator to rotate at a considerable speed called synchronous speed [9]. When the machine has reached synchronous speed, an external DC source of power is fed to the excitation systems [9]. When the electric generator is fully excited, an electromagnetic field (EMF) is induced. The EMF generates a voltage and the flow of current is generated when the generator is connected to an electrical load. Creating a balance between supply and demand is very critical in this kind of power system. This means that, the electricity generated should be able to match with the available load. Load matching control schemes determines the stability of the electric power systems. The control schemes start from the local generating station with a control function known as primary control. The speed governor mainly handles primary control of the individual generator. In the case where several machines are synchronized together an advanced control and monitoring scheme [10] is implemented which uses programmable logic controllers, the internet of things, communication protocols like fibre optics, switches and routers, servers, GPS systems, weather stations, protection relays and transducers. These facilities are integrated into one common scheme called the supervisory and data acquisition (SCADA) systems according to J. D. Markovic-Petrovic and M. D. Stojanovic [10].

According to Steffen B et al [11], the development of pumped storage facilities has evolved once again in the Germain energy generation mix simply because of the large share of renewables. These renewables which include wind and solar are intermittent in nature and the need for storage is very important. On the other hand, Norway which contributes almost 50 % of hydro power in the Nordic region has invested in the design and implementation of bulk energy storage facilities due to the intermittent nature of the solar and wind energy in the area as pointed out by F. Geth, T. Brijs, J. Kathan, J. Driesen, and R. Belmans [12]. This sudden shift in the generation mix towards the reduction of carbon dioxide emissions has made it possible to incorporate the renewables. The price of fossil fuels is on the increase and other diminishing products that need quick replacement with long term solutions [13]. The Table below shows the world installed capacity of pumped storage facilities.

Table 1.2 World installed capacity of PHPS [14]

Location	Installed Capacity (MW)
Africa	3 376
East Asia and Pacific	66 454
Europe	51 679
North and Central America	22 986
South and central Asia	7 541
South America	1 004
World total	**153 040**

From Table 1.2 the total world installed capacity of PHES was 153 040 MW as of the year 2017. Most of the concentration is in China and Europe although Africa has the largest potential. In this regard, installing a pumping system for the Zambian electricity market will help to improve the efficiency of coal thermal plants and the heavy fuel stations which normally operates at lower efficiency during off peaks on which the price of electricity is low and saving the water to be used later when prices of electricity increases especially at peak hours of the day.

1.5.2 Current status of world PHES systems

In accordance with the international hydropower association (IHA) [15] report of 2018, there has been an increase of world installed capacity of hydro power technologies. By the end of the year 2017, 4 185 GW of hydropower was added and a total of 5.3 GW of pumped storage facilities where added worldwide. The increased hydropower capacity reduced the carbon dioxide emissions to the environment by 4 billion tones. East Asia and mainly China had the highest contribution to both hydro and pumped hydro capacity with an addition of 9.8 GW to the system, South America also increased its capacity by 4.1 GW and followed by South and Central Asia at 3.3 GW, Africa and central America also contributed 1.7 GW and 0.5 GW respectively [15]. The IHA report also cited pumped hydro facilities as the highest enabler of renewable energy technology penetrations like wind and solar power systems. The use of hydro power systems effectively manages the water resources and reduce floods, create employment for the local people, increase international relations, boost trade and infrastructure development in countries where facilities are installed. The tracking tool used by the IHA reports that over 75 GW of pumped storage facilities are under construction as of today.

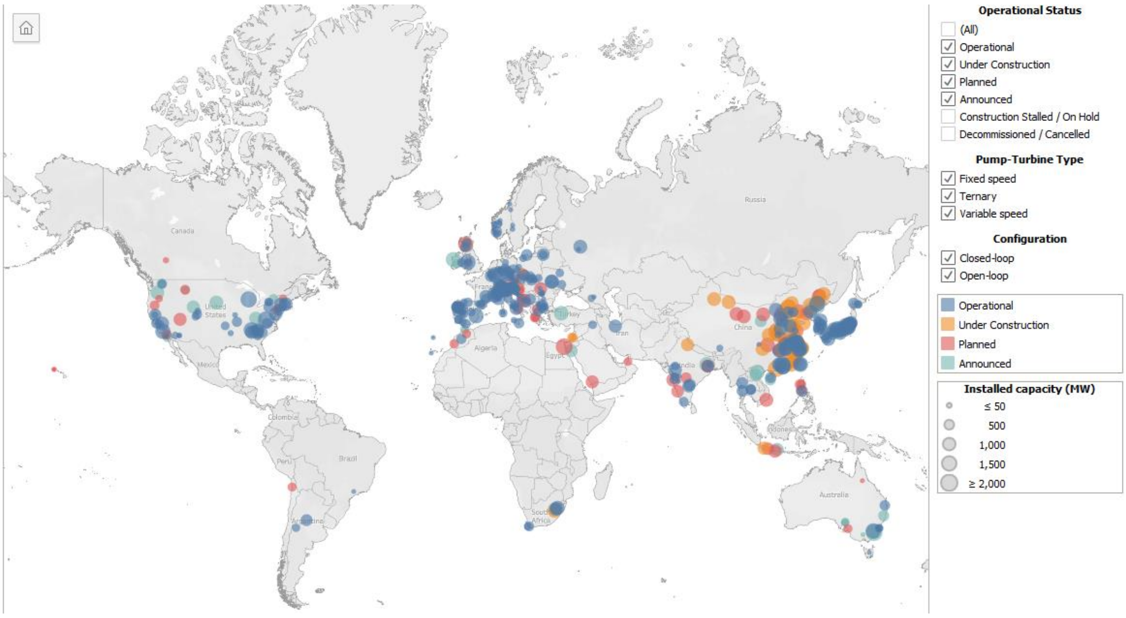

Figure 1.7 World installed and status of new pumped hydro systems [15]

Figure 1.7 shows the world installed pumped storage plants and the facilities which are under construction [15]. Larger systems of over 1000 MW in both pumping and generating mode exist in China. The perfect example of the system under construction is the Ataqa mountain of Egypt with installed capacity of 2400 MW at 330 m maximum head and scheduled for commisioning in the year 2024 in accordance with the world energy resource for hydro power [16] updates for the year 2019.

1.5.3 Future for PHES systems

PHES systems are the only know mature technology for bulk energy storage. Though there was a slow movement towards project implementation of pumped storage facilities, the dynamic shift globally towards renewable energy systems has stimulated interest in many stakeholders. The push towards 100 % carbon dioxide free renewables by the year 2050 has made it possible for the portion of large-scale pumped storage facilities [16].
The intermittency nature of renewables can only be compensated by pumped hydro facilities on the large scale. The long life and the ability to control the dispatchable power using hydro machines is the huge benefit for renewables integration. The IHA report of 2018 [15] also stated that, 58.8 % of descion makers interviewed according to the survey conducted are planning to increase the installed capacity of hydro and hydro pumped storage facilities in the next three years. This meant that, the future for hydro power systems is very bright.

1.5.4 Types of PHES

Four types of PHPS exist which include off-stream, pump back, diversion type and sea water [16]. The off-stream type mainly can have a multipurpose dam and a common connecting tunnel between the upper and the lower dams. Diversion systems are the most common like the case of this project where the water is diverted from the Kafue river to the power station and back again to the main river. Sea water are not so much common as they depend on the location as in the case of Okinawa in Japan. The investment cost of these pumping stations is site specific with an estimated levilised cost of energy (LCOE) in the range 500- 1000 $/kWh for bulk energy storage. However, regardless of the system configuration only two types of PHES systems exists and these are closed, and open systems as outlined by N. Osamu, H. Mikisuke, T. Kiyohito, and O. Dr. Eng. Takashi [17].

1.5.5 Open loop systems

Open loop systems obtain the water from ground surface water bodies like rivers, oceans and lakes. These water masses are linked to the powerhouse where generators and pumps are housed, from the powerhouse, water is channelled to the lower dam through concrete penstocks and tunnels. The lower dam is also an open surface water storage facility which is connected to the upper dam using either steel pipes or concrete pipes for providing the pumping action using separate pumps and, in some cases, reversible machines [17], the case for Takami power station in Japan, 200 MW, 104 m maximum head with 1.91 GWh of storage capacity.

1.5.6 Closed loop systems

These systems utilize the water bodies that are not continuously tied to the ground surface water like dams and rivers. They have a mix of both underground water facilities and the open surface waters. An example is the Drakensberg pumped hydro plant in South Africa which was commissioned in 1981 [17] with an installed capacity of 1200 MW in generation and 1200 MW in pumping mode, this plant has a net head of 480 m with an estimated capacity of 33.1 GWh.

1.5.7 Benchmark for PHES machines

Since the inception of pumped storage facilities, two key issues which where arrived at are the use of the pump/generator strategy. The many of the traditional hydro power stations with pumped storage facilities 270 [15], utilizes a mix of the single speed and the variable machines. In this section an understanding of the behaviour of these machines with reference to the penetration of renewable energy technologies is considered. The operation of traditional machines is that they only operate at synchronous speed to maintain the system voltage and frequency. Mainly in generating mode, the power output is variable depending on the load at the given time. This action is accomplished by the machine regulation of the turbine speed, by adjusting the wicket gates to allow more water to move from either the upper reservoir or the river depending on the configuration of the scheme adopted. Single speed turbines have faced challenges with the penetration of renewable energy technologies like wind and solar in coping with the pumping mode strategy in accordance with a NHA report by M. Manwaring [13]. Single speed pumping schemes have the disadvantage that they are unable to provide fast response time [13] in the pumping mode. This is one key for decision makers to consider before implementing on a new project like the KGLPS.

With the world demand that the penetration of renewables should reach in the range 20-50 % by the year 2030 [15], manufacturers of electrical and mechanical machines have advanced the design of the traditional machines for hydro power generation schemes incorporating pumping modes. The design of what is tamed, adjustable speed pumped storage has revolutionalised hydro power engineering. The adjustable speed pumping methodology offers numerous advantages which includes, load matching, compatible to work with intermittence power from either wind or solar [16], this also contributes to the stabilization of the power system.

1.5.8 Configuration of single speed pumping scheme

Single speed pumping schemes have a one directional control of speed in either pumping or generating mode. This can be referred to as a two-quadrant of operation. In this method, the machine operating in generating mode receives only one instruction of controlling the wicket gates at synchronous speed only. The wicket gate opening allows water from the upper storage dam to rotate the turbine, this rotating motion of the mechanical turbine causes rotation of the generator. Once the machine is rotating, speed measurement device normally a tachometer picks the speed signal from the shaft and its value inputted in the electronic speed governing device. This speed signal is converted to frequency. In the same vein, the speed governor picks a signal from the system frequency i.e. of the utility grid. When the two frequencies are matching and the voltage which is regulated by the voltage regulator, the machine is synchronized to the system. In this case, the machine will continue to operate in this state of synchronism for as long as voltage and frequency stays within the acceptable ranges. When the system voltage and frequency become compromised by the system overload, line faults and transient faults that has as an effect on the dynamic stability of synchronous machines, speed governors, voltage regulators are able to respond accordingly unlike addition of renewable energy technologies which has the variable output depending on the conditions of the weather is the basis of this study. A parallel operation of solar PV systems with pumped hydro facility will not only provide energy storage but also provide system security and redundancy of power at any time of the day.

1.5.9 Adjustable speed pumping schemes

The invention of adjustable speed pumps has made it so easy to accommodate smart grids, flexible AC transmission systems and pumped storage facilities. The configuration of the adjustable speed mechanism as applied to a modified conventional electric synchronous machine is as shown on Figure 1.8.

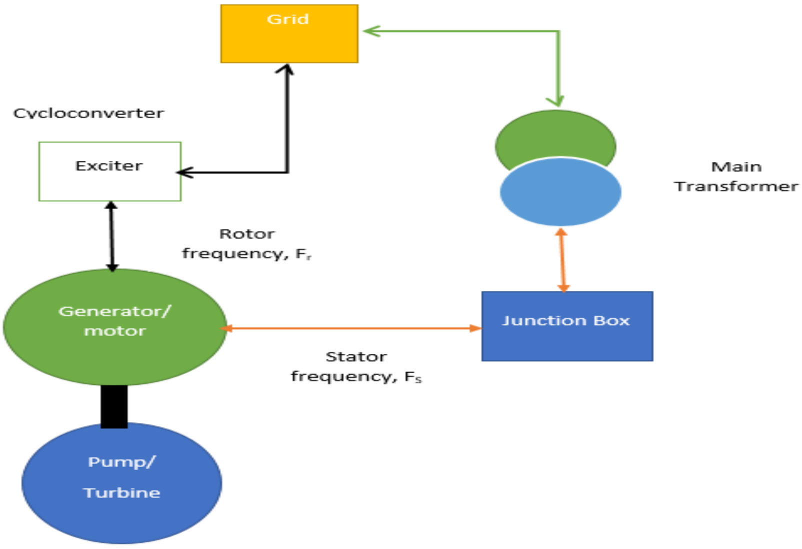

Figure 1.8 Double fed induction machine adjustable speed control [17]

The operation of this control mechanism on each of the machines working in both pumping and generating modes is such that, if the static frequency converters are used for smaller machines and larger units above 50 MW, a doubly fed induction machine is utilised. The frequency converter is mainly coupled to the rotor, in this case the magnetic field of the rotor is maintained within a certain range. This technology allows the machine to be operated at variable speed. This speed tolerance also known as slip frequency is in the range +/- 10 % of the synchronous speed. The speed of operation is adjusted electronically within the band and tolerances without compromising of grid frequency. Variable speed machines have key advantages amongst these include, possibility of power control in the turbine mode, wide range of operation in the frequency band, network stability by providing reactive power control and these machines supports high head variations [17]. The difference between a single fed induction machine and a doubly fed induction machine is that the magnetic field created by the in the rotor is not static as it is created using three phase alternating currents (AC) instead of direct currents (DC) and rotates at the speed $n_{\emptyset}$ rotor ,which is proportional to the frequency of the AC currents fed into the generator windings. I this case, the rotating magnetic field does not depend only on the generator rotation but also on the rotational effect created by the AC fed into the generator rotor windings [18].

1.5.10 Research studies on hydro/solar pumping systems

In accordance with the study that was done on the Lebanon electricity system by El-Jamal et al (2009), incorporating a solar photovoltaic system on the unstable system with pumped storage revealed a greater increase in the system availability and security of electricity supply to the customers [18]. The application of pumped storage was in the area with a potential drought and reduced water river inflows needed for electricity generation. The share of renewable energy was poised to increase together with the increase of hydro power development by creating some dams in certain rivers. The other thing of importance was that the demand for water is slowly increasing and the country could face serious power shortages if water economics is not handled in a conservative way. The writer proposed for the hybrid system of solar and hydro since this energy is carbon dioxide free, fast response times of hydro pumping stations and security of electrical supply in case of emergencies. In this study, the losses due to head pipe losses where no considered in the simulations. The study was purely theoretical in some way with key assumptions which could affect the performance of the hybrid system. Two useful quantities that are needed in the scheme where derived and these are pumping efficiency, expressed in m^3/kWh and generator efficiency expressed in kWh/m^3.

The conclusion from this study was that the cost of producing electricity was less than one US dollar (1$ kWh) [18] which was below the cost of purchasing power from the utility grid. Implementing this facility was going to reduce carbon dioxide emissions for the country.

The facility was proposed to be installed to near load centres to reduce the cost of transmitting power and reduce the losses in the network. The other notable issue is that, pumped storage facilities will enable the operation of thermal power plants at full capacity.
Another study was done by professor Wuuna Swe (2018) on the application of PHES for PV based rural electrification in the republic of Myanmar [19]. In his publication for the village of Myanmar, investing in the PHES was going to reduce the cost of electricity, increase the stability of the system, provide electricity even during night times and periods of variable solar power resource. The application of PV and PHES for the isolated system from the grid provide a robust storage that can provide power for a long period of time. On the other hand, he stated that PHES systems although they take land and become expensive at installation stage, the lifetime costs are cheaper than battery storage systems which has a short life span.

1.5.11 Sensitivity and uncertainty analysis

Throughout the study, the parameters that are considered are with three most significant figures and therefore, figures are rounded off to suit the sensitivity articulated. The hydro input for the stream flow was taken from the water usage at the KGUPS, this was done to eliminate inaccuracy of water due to evaporation, precipitation and wind speed. The input parameters for irradiation where downloaded from the internet (NASA satellite). Calculations done by Homer software are performed based on the stated inputs, an error may occur if ground measurement data was used for the site. However, this can be done in future studies on a similar topic and results can be compared in order to determine the percentage error. The water input to the KGUPS dam is extracted from the ITT dam that s situated 220 km from the KGUPS.

The calculations done in estimating the parameters for the head loss and penstock diameters can also be reviewed in future as they may carry a percentage of error. The financial analysis considered in this project may vary as well in a different context as the prices of commodities on the international market keeps on fluctuating. The prices of photovoltaic panels keep on dropping and new efficient modules which may affect the production of electricity will soon enter the market. Similarly, the project life may change from project to project. The PV plant has an estimated life of 30 years and the hydro power plant also has a maximum life span of 100 years; this however may change especially for critical equipment's in the power plant that need periodic replacement. The percentage error from the PV system results for the energy calculation is within 5 % [31] due to the software used Homer, PVsyst and PVGIS interactive tool. Similarly, the calculations for evaporation using the Pan method have an error in the range 2 – 10 % due to the variable temperatures over KGUPS dam and the amount of water leakages that have been neglected as part of the study. The financial performance for the PV system done also has an error due to the unstable value of exchange rate in Zambia which depends on the price of copper on the world market as Zambia is the major exporter of copper in Africa. The value of the local currency Kwacha has gone low against major currencies, trading at 12.6 ZMW per US $ as opposed to 9.6 per US$ in the past three - four months as seen from the Bank of Zambia daily reports [29].

2 Experiments, measurements, simulations, calculations

2.1 Calculations

The calculations in this project are carried out in relation to water management in the KGUPS dam. The overall dam capacity is 785 10^6 m^3 and from this volume, we can be able to calculate the number of autonomy days that are needed for the plant to operate at full capacity. Some of the equations that could be useful for this study are discussed below. One of the notable equations which also has been used in Homer software to calculate the autonomy days for the storage facility is,

$$E_s = N_{hour} \cdot \rho \cdot g \cdot h \cdot \frac{V}{3.6 \times 10^6 [\frac{J}{kWh}]}$$ *Equation 2.1*

Equation 2.1 is the expression for the stored energy in the upper dam which is the product of (ρ) density of water, (g) the acceleration due to gravity, (h) the power plant head and (V) the water volume and (N_{hour}) is the number of hours on which the dam can be able to store the water and keep the hydro power plant producing electricity. The other equation that is useful for the energy balance in the dam is Equation 2.2 on which losses due to leakages and evaporation from the study by Jamal et al (2009) were neglected but however only evaporation losses will be considered for this study. This is given by Equation 2.2 for the total amount of water stored in the upper dam. This equation is expressed as the available water in the upper reservoir ($Q_{UR}(t)$) at the given time which is the sum of the water from precipitation ($Q_p(t)$) and the difference of water lost from the dam used for power generation on the turbines (Q_t). The loss factor due to evaporation is depicted by α.

$$Q_{UR}(t) = (1 - \alpha)Q_{UR}(t - 1) + Q_p(t) - Q_t$$ *Equation 2.2*

2.1.1 Autonomy days

From Equation 2.1, the number of days that the storage dam can keep the plant at full capacity are calculated from the formula below,

$$N_{days} = \frac{\rho \cdot g \cdot h \cdot V}{E_{load} \cdot 3.6 \times 10^6 [\frac{J}{kWh}]}$$

The energy output of the power plant is variable as it depends on the flow rate into the main reservoir, a decrease in the inflow largely affect power production and subsequent revenue. The daily power production for KGUPS for the year 2012 is as shown in Figure 2.2. The year 2012 is considered as the base case in which the country received normal to above rainfall and 2016 is considered as the worst year in which the country received rainfall below normal [20]. From the 2012 generation figures, the daily average production was 18.6 GWh. Using Equation 2.1, the calculated number of autonomy days is 5 days. These five days are depended upon the water flow and the river level maintained at a certain amount to keep the machines running within the designed limits. The Francis turbines should be able to operate within the operating conditions specified by the manufacturer. In a case where the dam level falls to 50 % as stated by K. Adams et al [21] state of charge, the autonomy days reduce to 2.5 days. The equivalent flow rates and its associated generation is shown on Figure 2.1 for the year 2012 and 2016.

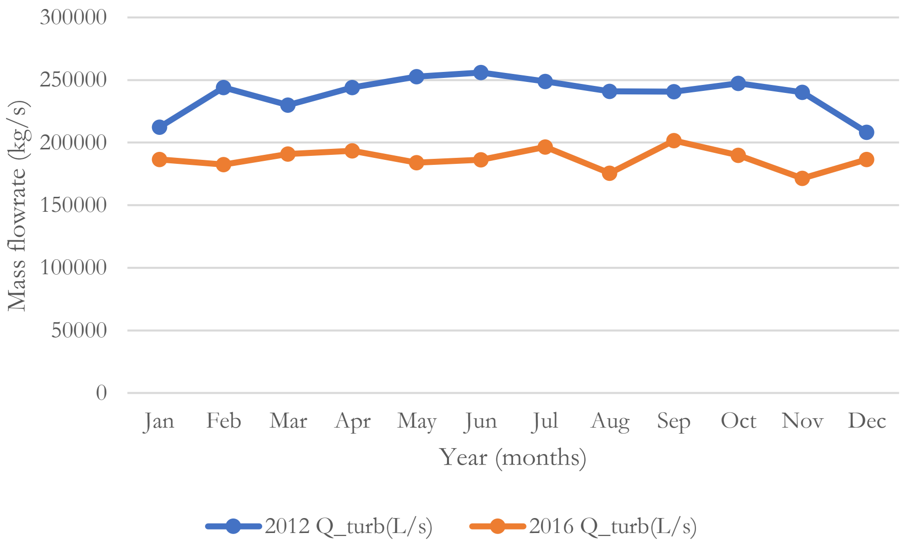

Figure 2.1 Volumetric mass flow rates for 2012

Figure 2.1, shows the generation figures expressed as water outflow from the KGUPS storage dam, it can be clearly seen that the peak production occurs in June when the water flow is at its peak, from June to December, production reduces due to the reduced inflow of water from the dam. On the other hand, the local rains contribute to the increase in production in the month of February and March (this is the rainy season). The dry period is from the month of August to December. In the later years, rains used to start in the late month of October and end in late April to May [22] but things have now changed due to the climate change. The performance of the power plant in the year 2016 in relation to generation figures and water usage is as shown on Figure 2.1 as well. The comparison of the year 2012 which was a good year and year 2016 in which the country received a drought is the basis for this study as this occurrence reduces the power production considerably.

2.1.2 Daily load profile for KGUPS

Figure 2.2 on the next page shows the load profile for the station. The peak demand is during the evening peak from 16:00 hours to 20:00 hours daily. In order to meet this demand, there is considerable need to have enough generation throughout the year. The increased demand for electricity not even during the evening peak has contributed to the embarkment of projects like the KGLPS and the scaling solar projects across the country. The power demand has continued to increase and, in most cases, to cover the peak energy demand is a challenge. The power grid gets constrained, frequency and voltage get compromised and to avoid system collapse, power generation, transmission and distribution systems are controlled by their respective national control and regional control centres. Figure 2.2 shows that on 15th June the peak load of 958 MW was reached at 19:00 hours and the average load was 860 MW. This day is selected as it is the day on which there is high demand for heating as the temperatures in Zambia drop down between 5 – 10 degrees.

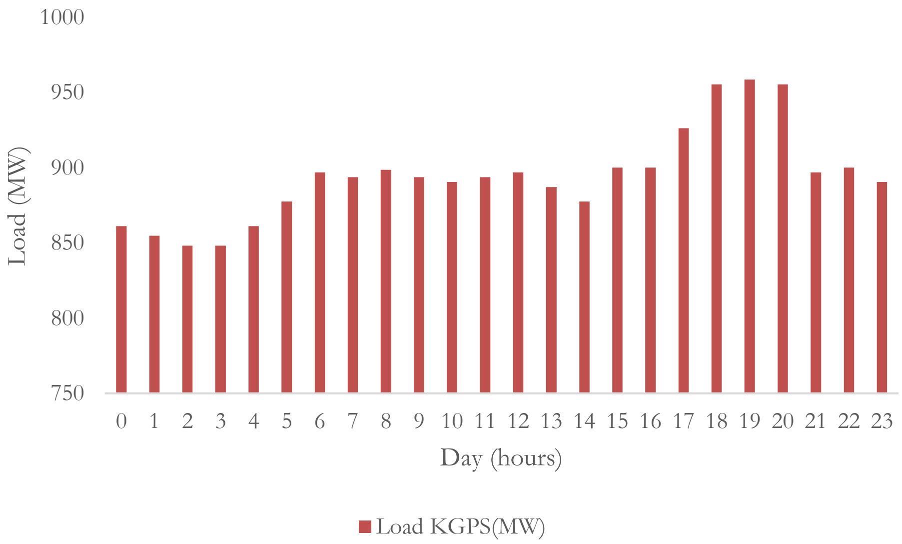

Figure 2.2 Daily average load profile on 15th June 2016 for KFGUPS

The load profile expressed in terms of volume flow rates is expressed in Table 2.1 in the appendix section. From Table 2.1, the monthly average flows represent the water usage from the KGUPS and ITT dam for power generation. Peak demand occurs in the month of June at 914 MW with the equivalent flow of 256 m^3. In accordance with the water release strategy, this coincides with the time on which the water reaches the KGUPS dam as it takes nearly 60 days for the water to move from ITT dam to KGUPS dam.

2.1.3 Factor of redundancy

In this design, the type of scheme proposed is the single machine to work in both generating and pumping mode. This system incorporates turbine/pump and generator/motor in one machine. Due to the increased need for energy storage to accommodate renewable energy technologies, many manufacturers have started migrating towards the design of this type of machines [21]. For the case of redundancy, the design should accommodate three machines to be upgraded from conventional generator/turbine to accommodate motor/pump configuration of the pumping station. The two machines can be used at any time in the pumping mode and the other one to be used as an emergency machine and can be switched in at any time depending on the demand and the conditions of the water influx into the KGUPS.

2.1.4 Water inflow in the KGUPS dam

The inflow of water into the dam is very variable which is controlled by the ITTPS dam located 220 kilometres from KGUPS dam and the contribution from precipitation from mainly Lusaka and southern provinces of Zambia. The other critical item is precipitation as it is seen from Figure 1.5. The operation scheme of the ITT dam is such that the flow rate of water is constant at 180 m^3 throughout the year. This is to maintain the design flow rate for the six machines at KGUPS to 276 m^3. In accordance with the water release clause [24], the months October, November and December, only 100 m^3 of water is released from the dam and the expected time at which the water reaches the KGUPS dam is 60 days [24]. In January when the country receives rains, 250 m^3 is released and the peak release occurs in February at 350 m^3. The release clause enables regulation of water outflow from the ITT dam, reduces the risk of flooding the Kafue flats and damage to agricultural land. However, due to the increased farming (mazabuka sugar estate), population in urban areas Lusaka, Kafue town, Ithezhi-Thezi town, Namwala and other surrounding areas, water abstraction from the river has increased. This increase in water abstraction has reduced water influx into the KGUPS dam and has contributed to reduced electrical power production [24].

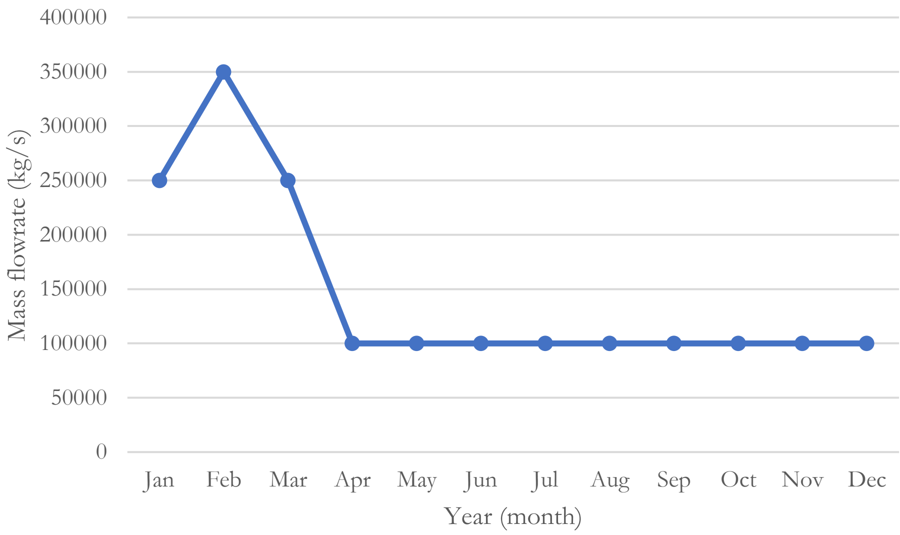

Figure 2.3 KGUPS dam water inflow from ITTPS dam [23]

The total water inlet to the dam is given by the formula in Equation 2.3, the evaporation losses are treated separately in 2.1.6, leakage losses are outside the scope of the study and in this case the total amount of water in the storage dam will be defined as from the Equation 2.3,

$$Q_{UR} = Q_{river} + Q_{preci} + Q_{pump} - Q_{eva} - Q_{turbine} \qquad \textit{Equation 2.3}$$

From Equation 2.3, different scenarios towards water management will be tabulated on the table for analysis. Water management will be compared in the base case and the facility incorporating a pumping scheme. The pumping scheme configuration will also be variable according to the system demand. The energy needed to drive the machine in the pumping mode will most of it come from the solar PV system which will be designed in the next sub chapter of the project. In this study, the base case includes the year 2012 and 2016.

2.1.5 Influence on precipitation

In this study, the contribution to precipitation is not very accurate as only contribution of rainwater from the surrounding areas in Lusaka province is considered to give an absolute value of contribution to precipitation. This value will also be affected by soil porosity, other dams and storages in Lusaka that does not contribute to the addition of water into the Kafue river. This contribution however is outside the scope of this work. The average precipitation per year for Lusaka province is 831 mm. Assuming this rainfall was going to the storage dam, a total of 831 litres per square meter is collected. The total area for Lusaka is 21 896 square kilometres. The total volume of water received would be 8.342 10^9 m^3. However only less than 30 % [25] of this water goes to the river, the annual contribution will be 2.502 10^9 m^3. In order to find the daily contribution to precipitation on the river flows, the figure below shows the rainy days per month for the year 2012 and 2016. Figure 2.4, it is clearly seen that year 2016 did not receive any rains in the months May, October and November. This year had maximum 12 days of rain in February and only two days of rains in April. On the other hand, the year 2012 had a maximum of 17 days of rain in January and it rained throughout the rainy months with a minimum of one day in May [25].

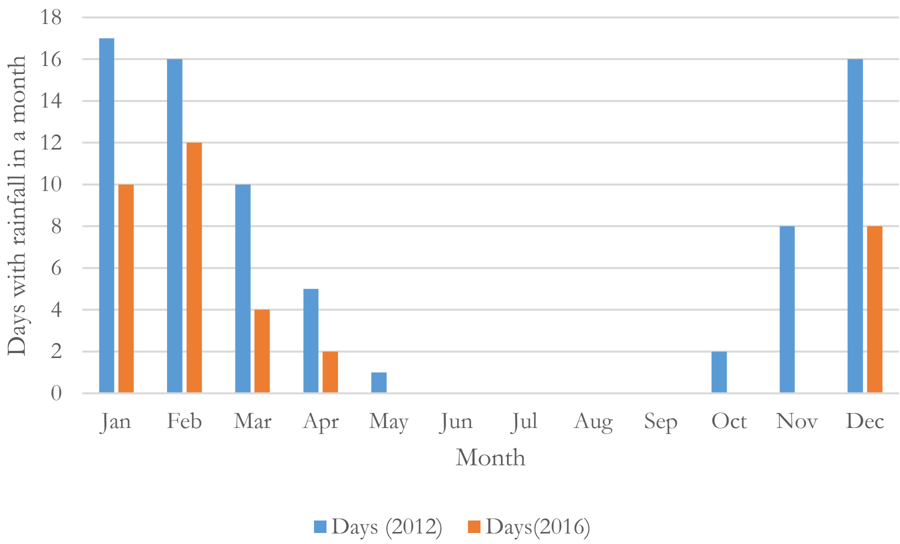

Figure 2.4 Days with precipitation for Lusaka province 2012 and 2016 [25]

The average rainfall per day is 2.8 10^6 m^3. Therefore, the estimated rainfall for Lusaka province going into the Kafue river is as shown on Figure 2.5.

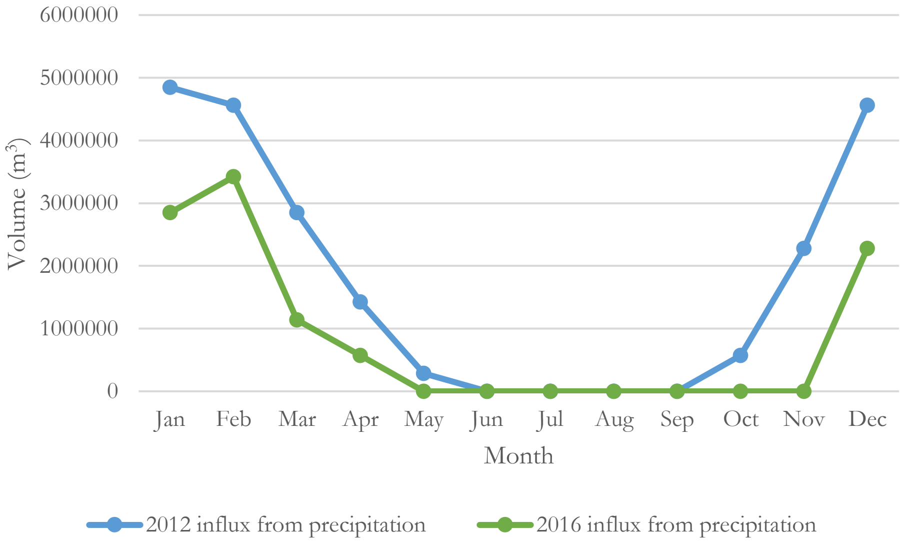

Figure 2.5 Volume of rainy water to KFGUPS dam for 2012 and 2016

From these values, the average daily flow rate from the contribution of rainwater in the surrounding areas to the storage dam for the rainy seasons is calculated. Equation 2.4 is used to calculate the volume flowrate at this instance.

$$u = \frac{V[m^3]}{t[s]}$$ *Equation 2.4*

Where, u is the volumetric flowrate and $\dot{V}$ is the mass flowrate
This value when converted to the equivalent mass flow rate using it becomes,

$$\dot{V} = u \cdot \rho$$ *Equation 2.5*

The calculated mass flowrate is 3300 l/s when converted to litters. On calculating the total inflows into to the KGUPS, the formula used is that from Equation 2.3
The comparison on the water inflow and outflow from the KGUPS dam is shown in Figure 2.6.

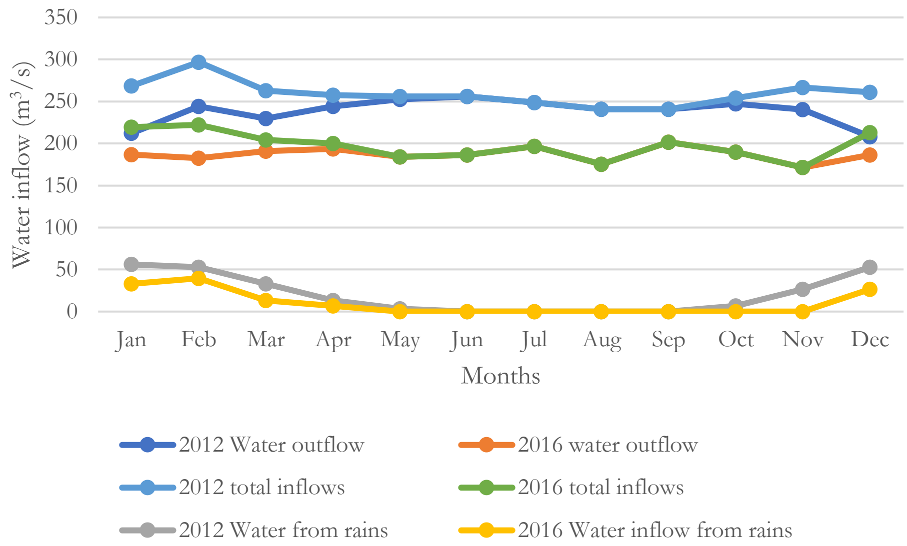

Figure 2.6 Water outflow and inflows into the KGUPS dam for 2012 and 2016

2.1.6 Influence on evaporation

Many methods of determining evaporation exist in theory, in this project the class A pan method is used. The analysis of the pan method is established by the energy budget method which is a combination of factors that determines the rate of evaporation on the water body [25]. The factors that influence evaporation include,

- The vapour pressure at the surface and above the surface of the water body
- The type of pan environment in which the water body exist
- The wind speed for the specific site
- The quantity of the atmospheric pressure
- The exchange of heat between the pan and the ground
- Distribution of the solar irradiation on the surface
- The quality of water on which the site is selected
- The air and water temperature and lastly the size of the water body

The rate of evaporation that is measured on the surface normally is collected from a weather station for a site. In this project, the weather data was collected form the SP (The meteorological station at Kafue polder) which is near the KGUPS [26]. In theory, the rate of evaporation is given by the pan method using Equation 2.6,

$$E = E_{pan} \cdot K_{pan} \qquad \text{Equation 2.6}$$

The pan method is accomplished by using the energy budget method which is expressed by Equation 2.7.

$$R_n = L_v \cdot E + H + G \qquad \text{Equation 2.7}$$

By neglecting G in Equation 2.7, evaporation is expressed as

$$E = \frac{R_n - H}{L_v}$$

The latent flux ($L_v \cdot E$), is calculated by using equation as shown below on Equation 2.8,

$$L_v \cdot E = \frac{L_v \cdot K_E \cdot M_w}{R \cdot T_a}[P_{vs} \cdot T_s - P_v \cdot T_a]$$ *Equation 2.8*

$$P_{vs} = exp\left[25.5058 - \frac{5204.9}{T}\right]$$

Using these equations and the data retrieved from the weather station from 2009 to 2018 [25], the average evaporation with the factors which affect its value are summarised on the Table 2.2 in appendix section. In Table 2.2, the value of evaporation that was collected from the weather station was converted to the equivalent mass flow rate denoted by Q_{eva} which was calculated using the formula from Equation 2.9,

$$Q_{eva} = \frac{\rho \cdot A_s \cdot E}{t_s}$$ *Equation 2.9*

From Table 2.2 on appendix one, Q_{eva} is the calculated value of evaporation mass flow rate from the KGUPS dam or the quantity of water that is lost during each month, the highest evaporation rate is October at 53763 kg/s and the minimum is in February at 26455 kg/s as expressed on Figure 2.7 Evaporation rate for KGUPS dam calculated for the year 2018.

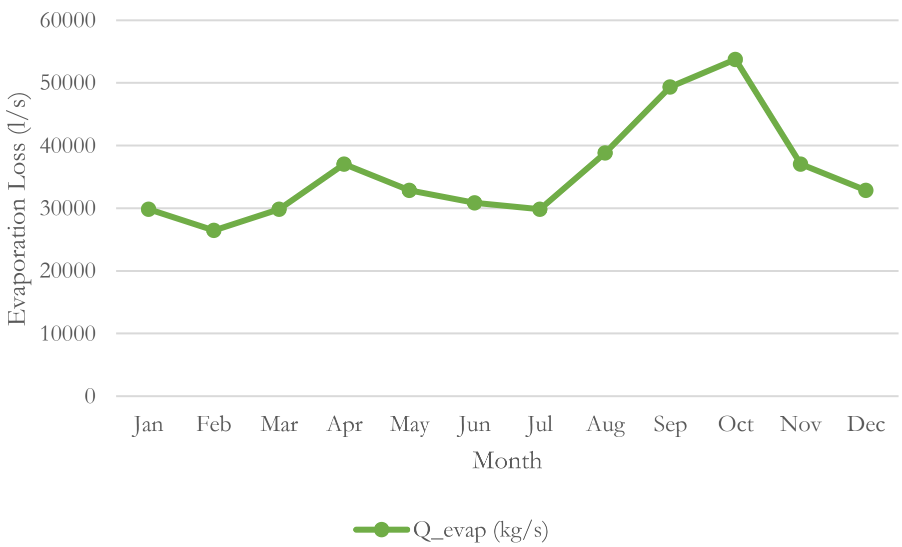

Figure 2.7 Evaporation rate for KGUPS dam calculated for the year 2018

Figure 2.7 shows the rate of evaporation for KGUPS dam, which is very variable as it depends on irradiation, wind velocity, temperature of the surface water and air above the dam. Evaporation also depend on humidity and size of the dam.

Table 2.3 in appendix shows the water utilization for the year 2012 at KGUPS, in accordance with the water release regulations for operating the Ithezi Thezhi dam, water takes two months for it to arrive at KGUPS. The available water was able to meet the load without any support from the grid.

Table 2.4 in appendix also shows the water utilisation for KGPS during the year 2016. The water release from the ITT dam is same as the year 2012 although there was less water being utilised to generate electricity due to the less precipitation throughout the year. A comparison of the flow rates from the appendix Table 2.3 and Table 2.4 is summarised on Table 2.5.

Comparing the water utilization for the year 2012 and 2016 as shown in Table 2.6 appendix, the peak shortage occurred in the month of June. The average monthly shortfall in water usage converted to its equivalent power is amounting to 147 MW. Therefore, if an alternative power source and in this study, the contribution from solar power can be able to reduce this deficit to meet the average load of 18.6 GWh.

2.1.7 Pumping power

For the design of the system to be complete, the pumping power of the pumping system need to be realized. In this study, considering that the ratings of each of the generators at Kafue gorge is as shown below on the Table 2.1

Table 2.1 KGUPS Machine specifications

Parameter	Quantity	Units
Rated capacity	165	MW
Effective head	400	m
Designed flowrate	46000	kg/s
Rated speed	375	rpm
Rated frequency	50	Hz
Number of units	6	

To calculate the pumping power, firstly we need to calculate the losses that can be resulted from the pipe head losses, as it said in chapter one, the horizontal distance between KGUPS dam and the KGLPS dam is 15 000 meters. Assuming a tunnel of diameter 4 meters is constructed between the two dams, the losses are given by the formula as stated in Equation 1.2 and Equation 1.3 respectively [20]. In order to calculate the pipe head losses, the Reynolds number considered and depicted by Equation 2.14 is in the order of 10^6. This is of the turbulence flow with the friction factor analysesd from the Churchill equation for fluid systems [20]. From these parameters, the pipe head losses for the penstocks is calculated from equation 1.4. Assuming circular pipe with diameter 4 meters as shown on Figure 2.8, the cross-section area calculated from Equation 2.10 is 12.7 m^2.

$$A = \frac{\pi \cdot D^2[m^2]}{4} \qquad \textit{Equation 2.10}$$

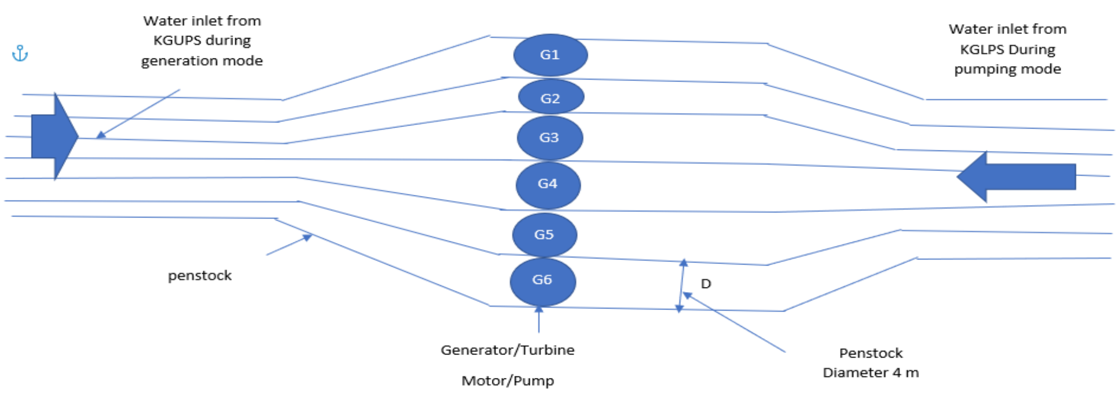

Figure 2.8 Schematic arrangement of penstocks and machines

Using this area, the volumetric water flow velocity during generation for each machine is 46 m^3/s. The equivalent velocity is calculated as from Equation 2.11 is 3.7 m/s.

$$V = \frac{Q\left[\frac{m^3}{s}\right]}{A[m^2]} \qquad \textit{Equation 2.11}$$

For each of the six machines the flow velocity will be 3.7 m/s and that using this velocity from equation 1.4, the total pipe head loss coefficient is

$$h_l = f_C \cdot \left(\frac{L}{D}\right) \cdot \left(\frac{V^2}{2g}\right)$$ *Equation 2.12*

The friction factor f_C, denoted by Equation 2.13

$$f_C = 8 \cdot \left[\left(\frac{8}{R_e}\right)^{12} + \frac{1}{(A+B)^{1.5}}\right]^{\frac{1}{12}}$$ *Equation 2.13*

Where,

$$A = \left[2.457\, ln\left(\frac{1}{\left(\frac{7}{R_e}\right)^{0.9} + 0.27\left(\frac{\varepsilon}{D}\right)}\right)\right]^{16}$$

R_e , is the Reynolds number, which has a range for laminar flow $R_e < 2100$, for intermediary regime, $2100 < R_e < 4000$ and turbulent regime has the Reynolds number $R_e > 4000$

The Reynolds number is calculated by using Equation 2.14,

$$R_e = \frac{D \cdot \vartheta \cdot \rho}{\mu}$$ *Equation 2.14*

From Equation 2.13,

$$B = \left(\frac{37530}{R_e}\right)^{16}$$

The summary of the calculated parameters is in Table 2.2

Table 2.2 Calculated parameters for the pipe head loss

Calculated variable	value	Units
ε	$3\ 10^{-4}$	m
A	$5.3\ 10^{22}$	m
B	$8.4\ 10^{-43}$	m
f_C	$1.1\ 10^{-2}$	m
F_h	27.3	m
h_l	6.8	%

The total pipe head loss can be calculated from

$F_h = 100 \cdot \frac{h_l}{H_u}$,

These loses are for the pipe diameter of 4 meters and these losses can reduce further by increasing the pipe diameter although this comes with an additional cost. Apart from the penstock only, other civil works involved are outside the scope of this study. The pumping energy is calculated from Equation 2.15,

$$E_{in,pump} = \frac{E_s}{\eta_p} \cdot 100\ \ [\%]$$ *Equation 2.15*

The pumped energy from the lower reservoir has another efficiency component that is define by Equation 2.16 [22],

$$E_{in,pump} = E_{in} \cdot \eta_{trans} \cdot \eta_{motor} \qquad \textit{Equation 2.16}$$

Before calculating these parameters, the stored energy from the upper reservoir is calculated from Equation 2.17

$$P_p = \frac{g \cdot Q \cdot h}{\eta} \qquad \textit{Equation 2.17}$$

The overall efficiency is calculated from Equation 2.18 below

$$\eta_{rp} = \eta_{trans} \cdot \eta_{motor} \cdot \eta_{pipe\ losses} \qquad \textit{Equation 2.18}$$

The typical values for these parameters are as shown from Figure 2.9 Losses breakdown of the pumping scheme.
The pump efficiency is calculated using Equation 2.18,

$$\eta_{rp} = \eta_{trans} \cdot \eta_{motor} \cdot \eta_{pipe\ losses1} \cdot \eta_{pipe\ losses2}$$

The summary of the calculated and machine efficiency is outlined in Table 2.3

Table 2.3 Efficiency parameters

Parameter	Efficiency	Unit
η_{rp}	77.8	%
η_{pump}	81.8	%
η_{trans}	99.5	%
η_{motor}	90	%
$\eta_{pipe\ losses1}$	93.2	%
$\eta_{pipe\ losses2}$	93.2	%

The pump efficiency is 95.1 % although during the pumping cycle, 81.8 % efficiency is achieved. From the breakdown of round-trip efficiencies of equipment's in the PHES systems, the overall round trip efficiency is 80-90 % as stated by K. Adams et al [21]. This breakdown of losses is given by Figure 2.9.

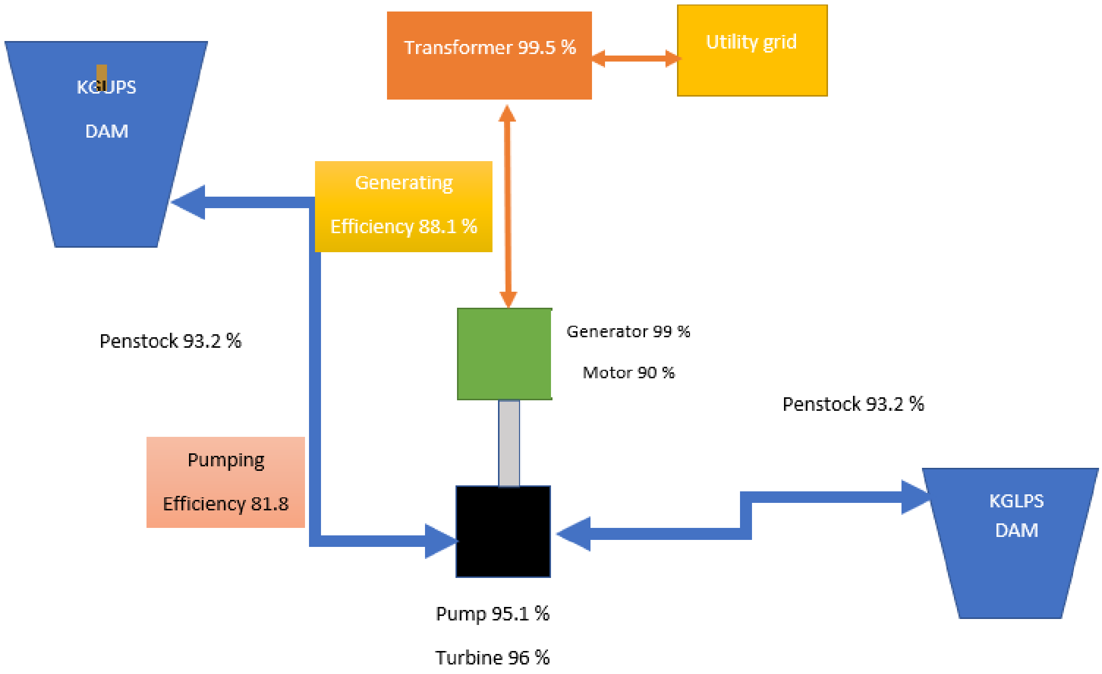

Figure 2.9 Losses breakdown of the pumping scheme

From Table 2.1, the power output of the machine in generating mode is 165 MW. After calculating the round-trip efficiency, the total pumping power needed for the machines working in pumping mode is assumed to be equal to the generating power. This means that the effective pumping power is 135 MW. However, in the pumping mode, the pump flow rate is given by the equation.

$$Q_{pump} = \frac{P_{pump} \cdot \eta_{pump}}{\rho \cdot g \cdot h} \quad \textit{Equation 2.17}$$

The pump curve shows a drooping characteristic of the pump which means that pump flowrate increases with the reduction of head. From Figure 2.10, the best pump efficiency occurs at 400 m with the flowrate as calculated above using Equation 2.17.The Figure 2.10 below is the pump curve for the pumping scheme, a pump flowrate of 34 m^3/s is realised with the head of 400 meters and efficiency of 81.8 %. These characteristics will enable the pump to deliver water from the KGLPS dam to the KGUPS dam. With a total system loss of 18.2 % which incorporates, transformer, motor and pipe head loses.

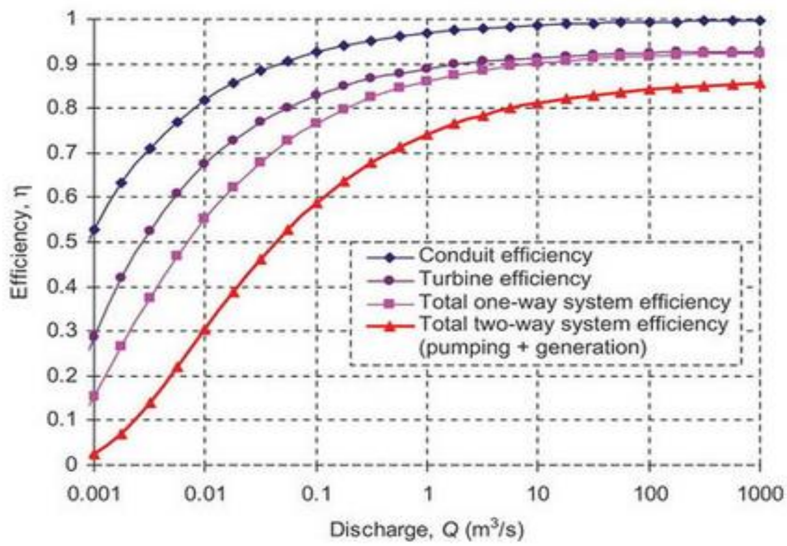

Figure 2.10 Efficiency and flowrate of the typical Francis turbine -pump system [26]

2.1.8 System model

Figure 2.11 proposed system model shows the configuration of each machine modelled as a reversible turbine/pump and generator/motor, the circuit is connected to the transformer for stepping up the 17.5 kV to 330 kV, the transformer connects to the 330 kV busbar where the load and the utility grid is connected as power is transmitted from the KGUPS, KGLPS and the solar PV system to the utility grid. The solar PV system has a standard DC Voltage in the range 600 - 1000 V [27], in this case the voltage is proposed be stepped up using a power transformer. In this study, only energetic performance is analysed and as such, cables, transmission lines and auxiliary equipment's are neglected future studies can consider the dynamic behaviour of the synchronous machines with the addition of solar PV power. The system should have power electronics controllers as depicted by the voltage source inverters, the DC/DC converters and the local SCADA on the machines. MATLAB Simulink was only used to carry out the proposed system layout of the power machines at KGUPS with PV system and no simulations where perform using MATLAB maybe it can be used in the future work for the similar study.

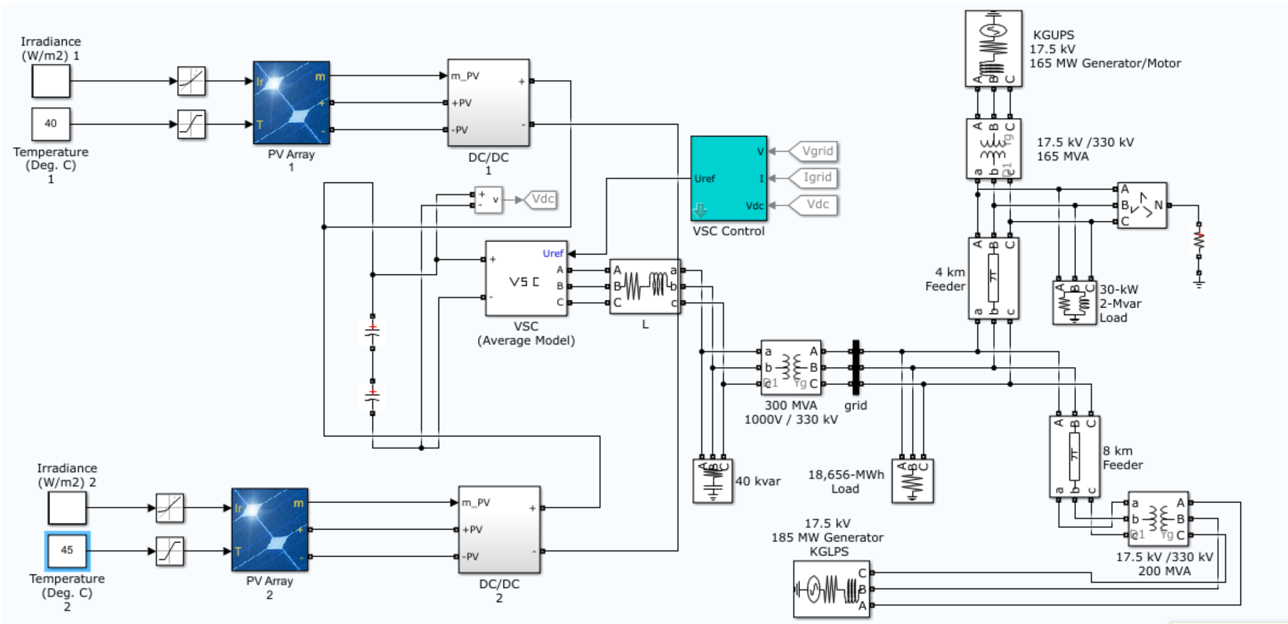

Figure 2.11 proposed system model screen excerpt from MATLAB Simulink

2.1.9 Modelling the system in Homer software

In homer software, only the energetic parameters are considered and the flow values for the load profile are as input. The penstock pipe head losses are also considered. The solar PV system will have its solar resource from NASA satellite, the inverter and rectifier circuits are defined by using the component called the converter which is the two directional equipment operating as in inverting and rectifying mode. The pumping storage facility is defined by the battery model component in Homer. The layout from Homer software is as shown in Figure 2.12.

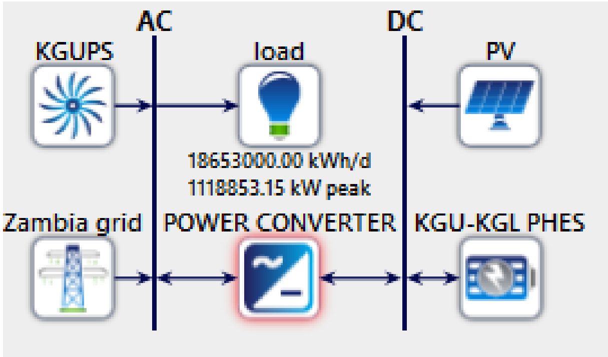

Figure 2.12 System model from Homer software

In Homer, the hydro power is modelled by one machine only represented by KGUPS, the water resource needed to generate electricity is derived from the water inflow into the KGUPS dam. Figure 2.13 shows the hydro water resource for the year 2016 which is considered as the worst year for the study.

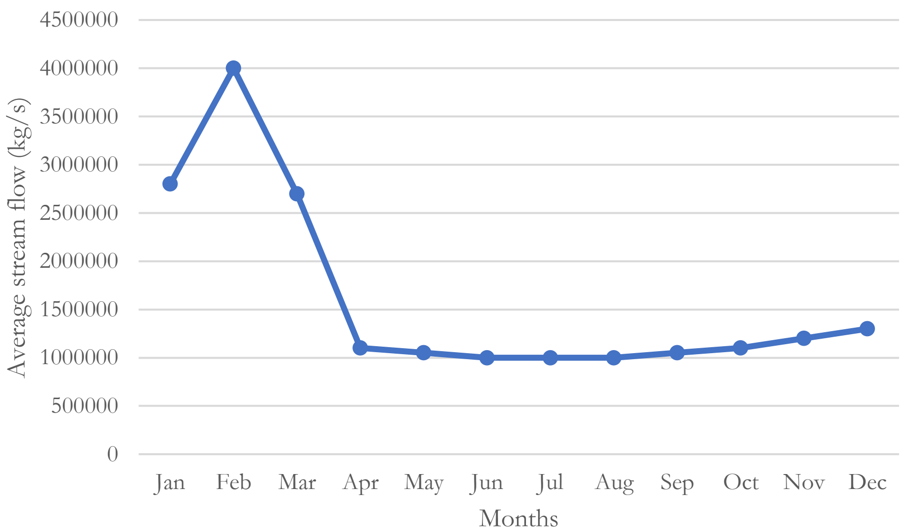

Figure 2.13 Hydro power water resource, 2016

After inputting the hydro resource, the solar resource is also downloaded as satellite data from NASA considering the location for KGUPS. The load profile in Figure 2.2 was also modelled in Homer. The storage dam is shown as a battery in Figure 2.12 System model from Homer software, a single battery in Homer has a capacity of 254.2 kWh. To be able to design a storage capacity to suit our specifications for a fully charged dam at 785 10^6 m^3, the equivalent value of capacity in GWh needed is 428 GWh. This assumes the round-trip efficiency of 81.8 % considering a battery of 240 V and 1 059 Ah as an input parameter in Homer software. This means that a total equivalent storage of 1.6 million batteries with 100 % efficiency and 2 million batteries for an efficiency of 81.8 % The pumping times considered per day is an average value for the day off peak hours. In Zambia, the morning off-peak is from 9 hours to 11 hours and the afternoon off-peak is from 14:00 hours to 16:00 hours [2]. These off-peak periods are cardinal for providing solar power to contribute to the stored energy that needs to be used during the evening peak period which occur from 16:00 to 20:00 hours of the day. These values are considered in the simulations as articulated in chapter 2.1.10. However, these pumping times are estimate values, since PHES systems offers network flexibility, pumps can be started at any time depending on the dynamic behaviour of the system.

2.2 Simulations

The simulations carried out in this thesis are categorized into different scenarios to come up with the best option and least cost project. The scenarios considered include the wet year 2012 and the dry year 2016. Scenario one for the year 2016 include the system with and without pumped storage. A comparison on this scenario in terms of PV power penetration is considered.

2.2.1 Scenario one, year 2016 for KGUPS system without PV and PHES

Scenario one consists of the existing system when subjected to a drought situation like the case for the year 2016. The hydro system is connected to the grid through the AC bus, homer does not take into consideration the electrical losses on the cables as it only calculates the energy balance i.e. the energy into and out of the system. The design consists the 990 MW KGUPS, the electric grid and the load profile for KFGUPS as shown in Figure 2.2 with an average load of 18.6 GWh/day. The results for this scenario will be tabulated in the results section. The system layout is as shown on Figure B.1 Appendix B.

2.2.2 Scenario two, year 2016 performance for KGUPS with PV only

In this scenario, a simulation of the performance for the year 2016 with an optimised size of the converter and the PV system is achieved. The load profile and the water resource are maintained as in scenario one. The system is connected to the grid as shown on Figure B.1 Appendix B to offer stability and reduction of power imports for load sustenance. The converter is introduced in the circuit to offer wave shape transformation from either AC to DC or DC to AC. This type of converter has a design suited for two directional state of the art power electronic equipment that can offer stepping up and down of voltage and current depending on the design duty cycle. The results of this study are discussed under Chapter 3 in this report.

2.2.3 Scenario three, year 2016 performance for KGUPS with PV and pumped storage facility

In this scenario, the performance for the year 2016 is simulated incorporating the pumping system from the KGLPS dam to KGUPS dam. The pumping power needed to achieve this performance is supplied by both the PV system and the Zambian electric grid. The Zambian grid consists of an interconnected network in the centre of the southern African power pool (SAPP). Power evacuation from both the KGUPS and KGLPS is done through step up transformers from 17.5 kV to 330 kV. The KGLPS which is yet to be commissioned has been proposed to be operating as a peaking station for most of the times. In this regard, to safeguard the dam and proper utilisation of the water in the two dams, power contribution from the KGLPS is cardinal in order to reduce the burden and size of the PV system. The system setup is as shown on Figure B.2. on Appendix B.

2.2.4 Scenario four, year 2012 performance for KGUPS with PV and pumped PHES

The year 2012 is considered as the favourable year in which the average precipitation for Zambia was normal to above normal. In this scenario, the load was supplied with the production from KGUPS only. Simulations are done in this case to determine the amount of power that is contributed by solar and the autonomy days that are offered by the pumping system. The contribution of power from the PHES and the PV should be able to attract profit realized from the sale of electricity to the national grid. The circuit arrangement for this scenario is the same as the for the year 2016 except the hydro resource is favourable for the year 2012.

2.2.5 Financial simulation

To carry out full simulations, Homer requires the input of prices for the materials used in the project. The total project capital cost is required and the project life. In this study, the solar project is estimated to have a life of 30 years and the hydro power scheme to have a life of 100 years. On the other hand, the replacement costs of equipment's especially for the solar PV systems is 15 years, this replacement cost is for inverters. The cost of replacement for hydropower system is mainly for the auxiliary equipment's as most of the machines which include generators, turbine runners, coolers, surge tanks, sluice gates, etc. have a long-life span of over 50 years. In this study, the major cost of the hydro power plant is for the construction of the tunnels between KGUPS and the KGLPS, the step-up transformers to allow power evacuation from the solar PV power plant. Chapter 2.3 discusses and analyses the project costs for different configurations. The section starts with cost estimates for solar PV power plants, these costs will consider the latest pricing for solar plants. It is worthy to note that pricing for these plants are very variable due to fluctuations in terms of module prices on the world market.

2.3 Cost calculations

2.3.1 Solar PV plants

The costs for solar PV plants are determined as shown on Table below. The calculations are for an optimized PV size of 300 MW which is proposed to be connected to the ZESCO grid. The project life for this PV system is 30 years designed by using mono crystalline PV modules from sun power with the rating of 480 W. In Zambia, the figures worth noting for the financial evaluation include, the interest rate which stands at 10 % and the inflation rate at 9 % which are downloaded from the Bank of Zambia website [28]. The prices for the PV modules and accessories are derived from the internet on PV insight [29]. The summary of the calculations done with system losses of 10 % consisting of 5 % soiling losses, 2 % due to PV module mismatch and 3 % electrical losses in the wiring.

Table 2.5 Financial analysis of the optimised PV system

Equipment and performance	Costs and production	Unit	State	Cost with VAT
Installed capacity	300 000	kW	DC	
Monocrystalline PV module rating	480	W		
Number of PV modules in series	12			
Number of PV module strings	49 375			
Number of pv modules	625 000			
System Voltage	1 000	V	DC	
Monocrystalline module price	0.3	$/W		
PV module Capital cost	**90 000 000**	**$**		
Number of inverters	25			
Rated inverter capacity	10 000	kW	AC	
Inverter price	0.07	$/W		
Inverter capital cost	**17 500 000**	**$**		
Project life	30	years		
Inverter life	15	years		
Electrical installation material cost	**5 375 000**	**$**		
Capital cost with no subsidy	**113 025 000**	**$**		
Subsidy at 35 %	**39 558 750**	**$**		
Capital cost with subsidy	**73 466 250**	**$**		
Cost of mounting and installation work	150 000	$		
Cost of replacement	1 225 000	$		
Total costs VAT inclusive	**113 025 000**	$		84 768 750
ACOM Costs	**565 125**	$		423 844
Interest rate	0.0993	10 %		
Inflation	0.09	9 %		
Soiling loss	0.05	5 %		
Mismatch and cable losses	0.05	5 %		
VAT	0.25	25 %		
Discounted rate	0.00853	0.853 %		
Annual Electricity produced	533 946 491	kWh		
Capital recovery factor	0.225			
LCOE	**0.0487**	**$/kWh**		**0.0365$/kWh**

These calculations where done using the excel sheet with the key formula used to calculate the LCOE as outlined in the Equation 2.19 below.

$$LCOE = \frac{C_0 \cdot CRF + ACOM}{NAE} \qquad \textit{Equation 2.19}$$

The time value of money(d) is referred to as the discounted rate. The discounted rate is calculated using the formula on Equation 2.20.

$$d = \frac{R - I}{1 + R}$$ *Equation 2.20*

From the discounted rate, the capital recovery factor is derived as

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1}$$ *Equation 2.21*

From Equation 2.21, n is the project life [years]. The NAE for this project is derived from homer energy simulation software for the optimised 300 MW system. From the simulation results, the PV plant capacity factor 20.3 %. The project cost for the PHES system is not carried out in this study due to lack of time. In future, the cost can be calculated and be compared with other bulk storage facilities. The initial capital cost for the PHES system in this context will reduce drastically because of using the already existing two dams, no money will be spent in displacing people and the cost of engineering will certainly reduce. The only key figures will be the cost of doing tunnels from KGUPS to KGLPS dam to facilitate the pumping system and the purchase, installation and commisioning of the pump/turbine machines and motor/generator systems with its associated control systems.

2.4 Proposed operation scheme for KGUPS/KGLPS with PHES and PV system

The conjunctive operation of this hybrid system with pumped storage facility will be with the view to preserve the water especially during the dry periods and the conservation of the environment. Water management on the 80 10^6 m^3 KGLPS should also be done in order to avoid overfilling of the dam which could endanger the lives of the people and the station as well. This means that, the water coming from the 750 10^6 m^3 KGUPS to the KGL dam can be controlled by running the machines at KGUPS in either generating or pumping mode. Also since by design [2], KGLPS is the peaking station during the day time deficit power from the PV system that is needed for the pumping system can be compensated by running one or two machines during the afternoon off-peak period so that water is pumped back from the KGLPS dam to the KGUPS dam. The proposed operation scheme for the KGUPS to be in operation with the KGLPS and the PV system should be able to allow the use of two energy sources efficiently which is water and solar energy. The demand for water in the country is on the increase both on the power generation, agricultural use and human consumption. The functional operation scheme for the plant should be able to be self-regulated within the confines of the set parameters. The dynamic behaviour of the system should be able to absorb solar energy during day times and the shift from generation to pumping mode of the KGUPS machines should be smooth such that the mechanical pumps and turbines are safeguarded.

2.4.1 PV power evacuation

To evacuate the power from the PV system, subsequent equipment's that is needed which include, power transformers totalling 350 MVA should be available. The transmission network should be in the range of 10 km. The PV systems can be distributed near load centres. The operation of the PV systems should be such that during sun hours of the day, power is fed into the grid totalling 241 MW peak during the month of October. The fed power from the PV system should be able to reduce dependence on hydro power during day times. This will ensure that water is saved to later be used during the evening peak periods.

2.4.2 KGUPS and KGLPS proposed operation strategy

The capacity of KGUPS dam should be able to be comprehended by the KGLPS dam. This means that water should be able to be pumped from KGLPS dam to KGUPS dam, in order to achieve this, the power which the PV system should be able to supply to the pumps if it is not enough, part of it should come from the KGLPS and the utility grid. The peak power from the PV system should be able to march the pumping needs, however solar power being intermittent, there is need to operate it together with hydro power machines. The variability of the solar resource should be able to be compensated by the hydro power. The operation times are not fixed to a specific time, however a four-hour pumping during the morning and evening off-peak periods are adequate to be able to keep the dam autonomous for most of the period of the year. During the morning off-peak from 9 am to 11 am, solar power from the PV should be able to supply power to the pumps. This strategy will help overfilling of the KGLPS dam which can pose a risk of flooding the station and a risk to few people that can be left on the downstream of the Kafue river before it joins the Zambezi river. However, the operation scheme should be flexible by detecting the dynamic behaviour of the grid, the available surplus power, water level in the two dams and the demand. The figure below is the proposed scheme for this system which should be backed up by the automated generation management system (GMS).

2.4.3 Scheme one

If, load for KGUPS < 777 MW (18,653 MWh/day), and solar PV power is available at 100 – 241 MW, then water is pumped from KGLPS dam to the KGUPS dam. In order to pump the maximum power of 241 MW, two machines are required to run in the pumping mode, and this requires a flexible scheme such that the dynamic shift from generating to pumping is very smooth in terms of power transfer, frequency regulation and voltage regulation. The use of power electronic converters and the doubly fed induction machines offers a reliable scheme for reversible machines. Careful operation of the machines should be at play, this is because at peak periods, it's not possible to take out two machines to work as pumps. Water is stored to be used during the evening peak period, frequency and voltage management is managed by the machines running at KGUPS in generation mode and the utility grid. This is an ideal case during the wet year/days in which power imports can be reduced by the power contributed from solar and KGLPS.

2.4.4 Scheme two

If, load for KGUPS >777 and available solar power during the day from 9 am to 5 pm is 100 – 241 MW, Pumping can only be done if surplus power is available from the grid. Otherwise, generation from the machines can be reduced to only maximise power from the PV and be able to save water. Available power during the peak periods can be supplied from the KGUPS machines and the power from the grid. This is the typical scenario during the dry years in which power demand is high in the region, but water availability is very low due to reduced inflows from rains and ITT dam. In this case, PV penetration can be high as well so that power imports are reduced, surplus PV and grid power can be used to store water in the upper dam.

2.4.5 Scheme three

The load power can always be controlled using the KGUPS and KGLPS machines and surplus power from the PV system can be exported during the day for the country to generate revenue. This can only happen during the wet years like the year 2012. Pumping system can be able to operate during the night on which the load is low. Surplus power from the grid and KGLPS can be used to pump water to the upper reservoir. This system will be able to address the carbon dioxide emissions from coal thermal power plants like Maamba coal power station. These schemes should be flexible as the dynamics of water flow, solar irradiation and load are variable. The automated generation management system with key components like a weather station, pyranometers, supervisory control and SCADA systems.

3 Results and discussion of results

3.1 Scenario one results- year 2016 without PV and PHES system

The results for this scenario which is the base case for the study as simulated from section 2.1.11 is shown from Figure 3.1. The results are based on the same load profile for KGUPS with an average daily load of 800 MW.

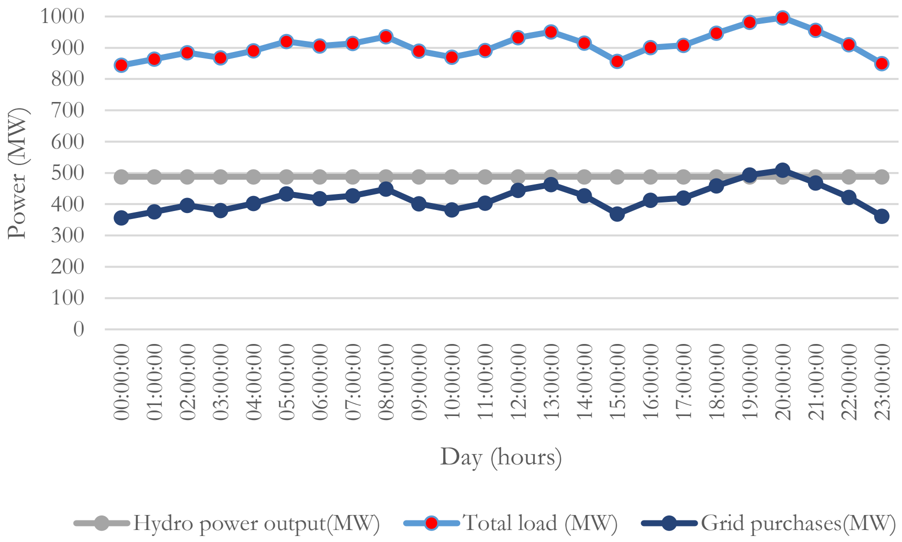

Figure 3.1 Simulation results for the year 2016 with no PV and PHES systems

The results show that on this day, 15th of June 2016, the maximum generation from the hydro power production was 734 MW and the average production was 488 MW, this represent the contribution of 63.7 % from the 990 MW KGUPS as outlined on Figure 2.2. This meant that, to supply a load with a daily average of 18.6 GWh, 36.3 % of electricity was imported from the grid. However, the utility grid could not supply this remaining 36.3 % as the power was imported from other countries within the southern African power pool (SAPP) [3]. During the morning, afternoon and evening peaks, power amounting to 550 MW was purchased from the grid. During the dry period of September to November, the peak import power of 560 MW was purchased. The reduced water inflows in the Kafue river led to the reduced generation from KGUPS.

3.2 Scenario two- year 2016 production for KGUPS with PV only

The introduction of PV system at KGUPS will have an impact on the dynamic behaviour of the system. PV system will not be able to provide all the power to the Zambian grid and the entire SAPP region depending on the capacity. The simulation results for this study considering different sizes of the PV system and its contribution to the grid is tabulated on Table 3.1 Simulation results for year 2016 for KGUPS with PV only. The table shows that for the load with annual demand of 6 808 GWh, the yearly production of 4 338 GWh from the hydro power station cannot be able to sustain the load demand. Power is imported from the grid and the contribution of solar energy will be able to reduce the power imports at the maximum 9 % for a 350 MW solar power plant. The increase in PV penetration reduced the reliance on grid purchases by 7.8 % from the optimised 300 MW PV power plant and 9 % for the 350 MW PV power plant. The maximum of 300 – 350 MW is chosen as it tallies with the available land and the hosting capacity for grid system at 30 % penetration of renewables [31]. In the next section, the results for the hydro, PV system with storage is discussed.

Table 3.1 Simulation results for year 2016 for KGUPS with PV only

PV Size (MW)	KGUPS (GWh)	PV production (GWh)	Grid purchases (GWh)	Total annual production (GWh)	PV penetration (%)
50	4 338	89	2 386	6 818	1.3
70	4 338	125	2 352	6 815	1.8
100	4 338	178	2 301	6 817	2.6
120	4 338	214	2 268	6 819	3.1
180	4 338	321	2 167	6 825	4.7
200	4 338	357	2 133	6 828	5.2
250	4 338	446	2 080	6 864	6.5
300	4 338	535	2 005	6 878	7.8
350	4 338	624	1 944	6 906	9

3.3 Scenario three results with PV and pumped hydro for the year 2016

Figure 3.2, shows the results for the 15th of June 2016 for the system with an average daily load of 800 MW. The total KGUPS output power consist of the PV and the hydro power output. The power purchased from the grid to support the load during the day reduced to the minimum at 81 MW around 11:00 hours. The contribution of solar energy from 07:00 hours to 18:00 hours can reduce the grid purchases by 7.8 % over the day. This contribution can keep the PHES at near an average 60 % state of charge for the longer period of the year.

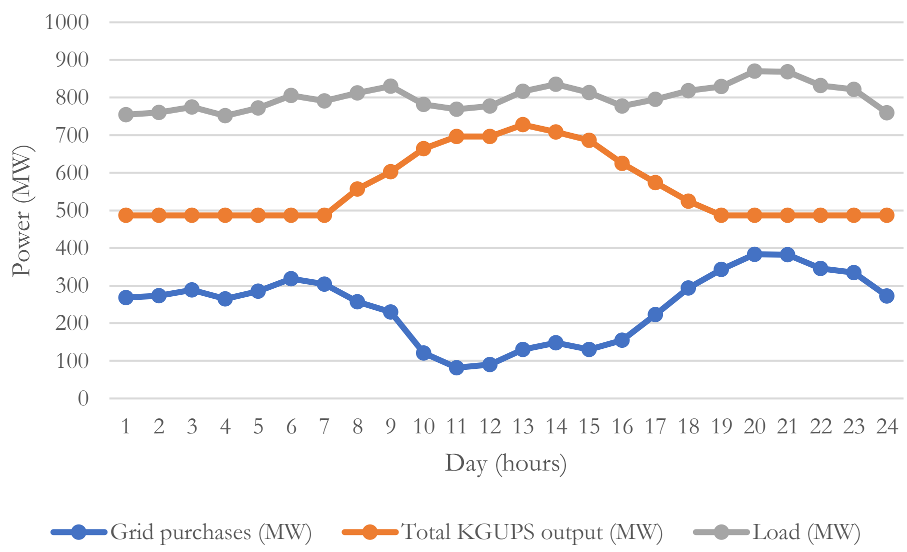

Figure 3.2 Simulation results for year 2016 with PV and PHES

Figure 3.3 shows the state of charge of the PHES system as contribution to the KGUPS when water is pumped from the KGLPS dam. Keeping this state of charge will ensure security of supply and be able to increase the penetration of Solar power plants in Zambia. The average yearly state of charge is 70 % with the maximum charge power of 205 MW. The charge power is the contribution from the grid and the PV system, this power is stored in the KGUPS dam and later discharged during the peak hours of the day. The negative values for charge power means power is injected in the pumps to pump water from the KGLPS dam to the KGUPS dam. The maximum pumping power of 205 MW it will require two pumps running as articulated on Figure 1.8 Double fed induction machine adjustable speed control [17].

The next section discusses the performance of the system on the 20th of October 2016 which is the worst day on which the country receives no precipitation as it is in the dry period of the year. The state of charge is kept above 50 % for most of the period of the year except the months, February to April where precipitation inflow has not yet reached the KGUPS dam. This PHES provide power security for 589 hours if the pumps are available.

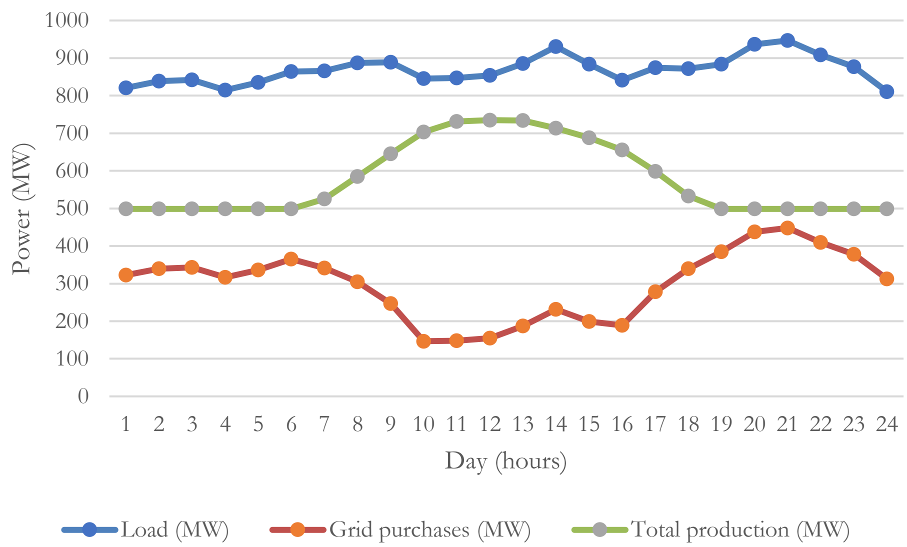

Figure 3.3 Performance of KGUPS with PHES and PV for October 20th, 2016 (Dry period)

Figure 3.3, shows the performance of the KGUPS during the dry period simulated for the year 2016, from 6 am to 6 pm, PV production was in effect with the peak power of 232 MW recorded at 1 pm. The contribution of the PV power leads to the reduced power import from the grid. The total production is the contribution from both solar and hydro power at KGUPS. Table B.2 in Appendix B shows that increasing PV system capacity from 50 MW to 300 MW with the annual energy output of 412 GWh from the PHES system. The increase in PV penetration increases the available electricity in the grid and this can reduce black out and power shortages that comes as result of low water levels in the reservoir for KGUPS. This also guarantees the security of supply of electricity to the customers. In the next section, the results for the year 2012 are discussed. Figure B.2 in Appendix B shows the yearly production from the KGUPS with PHES and PV system, the peak load occurs during the month of June at 920 MW and the minimum occurs in March at 520 MW. The PV power can reduce the power consumption from the grid by 7.8 % and the PHES system is kept fully charged for most of the period. The minimum state of charge occurs in the evening peak because during this time, the pumps are off, and power is generated using the available water that was stored in the KGUPS from the KGLPS dam. Figure B.4 Appendix B shows the power balance for the year 2016 with the total load saved, the PV output, hydro power output and grid purchases. The figure shows that grid purchases increased from March to April due to the reduced water inflow into the KGUPS dam.

3.4 Scenario four results for KGUPS for the year 2012 with PV and PHES system

The year 2012 is one of the best years in which the country received normal rainfall and in order to meet the daily load for KGUPS at 18.6 GWh, the hydro power station, solar PV systems and the PHES system are in operation throughout the year. The simulation results for one of the best days of 15th June 2012 are as shown in Figure 3.4. for the optimised 300 MW PV plant, 990 MW KGUPS and the contribution of PHES at 741 GWh/year.

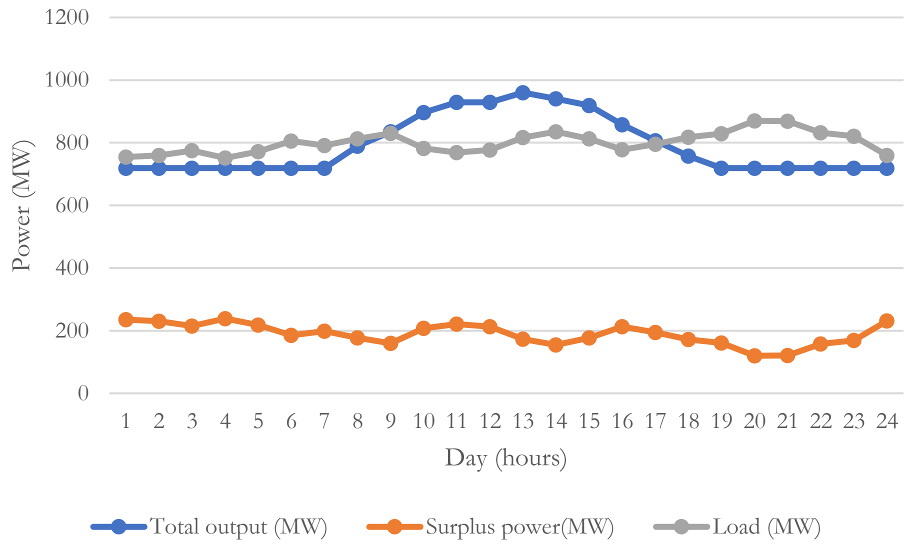

Figure 3.4 KGUPS performance with PV and PHES system for the year 2012 on 15th June

Figure 3.4 shows the results for KGUPS if the system is redesigned to have a PHES system with PV system. On this day, from 9 am to 17 am, the system should be able to receive a peak PV production of 241 MW at 12 am noon time and if the average load is maintained at 18.6 GWh/day and 860 MW as peak load. The system records a surplus total power of 4.5 GW/year an average of 189 MW as surplus power contribution from both the PV power and the hydro machines by not running at full load. During this period, two KGUPS machines that are redesigned to accommodate the pumping system can be able to run in the reverse directions in order to capture this solar energy and store it in form of water and later use it during the peak period on which the electricity prices are high. The two machines rated at 165 MW each can be able to share the 350 MW available as pumping power. Table B.3 on Appendix B is the summary of the results for this day in terms of power production from both PV and hydro system as well as contribution from the PHES system.

Implementing this system will ensure that during the afternoon we can have surplus power that can be able to be sold to the grid and generate revenue for the company ZESCO. The peak power export is 327 MW occurring at 1 pm in the afternoon. This power can be sold or depending on the condition of the grid network, the power can be saved in form of water. To support the evening peak of 870 MW at 7 pm generation from the hydro machines is increased and the water that was saved during the day is utilized. During the morning peak at 8 am, nothing is imported from the grid with 4.9 MW is exported to the grid. The state of charge contribution to the already existing KGUPS can be improved in accordance with the results as shown in Figure 3.3. The lowest state of charge contribution is 20 % which recorded during the period from March to April but however the pumps where able to raise the state of charge to 80 % for the longer period of the year. The addition of the existing system by 60 - 80 % state of charge during the dry period of the year is significant in reducing power shortages in the country. The results on this scenario are for the peak level in the KGUPS which normally occurs around the month of June. June is also the month in which the power station records peak power demand as it occurs during the winter period where the demand for heating increases. The next simulation results shown in Figure 3.5 are for the 20th of October, this day is in the peak period of the dry season on which no precipitation is recorded in the country.

3.5 Scenario five October 20th, 2012 KGUPS with PHES and PV

In this scenario, the simulations for the KGUPS with PHES and PV is considered. The PHES daily output was 963 MWh/day in accordance to the design.

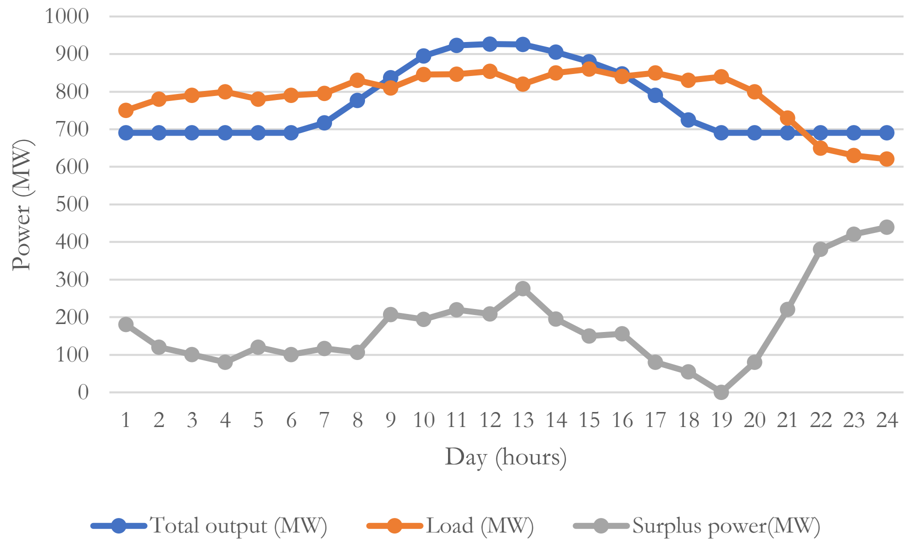

Figure 3.5 Scenario five for 20th October 2012 for KGUPS with PHES and PV system

From Figure 3.5, the peak power from the PV system is 236 MW which occurs around 12 am in the morning. During this day, power production from the PV starts as early as 6 am to 6 pm in the evening. During most the time in the month of October, surplus power from the PV system is recorded during the day which could be saved in the form of water as seen from Figure 3.5 above when the pumps pumped water at 2 pm using 150 MW as grid purchases. On the other hand, this power can be injected directly into the grid and the hydro generators can be regulated so that the output only meets the demand and water can be saved in the KGUPS dam so that it can be utilised during the times of high electricity demand. Figure 3.6 shows the state of charge against the charge power of the PHES system, it can be clearly seen that at the start of the year in January 2012, the PHES was fully charged and the charge reduced as the dry period started in the month of June. The pumps where able to raise the state of charge to 80 % between August and October.

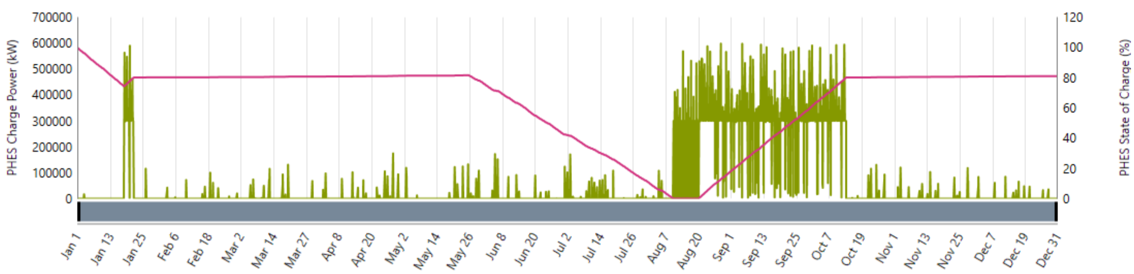

Figure 3.6 State of charge and charge power of the PHES system for the year 2012

Figure 3.6 shows the state of charge and charge power performance of the PHES system, the average maximum charge power was 350 MW which means that two generators where running in reverse as pumps to pump water to the KGUPS dam and the discharge power was minimum at 55 MW. The PHES was 80 % charged during January to May and the during the dry season the state of charge falls considerably between July and October. In this regard, the scheme should be able to allow energy storage using excess power during the dry period of the year or generation can reduced from the hydro power station and allow PV power to support much of the load so that water is conserved. The addition of this power into the grid will be able to mitigate power shortages and increase the security of power supply to the grid as well as increase the penetration of PV system into the Zambian utility grid.

3.6 Results summary

Table 3.2 Results summary for KGUPS yearly production from hydro and PHES with four scenarios with daily load of 18.6 GWh

Scenario	Configuration	KGUPS output (GWh)	PHES Capacity (GWh)	PV output (GWh)	Grid Purchases (GWh)	Excess electricity (GWh)	PV Penetration (%)	Autonomy days
1	KGUPS base case (2016) without PV and PHES	4 338	0	0	2 471	0		5
2	KGUPS base case (2016) with PV only 300 MW	4 338		534	1 989	19	7.8	5
3	KGUPS base case (2016) With PHES and PV of 300 MW	4 338	457	534	1 965	1.4	7.81	24.5
4	KGUPS (2012) With PV and PHES (300 MW PV system)	5 795	457	534	489	85	7.81	24.5

4 Discussion and conclusions

The results from the optimized system of 990 MW KGUPS, 300 MW PV and 457 GWh/year of energy storage from the PHES system are discussed in this section. PV system can support part of the load during the day from 6 am to 6 pm during the worst-case scenario as articulated in section 3.6. The peak PV output of 236 MW was adequate to support one pump at 165 MW, the surplus power was fed into the grid. In case the system needs to use two pumps, additional power is utilized from the utility grid. The state of charge of 80 % of the PHES system was able to be an additional power that can be contributed to the already existing KGUPS dam. This power can be able to be utilized during the peak period from 4 pm to 8 pm in the evening.

In accordance with the study that was done by Wunna Swe [19], PHES system is the only proven technology that can be able to offer a bulk energy storage in comparison to other energy storage technologies with a long cycle life of over 100 years. The 10 % energy savings can be huge in monetary forms. PHES systems have the capability of offering the levelling of power in the system and stabilizing the electricity grid. The introduction of pumped storage facilities has the capability of allowing the penetration of renewables in the Zambian grid. In accordance to the study that was done by G. Notton et al [27] for the analysis of pumped hydroelectric storage for wind/PV grid integration, the low weight density of water at 1000 kg/m^3 is good enough to be stored at the height of 400 meters although it requires a large surface area in terms of storage dams. G. Notton et al also stated that PHES systems can offer an efficiency of 75 to 85 % after eliminating the losses due to evaporation, pump head losses and losses due to transformer, motor and turbine losses. The calculated pumping efficiency for the pumping scheme designed in this study for KGUPS, PHES with PV system is 81.8 % which is within the range of the parameters outlined also in the IFC report [26]. From the results section, scenario one is the base case in the country in which there is dependence on hydro power to produce electricity. The daily load of 18.6 GWh for KGUPS cannot be met during the drought period of the year as power is imported from the national grid and other power utility companies within the Southern African Power Pool (SAPP) region as stated in the energy regulation report of 2016 [28]. The total power imports during the year 2015 to 2016 was 2 184 GWh which represented 179 % of power. This can be significantly reduced with high penetration of PV power and other renewables in the grid.

Scenario two shows that the penetration of PV system alone in the utility grid for the year 2016 can reduce power imports by maximum of 10 %. However, increasing PV system penetration only does not offer system security. This means that the PV/hydro hybrid system alone will add more pressure on the utility grid in terms of frequency and voltage control. PV systems are incapable of providing reactive power that is needed for the sustenance of the magnetic fields in the synchronous machines. This means that additional costs in terms of installing compensating equipment's at designated points can be incurred otherwise having a DC transmission line is an option although a costly design. Scenario three for the optimized KGUPS with PV and PHES is one of the best options which offers power stability, increased penetration of PV and the ability to have a daily energy storage of 1.2 GWh. However, the performance of the system depends on the adopted operation scheme as articulated in section 3.6. This system will provide power support to the grid and reduce the power import by 7.8 % if two machines are used as both generators and pumps at specific operation times i.e. four to five hours of water pumping from the KGLPS dam to the KGUPS dam.

From this study, it can be concluded that, pumped hydro facility with solar PV power in the Zambian grid will be able to provide yearly energy of 457 GWh, increase PV penetration by 7.8 % and also increase the autonomy days to 25 days from the initial 5 days which is inadequate. With the increase towards clean energy solutions in the Zambian grid such as wind and solar, pumped hydro facility at KGUPS will be able to stabilise the utility grid and reduce power black outs in Zambia.

5 Future work

The study carried out in this work did not cover the full financial model of the hydropower system in terms of equipment costing and designing as only the power metrics are carried out. The future work should cover the complete financial modelling of the hydropower system with its associated reversible machines and necessary power electronics components.

On the other hand, the future study should also look at the dynamic stability of the utility grid with the addition of solar power system, this study can be done using software tools like ETAP and Digi silent. These tools can simulate the fluctuations of voltage and frequency in the grid as well as short circuit analysis and optimum power flow. With these studies it is possible to determine the extent at which the penetration of renewables can be able to go, and these features are not included in Homer and PVSyst.

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Appendices

Appendix A: load profile and calculation tables

Table A.1 2012 Load profile for KGUPS in monthly terms

Months	Generation (MW)	Mass flow rate(L/s)
January	758.206	212332.573
February	871.451	244046.468
March	820.806	229863.688
April	871.785	244139.956
May	902.473	252734.123
June	913.979	255956.348
July	888.871	248924.893
August	860.067	240858.510
September	859.729	240763.844
October	883.293	247362.808
November	858.014	240283.487
December	743.320	208163.875

Table A.2 Monthly evaporation values for KGUPS dam

Month	Irradiation (kWh/m^2)	Radiation(W/m^2)	E (m)	Q_{eva}(L/s)
JAN	156	3146	0.1	29868.578
FEB	143	3146	0.08	26455.026
MAR	137	3208.083	0.1	29868.578
APR	101	2613.375	0.12	37037.037
MAY	75.1	2099.671	0.11	32855.436
JUN	56.9	1752.046	0.1	30864.198
JUL	66.1	1966.475	0.1	29868.579
AUG	96.3	2572.013	0.13	38829.152
SEP	140	3470.833	0.16	49382.716
OCT	191	4178.125	0.18	53763.441
NOV	177	3554.750	0.12	37037.037
DEC	166	3230.083	0.11	32855.436

Table A.3 Water outflow and inflows into the KGUPS dam for 2012

Month	Q_{ITT} (L/s)	Q_{preci} (L/s)	Q_{eva} (L/s)	$Q_{turbine}$ (L/s)	Q_{UR}(L/s)
JAN	250000	56100	29868.57826	212332.573	63898.85
FEB	350000	52800	26455.02646	244046.469	132298.5
MAR	250000	33000	29868.57826	229863.688	23267.73
APR	100000	13200	37037.03704	244139.956	-167977
MAY	100000	3300	32855.43608	252734.124	-182290
JUN	100000	0	30864.19753	255956.348	-186821
JUL	100000	0	29868.57826	248924.894	-178793
AUG	100000	0	38829.15173	240858.511	-179688
SEP	100000	0	49382.71605	240763.845	-190147
OCT	100000	6600	53763.44086	247362.808	-194526
NOV	100000	26400	37037.03704	240283.488	-150921
DEC	100000	52800	32855.43608	208163.875	-88219.3

Table A.4 Water outflow and inflows into the KGUPS dam for 2016

Month	Q_{ITT} (L/s)	Q_{preci} (L/s)	Q_{eva} (L/s)	$Q_{turbine}$ (L/s)	Q_{UR} (L/s)
JAN	250000	33000	29868.5783	186576.984	66554.4373
FEB	350000	39600	26455.0265	182600.926	180544.048
MAR	250000	13200	29868.5783	191016.695	42314.7271
APR	100000	6600	37037.037	193414.653	-123851.69
MAY	100000	0	32855.4361	184049.417	-116904.85
JUN	100000	0	30864.1975	186265.697	-117129.89
JUL	100000	0	29868.5783	196621.382	-126489.96
AUG	100000	0	38829.1517	175465.476	-114294.63
SEP	100000	0	49382.716	201606.002	-150988.72
OCT	100000	0	53763.4409	189881.83	-143645.27
NOV	100000	0	37037.037	171431.03	-108468.07
DEC	100000	26400	32855.4361	186501.703	-92957.139

Table A.5 KGUPS dam profile for 2016

Month	2012 Q_{UR}(L/s)	2016 Q_{UR}(L/s)	ΔQ(L/s)	ΔQ (m^3/s)	P(MW)
JAN	63898.849	66554.437	-2655.589	-2.656	-9.483
FEB	132298.505	180544.048	-48245.543	-48.246	-172.277
MAR	23267.734	42314.727	-19046.993	-19.047	-68.014
APR	-167976.994	-123851.689	-44125.304	-44.125	-157.564
MAY	-182289.56	-116904.853	-65384.706	-65.384	-233.478
JUN	-186820.546	-117129.894	-69690.652	-69.691	-248.854
JUL	-178793.472	-126489.96	-52303.512	-52.304	-186.767
AUG	-179687.662	-114294.627	-65393.035	-65.393	-233.508
SEP	-190146.561	-150988.718	-39157.842	-39.158	-139.826
OCT	-194526.249	-143645.271	-50880.978	-50.881	-181.688
NOV	-150920.525	-108468.066	-42452.458	-42.452	-151.591
DEC	-88219.311	-92957.139	4737.828	4.738	16.918
Year	-	-	-	**Average**	**147.178**

Appendix B: Circuit configuration and simulation results

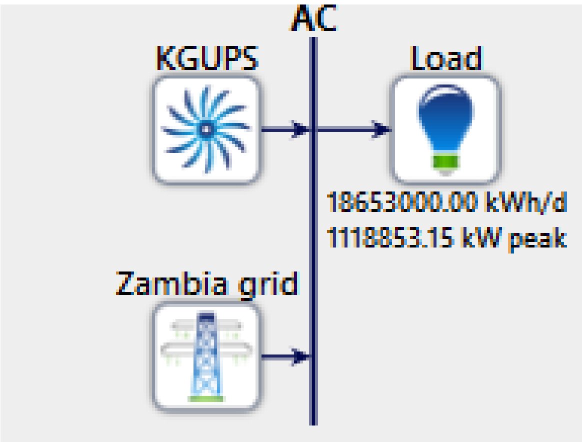

Figure B.1 Scenario one for the year 2016

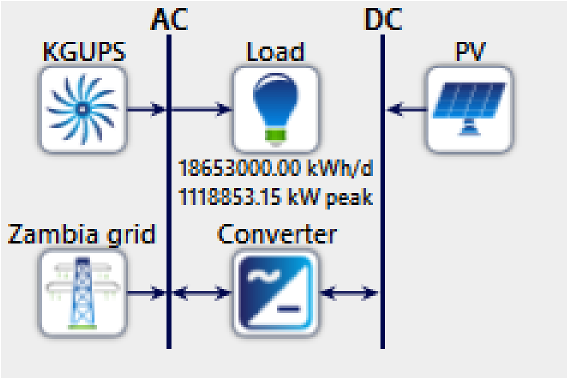

Figure B.2 Scenario two for the year 2016

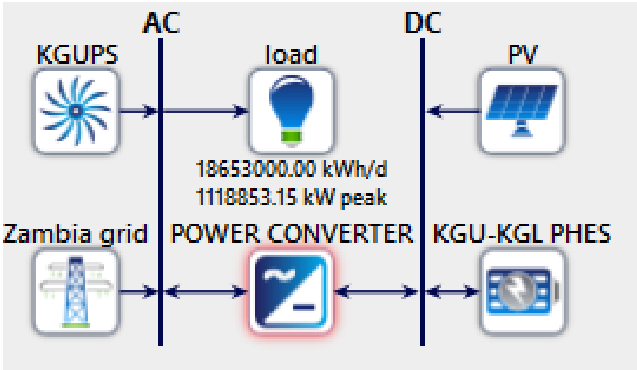

Figure B.3 Scenario three, year 2016 performance for KGUPS with PV and pumped storage facility

Table B.1 Scenario three results for KGUPS with PV and PHES

PV Size (MW)	KGUPS (MWh)	PV output (MWh)	Grid purchases (MWh)	Excess Electricity (MWh)
50	4,337,629	88,991	2,383,540	Nil
70	4,337,629	124,588	2,347,524	Nil
100	4,337,629	177,982	2,295,188	Nil
120	4,337,629	213,579	2,314,775	12,590
150	4,337,629	266,973	2,218,054	15,219
180	4,337,629	320,368	2,171,314	13,925
200	4,337,629	355,964	2,180,171	58,823
250	4,337,629	444,955	2,154,957	122,031
300	4,337,629	533,946	2,092,500	146,436

Table B.2 Summary results for KGUPS performance for the 15th June 2012

Time (Hours)	PV output (MW)	KGUPS Output (MW)	Load (MW)	Grid purchases (MW)	Grid sales (MW)
12:00:00 AM	Nil	719.116	754.737	35.621	Nil
1:00:00 AM	Nil	719.116	759.999	40.883	Nil
2:00:00 AM	Nil	719.116	775.021	55.905	Nil
3:00:00 AM	Nil	719.116	751.399	32.282	Nil
4:00:00 AM	Nil	719.116	771.807	52.691	Nil
5:00:00 AM	Nil	719.116	805.020	85.904	Nil
6:00:00 AM	Nil	719.116	790.976	71.860	Nil
7:00:00 AM	69.713	719.116	812.496	25.061	Nil
8:00:00 AM	115.824	719.116	830.357	Nil	2.267
9:00:00 AM	177.553	719.116	781.817	Nil	111.302
10:00:00 AM	209.850	719.116	768.659	Nil	156.110
11:00:00 AM	209.624	719.116	777.180	Nil	147.368
12:00:00 PM	241.009	719.116	816.534	Nil	138.771
1:00:00 PM	221.534	719.116	834.961	Nil	101.258
2:00:00 PM	199.711	719.116	812.756	Nil	102.077
3:00:00 PM	138.570	719.116	777.504	Nil	77.410
4:00:00 PM	87.575	719.116	795.182	Nil	9.758
5:00:00 PM	38.191	719.116	817.964	61.420	Nil
6:00:00 PM	Nil	719.116	829.449	110.333	Nil
7:00:00 PM	Nil	719.116	870.064	150.948	Nil
8:00:00 PM	Nil	719.116	868.761	149.645	Nil
9:00:00 PM	Nil	719.116	831.907	112.791	Nil
10:00:00 PM	Nil	719.116	821.297	102.181	Nil
11:00:00 PM	Nil	719.116	759.203	40.087	Nil

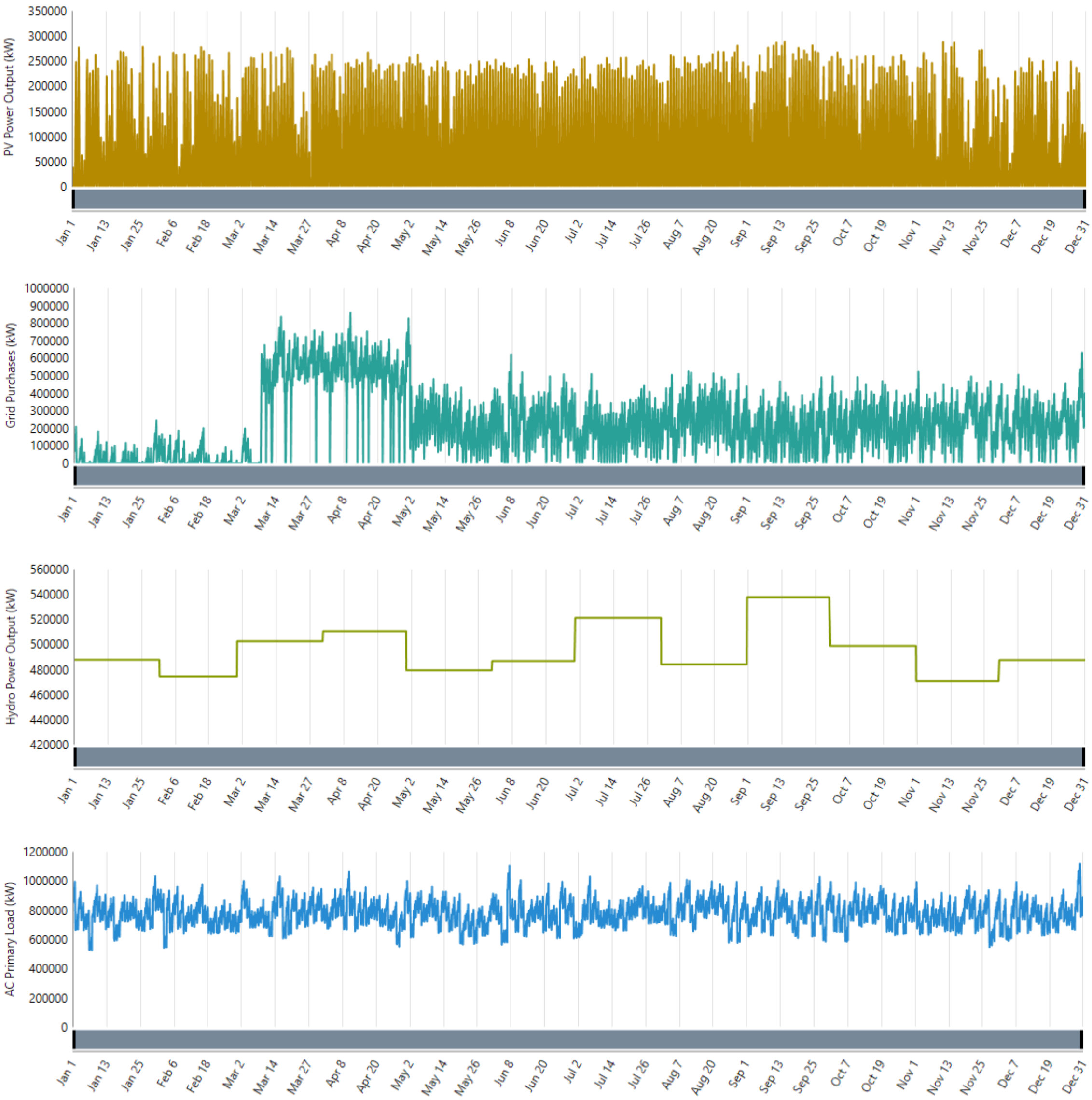

Figure B.4 Yearly output for KGUPS with PHES and PV system for 2016