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A Novel Design And Development Of A Community Based Micro-Hydro Turbine System With Hydrogen Energy Storage To Supply Electricity For Off-Grid Rural Areas In Tanzania. A Case Study Of Hhaynu Micro-Hydropower Plant

Daniel H. Ngoma[1)] and Melkior Urbanus[2)]
Lecturer, Arusha Technical College (ATC), P. O. Box 296, Arusha 23105, Tanzania
Assistant Lecturer, Arusha Technical College (ATC), P. O. Box 296, Arusha 23105, Tanzania

Abstract
Micro-hydropower plants are used to supply electricity to the rural and off-grid areas of most developing countries like Tanzania. Their power capacity ranges from 5 kW to 100 kW which is equivalent to supply electricity from few households to several villages. The challenges that have influenced to undertake this research project are centred on the possibility of designing and developing a novel micro-hydro turbine system that can meet the dynamic load demand from the rural off-grid users and at the same time achieve high energy utilization efficiency with minimum energy losses using integrated renewable energy storage technologies such as a hydrogen energy storage. The method used in this research study is based on the field work and site data measurements together with power and energy determination as inputs to a novel system design, modelling and simulation which will determine system characteristics. The results from data analysis show that the feasible water flow discharge for the micro-hydropower plant is 0.45 m^3/s with the gross head of 25m which gives a turbine power of 79.5 kW and generator power of 75.5 kW as a power supply. On the other hand, results of the demand power analysis from the case study villages shows the load profile has a low demand power of 8.42 kW and high demand power with peak power of 101.8 kW during the evening hours with the daily average energy of 1,114.38 kWh/d while the micro-hydropower can produce a maximum energy supply of 1,812 kWh/day. When supplying power to the load demand, the results show that the micro-hydro system produces excess power of up to 60 kW during low demand hours. In additional to this excess power production, it is also noted that the power supply is not sufficient to supply power during the peak hours of the day. So, in order to supply this peak power deficit, an energy storage system is introduced to store the produced excess electrical energy from the micro-hydro turbine system during the off-peak hours and then export it during the peak hours. Several energy storage options have been studied and analysed and based on the optimization results, the novel design of using micro-hydro turbine system with an electrolyser system and hydrogen fuelled internal combustion engine-generator system have been selected. The use of excess electricity to supply to the electrolyser system reduces the excess power to the dump loads to a minimum which results to an increase in the plant capacity factor and make the micro-hydro turbine system more energy efficient.

Index Terms: *Micro-hydropower, Hhaynu river, Rural and off-grid area, kW, Mbulu, Tanzania*

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I. Introduction

Background

Micro-hydropower energy resources are renewable energy technologies that have a large and sustainable potential for electricity and power generation in developing countries like Tanzania and especially in the rural village community areas where there is no electricity connection from the national grid [1]. The micro-hydro turbine technology can play a very important function by providing electrical power to the rural and off-grid areas in developing countries like Tanzania where there is no future plan for the grid extension. The technology is basically relying on a fast water flowing stream which has been channelled through a pipe (penstock) that is directed to a turbine which is connected to a generator and produce electricity as shown in Figure 1.1 below.

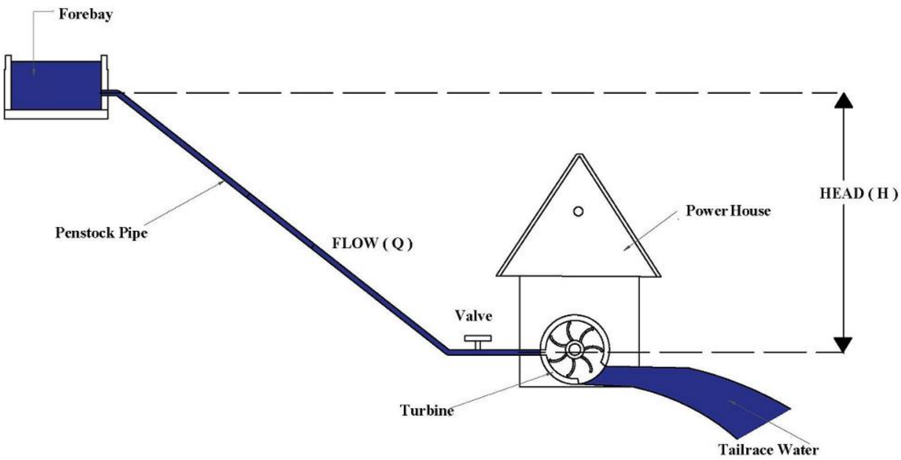

Figure 1.1: General layout - micro hydro system

Literature has shown that there are several combinations of renewable energy technologies at the micro level on which some of them includes several combinations for integrated micro-hydro turbine with solar PV, wind systems and energy storage systems [2] etc.

In Tanzania, micro and small hydropower potential are not well known but recent studies estimate at around 250 MW [3]. Few scholars have highlighted the reasons as to why despite huge potential, most of the micro hydro potential in developing world like in Africa have not been much exploited and developed [4]. When considering among the hydropower-based energy technologies, small hydropower (micro hydro and mini hydro) are the only classes that suit best with typical conditions of several off-grid and rural areas of developing countries especially in Africa [5]. But despite their technological advantage, there has been very little on their development and the level of installations is very low and this is due to several factors which among them include, small hydropower technologies is quite lacking in the region and other factors that are taken into account include financing and policy issues, which in recent years has been addressed [6, 7]. Despite these challenges, still, micro-hydropower can be set up in the rural and off-grid areas with minimal investment cost from the private investor or government subsidies and also within a short period of time with the local community ability to take charge of the plant [8, 9]. In remote areas where the energy demand of the rural communities is mostly limited to several local villages, micro-hydropower schemes are the best suitable technology that can meet the energy needs because they can be adapted to the local demand and also are able to integrate with other renewable energy systems.

In Tanzania, one of the potential sites for the development of the micro-hydropower technology is in the Mbulu district in Manyara region, North-West of Tanzania. The local area has water resource from a river called Hhaynu which has the potential to develop a micro-hydropower that will be able to supply electricity to the local off-grid villages. The lack of reliable power sources in the villages made the local farmers to send their post-harvest crops to the nearby towns which is costly due to the nature of transport and road networks. This in turn, increases the prices of processed crops like maize flour and rice in the local villages. In additional to that the local schools and health centres are not supplied with reliable electricity, as a result, the local quality of education has dropped significantly in recent years and also health care services to children and pregnant women has been affected significantly as compared to the neighbouring nearby villages with access to electricity [10].

Despite this potential, research in renewable energy development in recent years in off-grid remote areas of developing countries like Tanzania has been focusing on the integration of different renewable energy technologies to effectively and efficiently utilise the available energy resources [11]. This is due to the effects caused by the dynamic nature of load demand, a variation of water flow rate for micro-hydropower development which have been caused by seasonal climate changes, multipurpose water usage in streams and rivers eg. Irrigation and water supply usage [12].

To address these problems, a reliable energy source needs to be developed in the local area that will supply sustainable energy to the available load demand power for the local community and also integrate with the local economic activities in the area and this is what this research project work will be addressing.

Problem statement

Many research studies have shown that majority of micro-hydropower plant installations are in off-grid rural and remote areas of the country and the available load demand power is relatively low due to low economic activities and low population density in those areas. This effect causes more power to be produced than it can be consumed on which an energy storage option may be a better solution. But due to the cost limitation on investment, most of the micro-hydropower plants prefer to use battery energy storage (cheaper option) for storing electrical energy that is produced [13]. Based on the small power plants in operational, the commonly used storage batteries in micro-hydropower plants have limited storage capacity, charging and discharging efficiency and low service life. When install these battery systems in a micro-hydro it leads to a large percentage of excess electrical energy to be dumped to the ballast as thermal loads which is a power wasted especially during low demand hours of the day [14]. So due to this effect, different kinds of energy storage systems which are used today need to be studied and analysed in order to bridge the gap in the knowledge which lies on the optimization of the available excess electrical power produced from the micro-hydropower plant that will result to a minimum power loss to the dump loads and also the use of renewable energy storage system which is environmentally friendly like the use of hydrogen energy storage.

Contribution to the knowledge

Many existing literatures and research reports have highlighted the usefulness of installed micro-hydro turbine system for supplying electricity to the rural and off-grid areas. There are different kinds of micro-hydro turbine technology but in terms of their configuration, both types are used to supply constant power to the load demand in the local community. Studies have shown that the load demand power is not constant and changes each hour of the day and this does not coupe with the power supply capacity [15]. This unbalancing power between the supply and the demand causes excess electrical power to be produced in the micro-hydro system.

To reduce this effect, most of the existing installations and research reports shows that several micro-hydro turbine system designs include a dump load component on which all the excess electrical power produced is diverted into these dump loads. Depending on the available load demand power at the available time, the amount of dump load power capacity can be up to the rated power capacity of the micro-hydro turbine which is a lot of power wastage.

Some of the literature also shows that few of the micro-hydro turbine system uses the excess electricity produced to be stored in battery storage systems which is the common method of energy storage used with the micro-hydropower system [16]. But due to cost limitation, conversion efficiency and storage capacity, the battery energy storage systems do not provide enough capacity to the required load demand power and their installation does not reduce significantly or eliminate the availability of dump loads on the micro-hydropower systems.

II. Materials and Methods

System Layout

The general layout of a micro hydropower system configuration consists of mainly three main areas that include the intake system which mainly comprises of civil components, while the other part is the turbine system which mainly consists of mechanical components and the last part is the generator and load system which is mainly electrical system components as shown in the Figure 2.1 below.

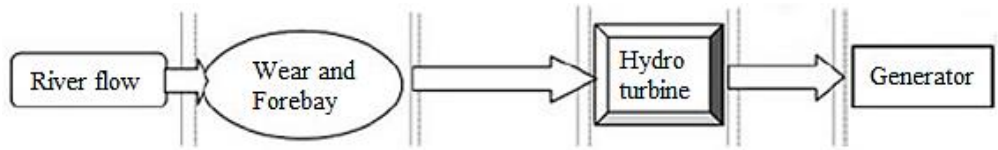

Figure 2.1: Schematic layout diagram of the hydro turbine-generator system

For the micro-hydro turbine system with small output power and not connected to the grid (off-grid), the generator power is usually supplied to the main load but during low demand, the excess power is diverted to the ballast loads using the generator controller as shown on Figure 2.2 below.

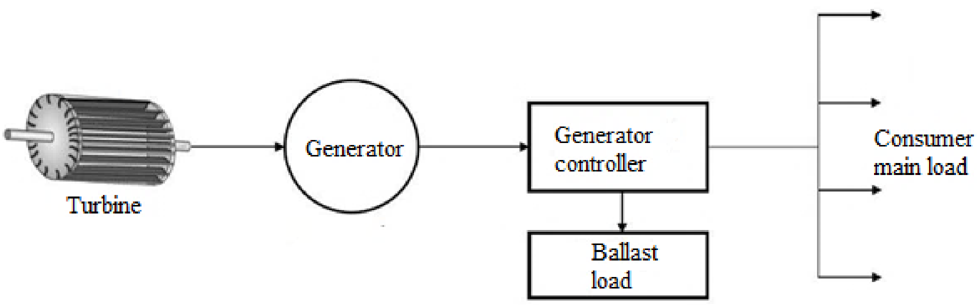

Figure 2.2: Layout diagram of the hydro turbine-generator and load system

Design methodology

The design of a micro-hydro turbine system with an integrated energy storage system using the developed system layout is undertaken by using a number of design equations and relations as shown in detail in the following sub-sections.

Micro-hydropower system

The micro-hydro turbine system uses the power of moving water to drive a turbine that rotates the generator system which produces electrical energy. This electrical power output is used to supply power to the consumer load demand.

Power and energy supply

In order to obtain the power supply, the mechanical (turbine) power need to be obtained first using the following equation:

$$Q_{site} = S_f \left[\frac{A_{site}}{A_{Catchment}}\right] Q_{catchment} \quad (2.1)$$

where from site data; Q_{site} = river flow average discharge at the site location (0.9 m^3/s), $Q_{catchment}$ = catchment flow discharge from the run-off (23.5 m^3/s), A_{site} = site area (37,500 m^2), $A_{catchment}$ = catchment area (112,500 m^2) and S_f = scaling factor (0.115)

During the turbine design, the obtained mechanical power is used to drive the generator system and the output electrical power supply value is given by the following equation:

$P_{MHP(t)} = f(QH)$ which gives the following equation:

$$P_{MHP(t)} = gQH\eta_{turbine} \ (kW) \quad (2.2)$$

where $P_{MHP(t)}$ = micro-hydro turbine power (mechanical power), g = acceleration due to gravity (9.81 m/s^2), Q = discharge at the site (m^3/s), H = effective pressure head (m), $\eta_{turbine}$ = turbine efficiency and $\eta_{generator}$ = generator power

Note: Mechanical power $P_{MHP(t)}$ is related to the generator power $P_{MHP(g)}$ by the following:

$$P_{MHP(g)} = P_{MHP(t)} \times \eta_{generator}$$

During the system operation, the designed micro-hydro turbine system does not provide 100% of the required power supply capacity, so in order to determine the actual turbine capacity factor the following equation is used:

$$Cf\ (MHP) = \frac{P_{avg}}{P_{max}} \quad (2.3)$$

where $Cf_{(MHP)}$ = macro-hydropower capacity factor, P_{avg} = average power output and P_{max} = maximum power capacity

Consumer load demand

The load energy demand is the amount of energy that the consumers use when supplied by the available electrical power at a given time from the micro-hydro turbine system and is given by the equation:

$$E_{D(hourly)} = \sum_1^n (P_{D(hourly)} \ x \ t) \quad (2.4)$$

where: $P_{D(hourly)}$ = hourly power demand value (kW), t = time of usage (hour) and
n = number of electrical items

Excess power and power deficit

When the power supply from the micro-hydro generator system is higher than the available consumer load demand power then the excess power is produced which is given by:

$$P_{MHP(excess)} = P_{MHP(g)} - P_D(l) \quad (2.5)$$

For the excess power to be produced, the above equation must produce a positive value i.e. ($P_{MHP(g)} > P_D(l)$) and when the above condition produces a negative value i.e. ($P_{MHP(g)} < P_D(l)$) then the obtained value is the power deficit.

Dump load

Dump loads are obtained when the total excess power obtained from the micro-hydro turbine is not utilised and hence it is shunted to the ballast units to protect the generator system. The amount of dump load depends on the amount of excess power available and is given by the following equation:

$$E_{MHP(dump)} = \sum[(P_{MHP(excess)} - P_{stored}) \ x \ t] \quad (2.6)$$

where P_{stored} = stored power

When there is no provision for power storage in a micro-hydro turbine system, then all the excess power produce is sent to the dump loads as shown in the equation below:

$$E_{MHP(dump)} = \sum(P_{MHP(excess)} \ x \ t) \quad (2.7)$$

Energy storage

In order to reduce power loss due to the dumping of excess electrical power, the possibility of energy storage needs to be considered. Several energy storage combinations are available with the micro-hydro turbine system but in this research study two (2) energy storage systems have been studied, i.e. battery storage and hydrogen storage.

Battery storage

The battery system is another option that has been integrated with micro-hydro system for energy storage. The battery system uses excess electrical energy to store power that will be used to supply peak demand and load deficit. In order to store excess power in a form of energy to the batteries, the minimum size of the battery storage need to be determined first and also the total energy deficit value needs to be calculated based on the hourly average values from 18:00 hours to 22:00 hours as follows:

$$E_{D(deficit)} = \sum(P_{D(deficit)}\ x\ t) \qquad (2.8)$$

where $E_{D(deficit)}$ = energy demand deficit, $P_{D(defict)}$ = power demand deficit and t = time during power deficit

The total energy deficit can be used in the calculation of the battery storage capacity using the following equation:

$$B_{storage(c)} = \frac{E_{D(deficit)}\ x\ t}{\eta_{inv}\ x\ DoD\ x\ V_{battery}} \qquad (2.9)$$

where $B_{storage(c)}$ = battery storage capacity in Ah, t = time in days of autonomy, η_{inv} = inverter efficiency, DoD = depth of discharge and $V_{battery}$ = nominal battery voltage.

For the battery storage analysis, the following parameters have been used:

(i) Inverter efficiency of 85% (conversion efficiency from AC to DC)

(ii) Overall round-trip battery efficiency of 60%

(iii) Days of autonomy to be one (1) [Note that the batteries will supply power to the load deficit which is round 5 hours each day]

(iv) Battery nominal voltage to be 24V

In the system design, the selected batteries for use are the lead acid type with a single per unit battery storage capacity of 400 Ah, so the minimum amount of batteries required to supply the power deficit per day is given by:

$$N_{battery\ (min)} = \frac{B_{storage(c)}}{B_{storage(c/u)}} = \frac{B_{storage(c)}}{400} \qquad (2.10)$$

where $N_{b\ (min)}$ = number of battery units, $B_{storage(c)}$ = total battery storage capacity in Ah and $B_{storage(c/u)}$ = per unit battery storage capacity in Ah

But because the lead acid batteries have special characteristics called state of charge, on which they must be charged to 100% and discharged to a minimum of around 40%, so in this case the useful storage capacity of the battery that needs to supply energy to the power deficit is 60% and this is called depth of discharge value (DoD).

In this case, the maximum battery storage capacity required to supply the required energy deficit is calculated using the following equation:

$$B_{storage(c)\ [max]} = \frac{B_{storage(c)}}{DoD} \qquad (2.11)$$

Then the maximum number of storage batteries to be used in the storage system is calculated by using the following equation:

$$N_{b\ (max)} = \frac{B_{storage(c)(max)}}{B_{storage(c/u)}} \qquad (2.12)$$

The power supply from the micro-hydro turbine is in AC current while the battery uses DC power, so there is a need for AC-DC conversion using inverter-charger. In calculating charging or discharging current, the system phase voltage needs to be considered and since the turbine-generator system is in three phases and the inverter-charger is in a single phase, then charging or discharging current need to be converted to a single phase using the following equation:

$$I_{(AC)} = \frac{P_{MHP(g)}}{(\sqrt{3}\ x\ P_F\ x\ V_o)} \qquad (2.13)$$

where $P_{MHP(g)}$ = power value (+ve is charging and –ve is discharging), PF = power factor of resistive impedance load (1.0) and V_o = phase output voltage (240V).

But the battery storage system uses DC current during charging, then the calculated AC current value needs to be converted to DC current using the following equation:

$$I_{(DC)} = \frac{I_{(AC)}}{P_F} \qquad (2.14)$$

where P_F = power factor (usually 0.8 for Inductive loads).

Power factor of an AC power system is the ratio of the real power consumed by the electrical load to the apparent power flowing in the electrical circuit. Example of P_F values for some designed inductive electrical loads ranges between 0.5 to 0.98. In the generator system, the P_F value is used because electrical generator sets are rated in kVA at 0.8 power factor lagging, so in conversion from kVA to kW rating the P_F value of 0.8 is used eg. 100kVA generator rating produces 80kW of electrical power.

Design configuration

There are several electrical energy storage options that could be used with a micro-hydro turbine system but in this research study, two main options have been studied and analysed that include the following:

(a) Micro-hydro turbine system with battery storage
(b) Micro-hydro turbine system with hydrogen storage

In the above system design configuration options, the daily load demand power deficit is supplied from the energy storage system by using excess electrical energy to charge the battery for the battery storage and to produce hydrogen for the electrolyser system as shown in block diagram in the Figure 2.3 below.

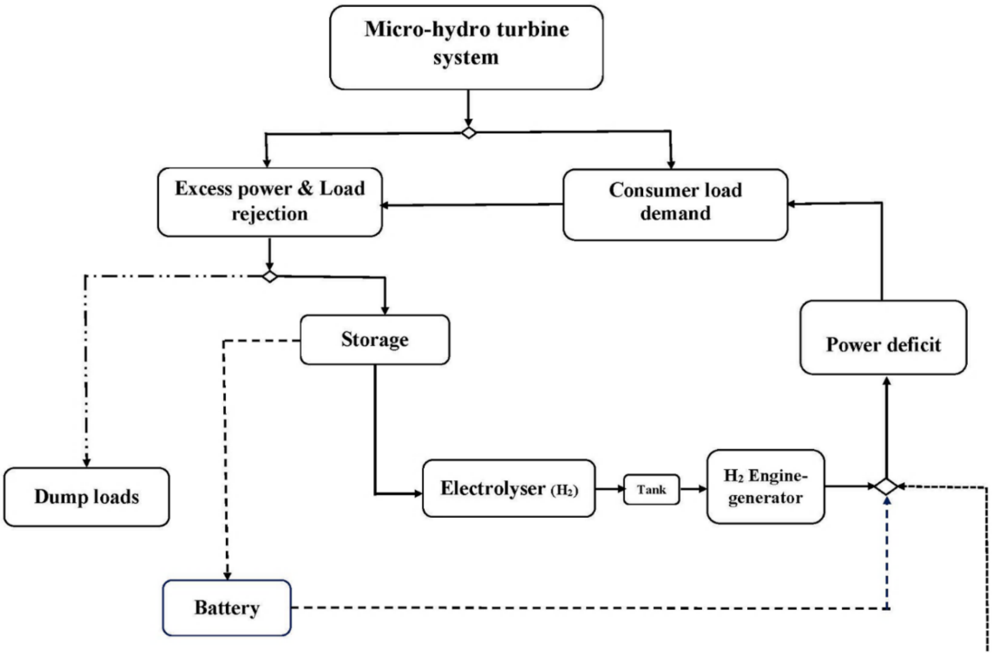

Figure 2.3: Systems design configuration

The design configuration for the micro-hydro turbine system has been focusing on supplying power to the consumer load demand. But results from the existing system design shows that the micro-hydropower system without energy storage is not able to supply enough power to the peak hours of the day, hence causes power deficit. This effect in power shortage and the option of supplying additional power to the load demand during peak hours has been analysed and evaluated in detail with the results from HOMER optimization model for renewable energy in the sub-sections below by integrating the micro-hydro turbine in the following energy technology system combinations:

(a) Micro-hydro turbine system without energy storage
(b) Micro-hydro turbine system with battery storage
(c) Micro-hydro turbine system with hydrogen storage

From the feasibility study data, the amount of water flow discharge taken from the river to the turbine through the penstock pipe is 0.45 m^3/s. This water flow amount through a turbine together with the site head elevation level of 25m will result in the generator power produced from a turbine amounting to 75.5 kW. Most micro-hydro turbine system like Hhaynu operate as a run-of-river system which takes water directly from the river only the amount required to produce electricity and with no water storage or reservoir facility.

Micro-hydro turbine system without energy storage

The system configuration for the micro-hydro-turbine system without any form of storage consists of water intake, piping system, controls, turbine and generator system. In this design, the water flow discharge from the river will be used to power the turbine and supply the required energy demand for the community. From the feasibility study data, the amount of water flow discharge taken from the river to the turbine through the penstock pipe is 0.45 m^3/s. This water flow amount through a turbine together with the site head elevation level of 25m will result in the generator power produced from a turbine amounting to 75.5 kW. Most micro-hydro turbine system like Hhaynu operate as a run-of-river system which takes water directly from the river only the amount required to produce electricity and with no water storage or reservoir facility as shown in Figure 2.4 below.

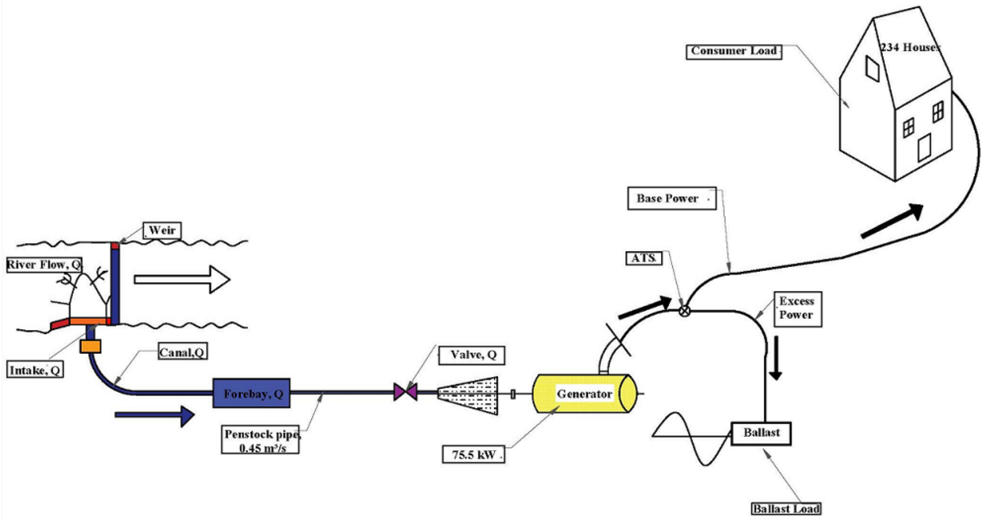

Figure 2.4: Hydro-turbine system configuration without storage

In the above system design layout and when considering the daily energy demand (low and high) with the energy supply in the area without the energy storage option, it is obviously that the micro-hydro turbine system without integrating it with the energy storage will not be able to supply the required energy deficit needed during the peak hours of the day.

So, in this case, a viable energy storage option needs to be considered and one of the possible scenarios to integrate micro-hydro turbine system with an innovative renewable energy storage system like the use of hydrogen storage or battery energy storage that will supply the required energy deficit during the peak hours of the day.

Due to the absence of storage component on this system design, the power produced from the micro-hydro turbine has high renewable energy penetration and this effect causes stability problem on the system. The stability issue, in this case, is related to the generator over speed due to excess power produced which makes this system design layout not a very suitable option.

Micro-hydro turbine system with battery energy storage

In this layout, an additional system to the micro-hydro turbine system which is the battery energy storage component has been added in order to store excess electrical energy produced by the main power supply. The system works in such a way that the micro-hydro turbine system is the main power source supplied to the load demand and during the power production some of the excess energy produced is not wasted but sent to the battery system for storage. Due to the nature of the battery system, the excess power produced from the main source needs to be converted to DC power by the use of a converter. A converter can be used to convert AC to DC during charging and also DC to AC during discharging. In controlling power to the different components, the power management unit called Automatic Transfer Switch (ATS) is used which allows power output to be directed to different consumer loads. In this system design, the battery system will only take around 7% of the energy produced while consumer load takes 66% of the energy produced. The rest of the available power produced which is around 27% of the energy produces will be available as excess power and because of no usage it is sent to the dump loads as shown in schematic diagram in the Figure 2.5 below.

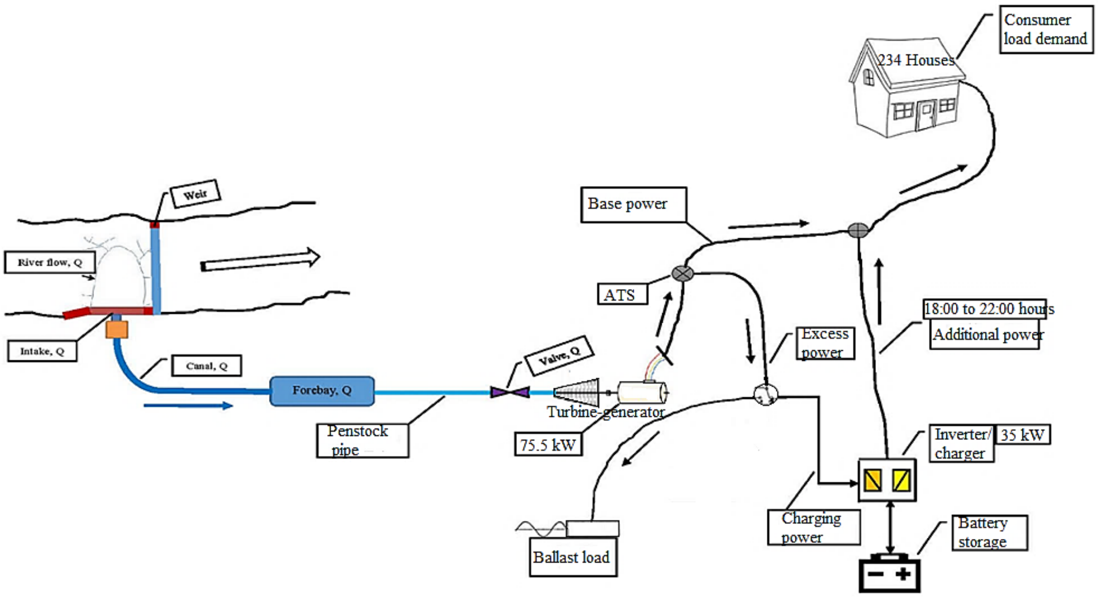

Figure 2.5: Micro-hydro turbine with battery energy storage

The battery energy storage option, in this case, has been selected due to its quick power responses, so it is best suitable during the power demand spikes and quick response power supply hours eg. during peak hours of the day. The limitation of the battery energy storage option is its low in energy storage capacity and also frequency replacement cost [17], thus it should only be used to supply intermittent load demand during the peak hours of the day. In calculating the battery storage capacity, the following configuration on Figure 2.6 has been used.

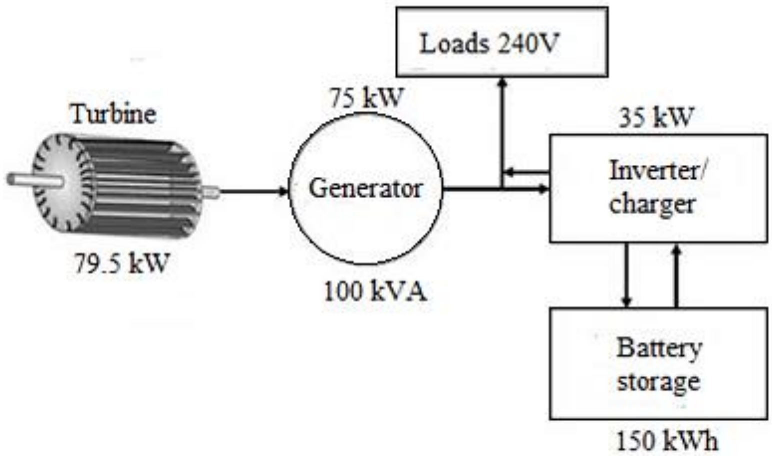

Figure 2.6: System configuration for the hydro turbine with battery storage

Micro-hydro turbine system with hydrogen storage

In this integration, the system design consists of a micro hydro-turbine system which will be used to supply the base load and because of surplus power to most of the time, additional systems are added. This include an electrolyser system together with hydrogen ICE engine-generator. Electricity surplus during low demand is used to power this additional system, especially during the night hours. Electrolyser is used to produce hydrogen gas by the electrolysis of water. During the peak hours of the day the micro-hydro turbine is not able to supply the required electricity demand and in this case, peak electricity demand is supplied by the ICE engine-generator system which is fuelled by the hydrogen gas. In this system design layout, no electricity storage is provided, instead the excess power produced is supplied to an electrolyser system. For safety reasons, the ballast loads are installed to consume the power due to abrupt changes in consumer load and load rejection. The electricity supply from the micro hydro turbine to the consumers, electrolyser and ballast loads are controlled and managed by automatic transfer switch (ATS). The produced hydrogen from the electrolyser is stored in a tank and is used to power the engine-generator system that supply additional electricity needed during the peak hours. On the other hand, the excess hydrogen produced by the system will be sold to the local fertilizer and oil industries to be used in the production of fertilizers and oil refinery processes respectively.

The advantage of this system layout as compared to the previous systems is that there is no energy storage with the batteries or pumped storage which have some drawbacks and also additional electricity supply during the peak hours is done by the hydrogen supplied ICE engine-generator which seems to be a viable option because no excess electricity is lost to the ballast loads in this design layout as shown in Figure 2.7 below

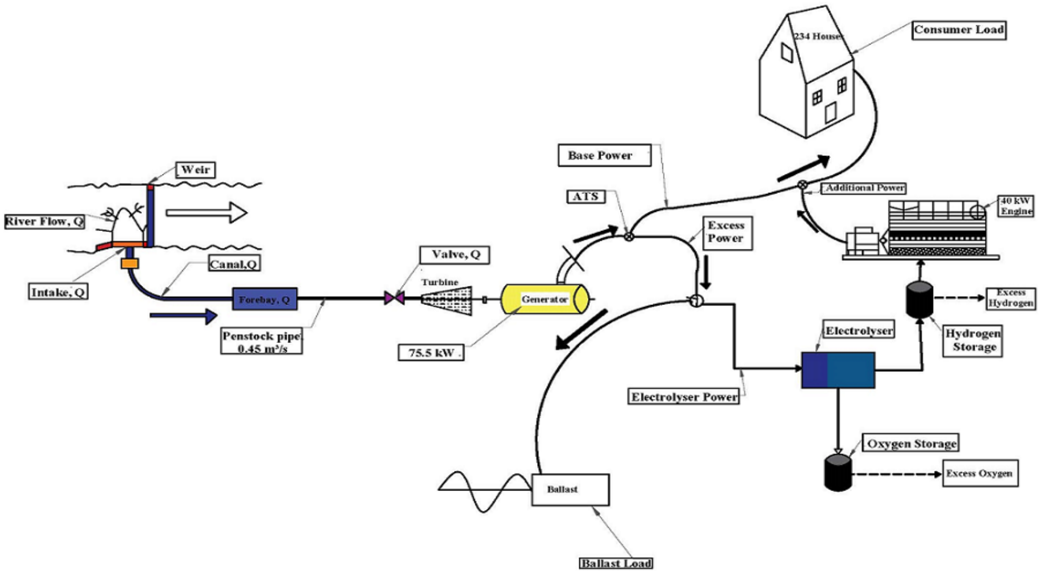

Figure 2.7: Micro-hydro turbine with an electrolyser and hydrogen engin

III. Results and discussion

Micro-hydropower without storage

The daily power produced from the turbine system is supplied to the consumers in the local area and the study shows that the available load demand is not constant while the power supply is at a constant value. This fluctuation in the power demand, causes effect to the available power supply on which during low demand hours more power is produced than it can be consumed by the available load demand power hence excess power is accumulated while during the high demand and peak hours less power supply is available which result to power deficit on the system. The characteristics of this system configuration is that there is no energy storage option which means that the available power produced at a particular time is only supplied to the available power demand at that particular time of the day. This phenomenon of micro-hydro turbine system to produce more power than the available load demand will result in the instability of the generator system by increasing its speed and frequency. In order to reduce this effect, most micro-hydro turbine systems are installed with the ballast loads component which is used to consume all the excess power and load rejection as shown in Figure 3.1 below.

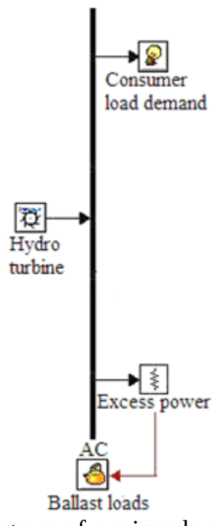

Figure 3.1: Schematic diagram of a micro-hydro turbine without storage

For this option of a micro-hydro turbine without energy storage, the system can be represented as a single power supply source with the main and only power output comes from the micro-hydropower system. The optimized system design values from the model results shows that the peak power demand is around 101.8kW which is specifically at 19:00hours each day and the total energy demand per day is 1,114.38kWh/d which must be supplied by the hydropower system.

Due to the absence of storage component on this system design, the power produced from the micro hydro turbine has high renewable energy penetration and this effect causes stability problem on the system. The stability issue, in this case, is related to the generator over speed due to excess power produced which makes this system design layout not a very suitable option.

On the other hand, during the low demand phase or off-peak hours, part of the power produced from the hydro turbine is used by the main load while the excess available power is sent to the ballast loads in order to stabilize the system. For this study, the minimum demand power value from the consumer load is around 8.42kW (after mid-night) when the turbine is producing 40kW (53.33% of rated capacity) power supply, thus in this case around 31.58kW is sent to the ballast load using Electronic Load Controller (*ELC*) and Automatic Transfer Switch (*ATS*). The energy production and consumption from the micro-hydropower is based on the results from the optimization of the system design. In this case, the average power produced from the optimized micro-hydro turbine system is 70.12 kW while the nominal capacity is 75.5 kW.

On the other hand, excess electricity produced seems to be high at 39.6 % of the total hydropower production which is equivalent to 666.8 kWh/d and this is because of high hydro penetration. The optimization results also show that the occurrences of excess power at different power capacity values. The minimum excess electricity value produced in this system design is 2.5 kW which occurs during the high demand hours that is mostly in the afternoon and evening hours while the maximum excess electricity value of 62.5 kW is produced during the night hours. The usefulness of knowing excess electricity values at a different time of the day is to be able to properly design the shunt load rating capacity. Thus, in this system design option the selected ballast load values should have a minimum of 2.5 kW and a maximum of 62.5 kW rating capacity in order to consume all the excess power that the system will produce a different time of the day as shown on Figure 3.2 below.

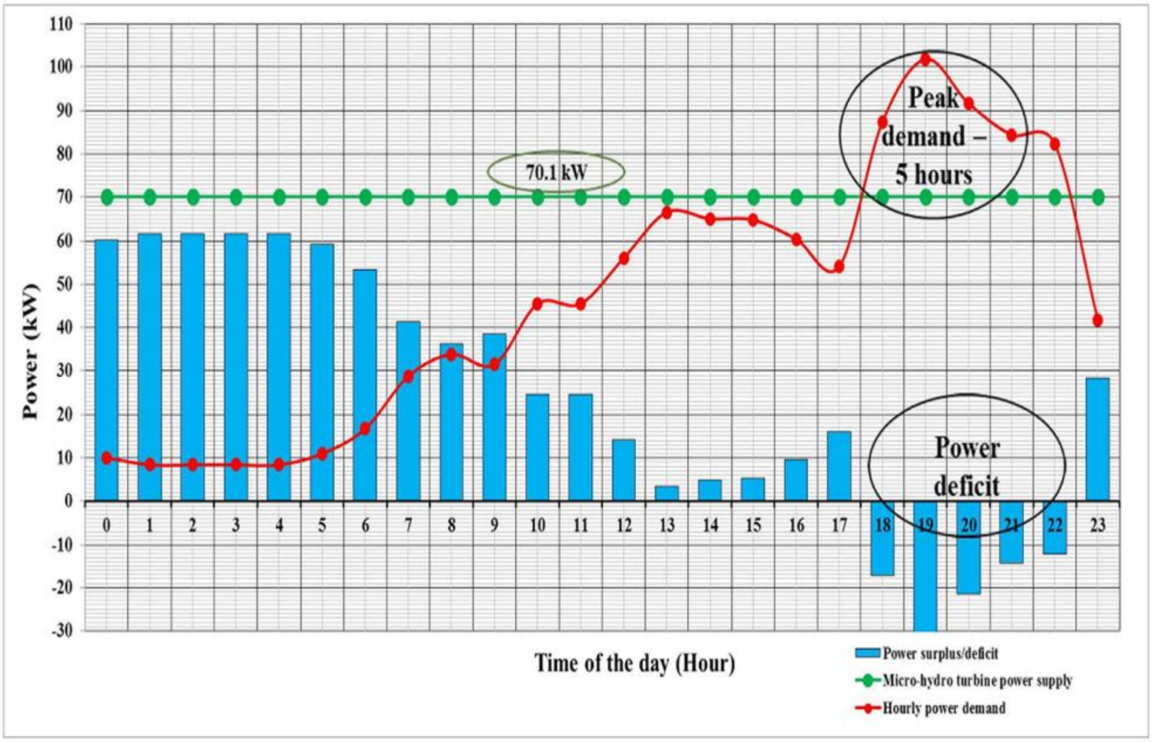

Figure 3.2: Micro-hydropower supply and power demand with surplus/deficit

Micro-hydropower with battery energy storage

The performance of a micro-hydro turbine system with battery energy storage have been analysed using Homer Energy software on which the design data have been optimized to obtain the best system values. In this case, there are both AC and DC busbars that are interconnected by a converter. The AC power source from the micro-hydro turbine system supply power to the load demand and converter system that convert AC power to DC power for charging the batteries. The ballast loads in this system design makes use of the excess energy produced from the hydro turbine system during the low demand hours and serves as safety system (power sink) during abrupt excess power production or power rejection in order to stabilise the generator system as shown on Figure 3.3 below.

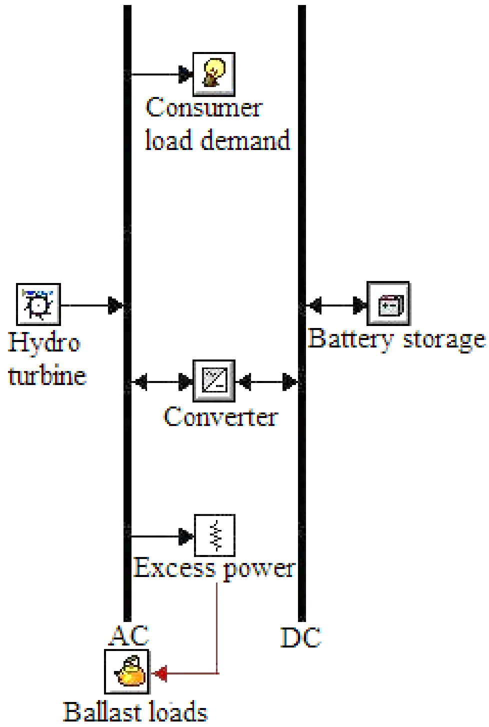

Figure 3.3: Schematic diagram of a micro-hydro turbine with a battery storage system

Based on the design calculations and also simulation results, it is conclusive that in order to supply the required load demand from the battery storage during the peak hours of the day, the available energy storage capacity from battery system must be at least 72.35 kWh. On the other hand, it should be noted that the excess power for battery storage comes from the micro-hydro turbine system and is in *AC* power while the battery system uses *DC* power

The produced energy need to supply power to the AC primary load amounting to 406,269 kWh/year (66%) for the consumer load demand, 43,000 kWh/year (7%) for the battery storage from the converter and 165,710 kWh/year (27%) as excess energy to the ballast loads as shown in Table 3.1 below.

Table 3.1: Micro-hydro turbine with a battery storage system

Item	kWh/year	%	Remarks
Micro-hydro turbine	614,284	100	Production
AC primary load	406,245	66	Consumption
Excess energy (ballast loads)	165,710	27	Consumption
Battery energy storage	43,000	7	Consumption

Micro-hydropower with hydrogen energy storage

For the micro-hydro turbine with an electrolyser and hydrogen engine-generator, the system architecture have also been developed and optimised by Homer Energy System Software and based on the energy supply and demand results, the system will consist of 75.5kW micro hydro turbine as a primary power supply, 40kW engine-generator system as a secondary power supply, 70 kW electrolyser system, 1,114.38 kWh/day consumer load demand and dump load (ballast). The electrolyser system is operated during the low demand hours of the day and supplied by the the excess electricity from the micro-hydro turbine. The produced hydrogen gas in the system design will be stored in a hydrogen tank and with the maximum storage tank capacity of 30 kg as shown in Figure 3.4 below.

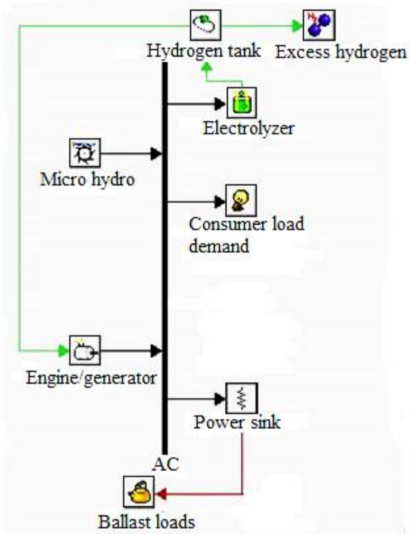

Figure 3.4: Micro-hydro turbine with an electrolyser and hydrogen engine-generator

In this system design, an additional source of electricity production is from the hydrogen ICE engine-generator system with the 40kW rated capacity which will be operating during the peak hours and power deficit hours of the day. In comparison between the two electricity production sources, the hydro turbine will have the major contribution of around 95% of the power supply while the engine-generator can only supply around 5% of the required load which is mainly during the peak load demand hours of the day.

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Energy consumption is also divided into two main categories, which are AC primary load that accounts for about 63% of the total load demand and an electrolyser load for the hydrogen production that accounts for about 37% of the total load demand. These two consumer loads are the main energy consumption for the system on which there is no excess electricity that is produced and sent to the ballast loads as shown in Table 3.2 below.

Table 3.2: Annual energy production and consumption

Item	**kWh/year**	**%**	**Remarks**
Hydro turbine	614,284	95	Energy production
Engine/Generator	35,374	5	
A/C primary load	406,269	63	Energy consumption
Electrolyser load	243,385	37	

Hydrogen production

The produced pressurized hydrogen gas is stored in the storage tank and in this system design, the rated capacity of the hydrogen tank is 30 kg. Based on the available excess electricity the produced hydrogen storage tanks will have the following characteristics from the design optimization results as shown in Table 3 below.

Table 3.3: Hydrogen storage tank capacity

Quantity	Value	Units	Remarks
Maximum tank storage	30.0	kg	Rated capacity
Energy storage capacity	1,000	kWh	1 MWh
Tank autonomy	21.6	hours	
Minimum tank storage	15.0	kg	50% rated capacity

In this case, the minimum tank level that the system can operate is 15 kg (50% rated capacity) which is often available at the beginning of the cycle while the maximum tank level for hydrogen gas storage is 27 kg (90% rated capacity) at the end of the cycle year. Based on this result, the tank level can operate at a range of 12 kg (40%) capacity throughout the year.

The hydrogen tank level capacity between 15 kg to 27 kg operated at different cycles in a year and the frequency of occurrences at this capacity rage is between 0.5% and 15.4%. Lowest and highest hydrogen tank capacity levels occur at around 0.5% of the time and 1% of the time respectively. The most frequency tank level capacity occurs at around 15.4% of the time with the capacity of 23 kg (76.67% rated capacity). For safety reasons, the tank level is only filled from 50% rated capacity to 90% rated.

Hydrogen ICE-Engine

The common hydrogen powered engines have been developed by converting Internal Combustion Engine – ICE (petrol engines) to run on hydrogen and they are similar to any standard ICE engine. The only difference is that the hydrogen engines run on hydrogen as fuel and emits very low NOx emissions and zero CO_2 when compared to other engines, hence they are very environmentally friendly engines. The hydrogen engine (H_2-ICE) in this research study will be coupled with a generator system which provides additional electricity during the peak hours of the day. The produced hydrogen gas from the electrolyser will be fed to the engine as fuel and run for 5 hours each day at different power capacities. From the system design optimization results, the rated capacity of the engine-generator is 40 kW. The engine capacity selected is available commercially with the use of different fuel gases as shown in Table 4 below.

Table 3.4: Hydrogen engine-generator system capacity (simulation results)

Quantity	Value	Units	Remarks
Hours of operation	1,825	hours/year	5 hours/day
Number of starts	365	starts/year	
Operational life	8.22	years	
Electricity production	35,374^a	kWh/year	Production
Mean electrical output	19.4	kW	
Minimum electrical output	12.2	kW	
Maximum electrical output	31.7	kW	
Hydrogen consumption	2,074	kg/year	Gas consumption
Specific fuel consumption	0.059	kg/kWh	
Fuel energy input	69,120^b	kWh/year	
Energy efficiency	51.2^c	%	

Note: Density of Hydrogen (H_2) gas = 0.090 kg/m^3 @ 0^0C/32^0F, 1 bar and $c = \frac{a}{b}$

From the above Table 6.12, the energy efficiency is calculated based on the ratio between the electricity production (kWh/year) to fuel energy input (kWh/year) and the specific fuel consumption is the ratio between hydrogen consumption (kg/year) to electricity production (kWh/year). Based on the above simulation results which shows that energy efficiency value is above 50% and this conclude that the system design specifications are on the recommended range for the chosen engine-generator size. The engine specific fuel consumption is determined in terms of how much quantity of gas consumed (kg) in order to produce a unit amount of energy (kWh) and from the design calculations, the specific fuel consumption is 0.059 kg/kWh.

The interpretation of this value is that, for every 0.059 kg of fuel hydrogen gas consumed by the engine unit can produce 1 kWh of electrical energy on which this can be interpreted as 1 kg of fuel hydrogen gas can produce 16.95 kWh of energy (which is 50.9% of the LHV)

From the results of the system design and also analysis of the above energy storage options, the use of electrolyser system and hydrogen engine-generator system which is currently available on the market have significantly reduced the loss of excess electricity to the ballast loads (waste electricity) and this resulted to the increase in the energy storage capacity as compared to the battery energy storage system.

System optimization

In order to fully optimize the available power from the micro hydro turbine system for hydrogen production, the turbine system must be operated at its full capacity all the time. From the system design the rated capacity of the turbine-generator system is 75.5 kW but based on the simulation results this cannot be achievable due to the capacity shortage. So, based on this and in order to fully maximize the available power output, the use of simulation software have resulted to obtain an average power output from the turbine-generator system of 70.1 kW that must be supplied throughout the day in order to benefit with the max excess electricity production to supply to the electrolyser system. This resulted to the power supply from the micro-hydro turbine system being properly optimized to supply energy to the *AC* load demand and electrolyser system that produce hydrogen gas which is the fuel to power engine-generator system that supplies peak power as shown in Figure 3.5 below.

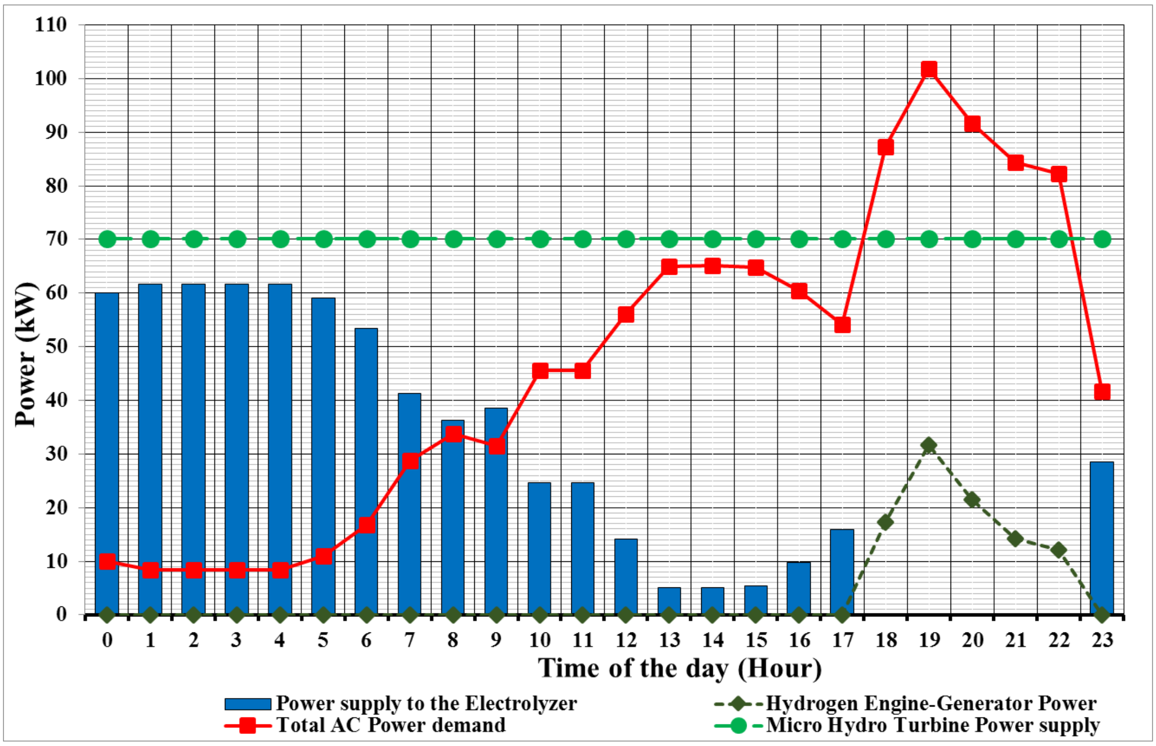

Figure 3.5: Optimized power supply and demand from micro-hydro and engine system

From simulation results, it has also been noted that the generator frequency changes are only applied to a certainly limit values of the generator speed drop and this is a special characteristic for most of the hydropower generator system that is related to speed/frequency changes and is called droop.

So, as a general remark and based on the positive results of energy utilization by using hydrogen gas that is produced by an electrolyser system as a fuel that is currently undergoing more research and development, it is obvious that the system design model of micro-hydro turbine with an electrolyser system and hydrogen engine promises better prospects in terms of innovations, better energy utilization, more research and development potential and hence it has been selected for the implementation.

IV.Conclusion

From the energy design calculations, the micro-hydro turbine system will produce a power capacity of 75.5 kW throughout the day but based on the energy supply and energy demand analysis, the micro-hydro turbine power capacity will not provide enough power during the peak hours of the day while during the low demand hours, more power is produced than it can be consumed. This situation causes un-balancing between the power supply and load demand, as a result, five (5) hours power deficit is observed during the peak hours of the day and excess power during the low demand hours of the day. In order to overcome this effect, the option of energy storage has been considered because the excess power production have reached up to 60 kW during the low demand hours.

In order to supply this power deficit during the peak hours of the day, an energy storage system has been considered to integrate with the micro-hydro turbine system. Several energy storage options have been studied and analysed in this research project which includes, micro-hydro turbine with battery energy storage and micro-hydro turbine with hydrogen energy storage. In all these energy storage options, the available excess electricity is stored in a form of chemical energy for the battery or hydrogen gas for the hydrogen system respectively. When evaluating the above storage options in terms of storage capacity, conversion efficiency, response time and energy content, the hydrogen energy storage system outperform the other option of battery energy storage despite its lowest usage in today's small scale energy storage technologies and based on these advantages it has been selected as a means of energy storage in this research study.

On the other hand, system design has also shown that, in order to fully maximize the hydrogen gas production to run the hydrogen engine-generator system to produce the required 35% additional power required during the peak hours of the day, the micro-hydro turbine system has to produce the maximum excess electricity possible, so in this case, it should be operated close to its rated capacity. Also, results from the simulation and power optimization shows that the micro-hydro turbine needs to be operated at an average power capacity of 70.1 kW (92.9% capacity factor). This will produce enough excess electricity to power a 70 kW electrolyser system and also additional power to supply to other auxilliary renewable energy systems.

So, based on the research study results, it is now clear that the final optimized system design for this project work is comprised of a micro-hydro turbine system which will supply the required base power, the electrolyser system which produces hydrogen and oxygen gas and hydrogen engine-generator system which supplies power deficit to the load demand. The designed micro-hydro turbine system optimization has increased energy utilization and minimizing energy losses which makes it different from other micro-hydro systems and satisfies the project objectives by answering all the research questions.

The general outcome of this research study and the developed project is that the availability of electricity in rural and off-grid area of Tanzania have shown a significance improvement in people's life in terms of improvement in local schools academic performance due to the increased study hours, improvement in the local health services, introduction of small business and agro-processing industries which have raised the incomes of the people and hence resulted to a significant poverty reduction in the village communities.

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