MODELING AND SIMULATION OF A MICRO-HYDROPOWER SYSTEM FOR RURAL ELECTRIFICATION (A CASE STUDY OF TEMECHA RIVER, AMHARA REGION, ETHIOPIA)

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DOI: https://doi.org/10.20372/zede.v41i.8628

ABSTRACT

It is well known that, there is an imbalance of electricity demand and supply in Ethiopia. Development of the Micro hydro power (MHP) system is an important technology to solve the problem. The main objective of this study was to do modelling and simulation of a micro-hydropower system for rural electrification in the case of Temecha River, Ethiopia. Yearly flow data were collected from Ethiopian Basins Development Authority and used to estimate the design flow rate. Next, modelling and simulation were done by using MATLAB SIMULINK. Some of the SIMULINK results were power and flow duration curves, and others. The nethead and design flow rates were found to be16.34m and 0.5731m^3/s, respectively. Based on the preliminary analysis, the turbine selected for the site is a Kaplan turbine. It is found that, the power output of this system is greater than the electricity demand of the selected site for 346 days of the year. Thus, the systemic found to be efficient in terms of generated electrical power as compared to similar works reported in the literature. The scale of the design can be re-modified to be implemented in other remote areas having river resources.

Keywords: electrical power, flow rate, Kaplan turbine, MATLAB SIMULINK, MHP, simulation

1. INTRODUCTION

According to a report by the World Bank [1], Ethiopia is the second most populated country in Africa with an estimated population of 114,963,583, next to Nigeria. The country has one of the fastest-growing economies in the world. Even though the demand for electricity is dramatically increased, the generation of power has not yet increased at the same proportion.

MoWIE also noted that[2] about56% of the total population lack electricity access. The lack of electricity in these areas affects the daily routines of the inhabitants who seek to earn a living [3].

The MHP is a class of hydropower plant system that generates power within a range of 11 to 500 kW. A MHP is categorized under run-of-river, small head, single purpose, and base load plant. One of the main reasons for MHP system development is due to the high demand of electricity in rural areas where small streams of water are locally available in many areas of Ethiopia. These systems have been used for a long time, particularly in the rural villages of developing nations. It can provide the best solutions to the sustainable development goals by providing electricity to support the local economy, education, health, and food and communications systems. To ensure their cost competitiveness for deploying a large number of systems in the future, they require further technological advancements, primarily the cost reductions and improvements in efficiency of MHP systems. Within this broader context of sustainable development, the aim of this research was to do modelling and simulation of a MHP system for rural electrification using MATLAB SIMULINK software. Technology wise, the system has additional features which will make it more valuable in the current market and provides an advantage for people living in rural areas [4].

Kilimo, A. S. G.,and Kahn, M. [5] have highlighted the possibility of using low-cost small hydropower plant that can supply power to communities which have small hydro potentials. Finally, the authors proposed the use of the merits of both synchronous and induction generators to reduce the investment and maintenance cost of the plant. If these are implemented properly, the plant is expected to be of low cost and hence, an economically viable power source for rural electrification.

According to some studies [6, 7], the steps followed in MHP developments include site visits, data collection, measurements, field surveys, meetings with local populations, and analyses.

A study on “Analysis of Micro Hydropower Generation for Rural Electrification”, showed that the fixed blade axial flow propeller turbine was one of the most cost-effective turbine options for the low head scheme [8]. As the paper states that in LoiUnn micro-hydropower project, 7 turbine-generator sets were installed. The capacity of the set was 3kVA (2.4 kW). Then, the total installed capacity was 21 kVA (16.8 kW). And, the utilized power was 13.8kW. Generally, the daily operating time was from 6 pm to 6 am because Loi Unn stream was enough to generate micro-hydropower throughout the whole year. But, in the rainy season, the excess water was diverted to the other side of the Loi Unn stream. After the implementation of the research on MATLAB Simulink software, the results that are found in the literature [8, 9] are that the turbine power and speed were directly proportional to the gross head, but there were specific points for maximum power and maximum speed in case of water flow variations.

In research [10], the author describes some problems related to energy crisis such as oil crisis, climatic change, electrical demand, and restrictions of wholesale markets a risen worldwide that leads to the increment of difficulties. This study aimed to suggest the need for technology alternatives that are used for generating electricity as near as possible of the consumption of site, using renewable and environmentally friendly energy sources such as wind, solar, and hydro-electric power plants. The system that has been done on this study is supplying power common electrical three-phase parallel RLC load. Finally, models were simulated using MATLAB Simulink. The simulation results show that with the proper choice of governing system for micro-hydro power plant leads to proper load sharing, constant voltage output, and constant speed with a variety of load values.

Additionally, Kusakana et al. [11] worked on “simulation and implementation of micro-hydro generation for small rural loads.” This study aims to develop a MATLAB/Simulink block of a simple run-off river micro-hydro system that could be used to simulate electricity generation at any location where the water resource and site conditions are suitable. They used data like water head, water flow and energy demand needed as input to the developed simulation models. Finally, the simulation results of the variation of the rotor angular velocity, the electromagnetic torque, and the stator voltages were included in their study.

Even though several works can be found for the micro-hydropower system in the literature, there is still a gap that is unsolved, the access of electricity distribution to rural areas like in Amhara region, Ethiopia.

2. MATERIALS AND METHODS

MATLAB SIMULINK was used for the simulation analysis of the system. Besides, the tasks like site selection, data collection, data analysis and others were done to finalize the modelling and simulation of a MHS for rural electrification in the case of *Temecha* River, Ethiopia.

The site is located at 10.5150N and 37.4870E. 345km far from Addis Ababa, Ethiopia to the North West and 285km far from *Bahirdar*, capital city of Amhara Regional state to the South East. The site elevation is within the range of 950 to 2800 mean sea levels [4]. The site selection was based on the scarcity of electricity access in the area and the all year- round flow of the river. The first step of this research after selecting potential site was collecting technical data (Head and flow rate) that were used for MHP development. Following this, the design approach combining theoretical expressions, extensive simulation and modeling were done. Finally based on the site data, method of turbine selection, determination of flow duration curve (FDC) and modeling each component of MHP has to be made and discussed. The methodologies that were followed to accomplish this research are summarized in Figure1.

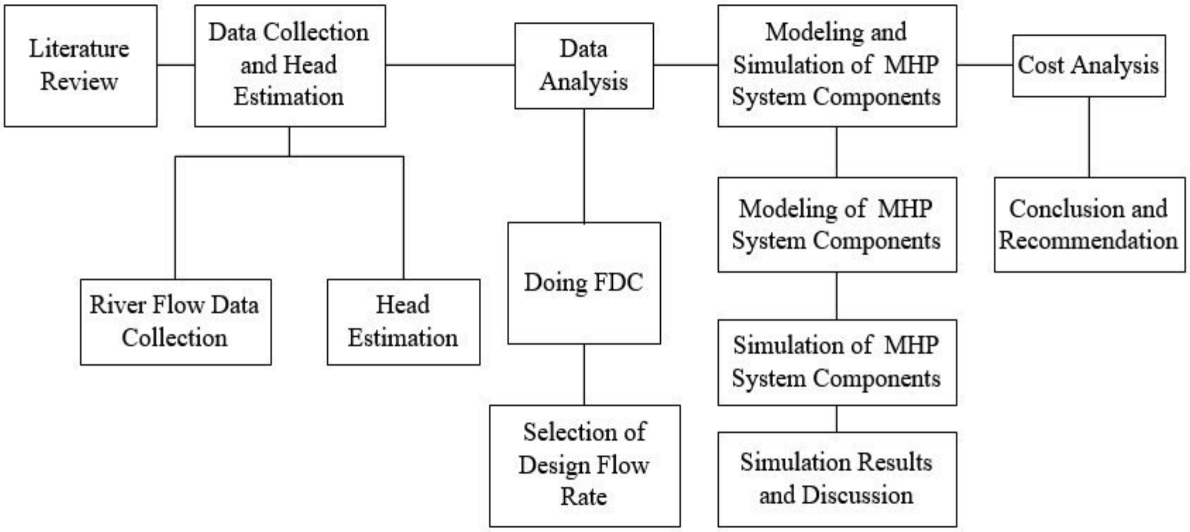

Figure 1 Methodology Flow Chart

Table 1 Summary of Load Demand Analysis

Time Interval	Load in kW	Time Interval	Load in kW
7:00AM-8:00AM	0	7:00PM-8:00PM	72
8:00AM-9:00AM	0	8:00PM-9:00PM	72
9:00AM-10:00AM	0	9:00PM-10:00PM	0
10:00AM-11:00AM	0	10:00PM-11:00PM	0
11:00AM-12:00PM	0	11:00PM-12:00AM	0
12:00PM-1:00PM	**72.72(Peak Load)**	12:00AM-1:00AM	0
1:00PM-2:00PM	0.72	1:00AM-2:00AM	0
2:00PM-3:00PM	36.72	2:00AM-3:00AM	0
3:00PM-4:00PM	36	3:00AM-4:00AM	0
4:00PM-5:00PM	36	4:00AM-5:00AM	0
5:00PM-6:00PM	36.72	5:00AM-6:00AM	23.16
6:00PM-7:00PM	72	6:00AM-7:00AM	22.44

3. RESULTS AND DISCUSSIONS

3.1`Load Demand Analysis

Table 1 shows the electricity demand analysis for the selected rural area. As seen from Table 1 and Figure 2, the peak load was around 72.72kW, the average load was 20.02 kW, and the minimum load was 0.72kW. In this case, the design analysis was done by taking the peak load value. Figure 2 indicates the summary of the load analysis for the selected rural areas. It was found out that, the area has around 1200 houses without access to electricity. The purpose of the electricity is for lighting, mobile charging, TV, microphones, and to drive machines like mill machine.

3.2. Determination of Flow Duration Curve

The flow duration curve (FDC), was used to assess the expected availability of flow over the time and the power and energy at a site and to decide on the “design flow” in order to select the turbine. Therefore, a stand-alone system such as a small hydropower system should be designed according to the flow that is available all year round; this is usually the flow during the dry and wet season. It is possible that some streams could dry up completely at that time [12].

Ideally, minimum flow over the year should be taken to calculate the design flow to ensure that power is available year-round. Thus, only a fraction of the available flow in the stream is used for power generation [12].

Firm flow is the flow being available p% of the time, where p is a percentage specified by the user and usually between 90% and 100% [12].

Minimum flows were determined according to the methodology applied elsewhere [12, 13]. For this research, the % of time considered for firm and design flow wereQ100% and Q95%, respectively.The FDC, Figure 3, depicts, the flow rate versus % of time of the selected river data,the flow that could be available 95% of the time or more [13].Thus, the resulting flow value for firm flow rate was 0.49m^3/s and that of the design flow rate was 0.5731m^3/s.

Figure 4 was developed with MATLAB SIMULINK software. It contains the 12-month flow rate of the site which are less than or equal to the design flow rate. As indicated in the Figure 4, greater changes were noted for the flow rate of 11 months of the year which was equivalent to that of the design flow rate. These are represented by the horizontal line. And also, the flow rate of February was less than that of the design flow rate for 16 days of the month. Similarly, the flow rate of March was less than the design flow rate for 3 days of the month. The flow rate of April was less than that of the design flow rate for 1 day. For the flow rates that were equal to the design flow rate, the system gets enough flow rate for those days without interruption.

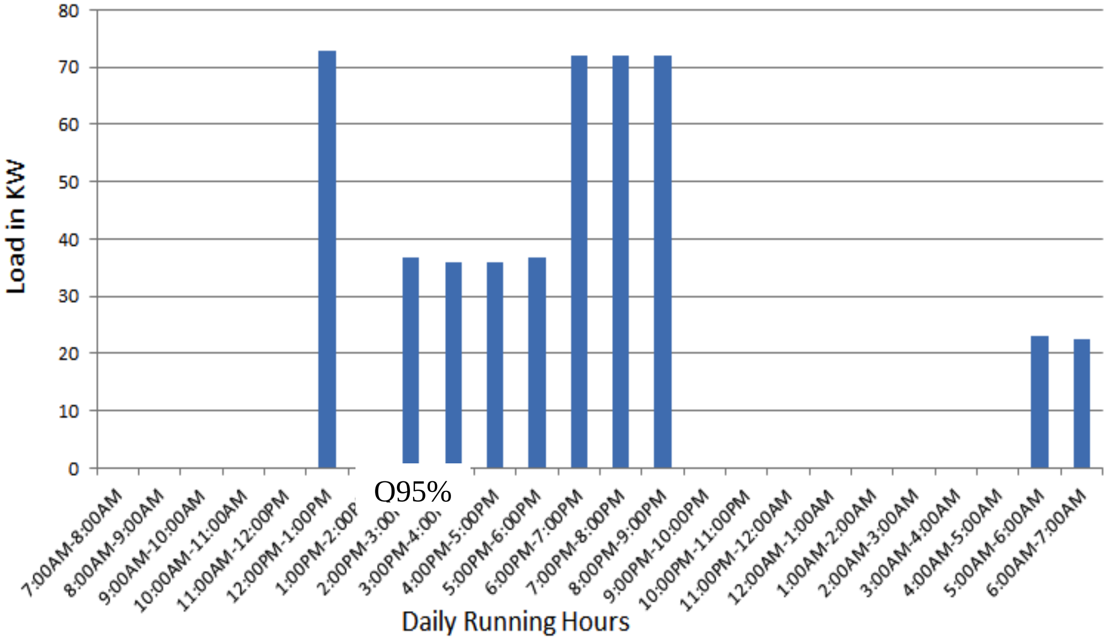

Figure 2 Load Duration Curve of the Site

3.3. Determination of Flow Head

The selected site, *Temecha* River has no head by nature, but it has available flow rate throughout the year. Therefore, based on the literature [16], a small weir was constructed for the site based on the following analysis.

Calculation of the Turbine Efficiency at each flow:

The specific speed adjustment to peak efficiency (${}^{\wedge}e_{nq}$) is:

$$ {}^{\wedge}e_{nq} = \left(\frac{n_q - 170}{700}\right)^2 \qquad (1) $$

Runner size adjustment to peak efficiency (${}^{\wedge}e_d$) is

$$ {}^{\wedge}e_d = (0.095 + {}^{\wedge}e_{nq})\,(1 - 0.789 * d^{-0.2}) \qquad (2) $$

Turbine peak efficiency (e_p) is

$$ e_p = 0.905 -^{e_{nq}+e_d} - 0.0305 + 0.005R_m \qquad (3) $$

where

$$ R_m = \frac{Turbinemanfacturer}{designcoefficent} $$

$(2.8\ to\ 6.1, 4.5\ isusedbydefault)$

Peak efficiency flow, $Q_p is$:

$$ Q_p = 0.75Q_d \qquad (4) $$

Efficiency at flows above and below peak efficiency flow (e_q) is:

$$e_q = \left[1 - 3.5\left(\frac{Q_p - Q}{Q_p}\right)^6\right] e_p \qquad (5)$$

The available mechanical power produced by the turbine is given by:

$$P_{avail} = \rho g Q (h_g - (h_{hydr} + h_{tail})) e_{t,Qd} \qquad (6)$$

The actual power from the turbine (Pdesign) as a function of design flow rate is given by:

$$P_{d,turbine} = \rho g Q_d h_g (1 - (h_{hydr} + h_{tail})) e_{t,Qd} \qquad (7)$$

Available power the MHP plant:

The power available and the flow rate are related with the equation below:

$$P_{avail} = \rho g Q (h_g - (h_{hydr} + h_{tail})) e_{t,Qd} e_g (1 - l_{trans}) * 1 - l_{para} \qquad (8)$$

The actual power from this micro hydropower system of (Pdesign) as a function of design flow rate by assuming generator efficiency of 95% is expressed as:

$$P_d = \rho g Q_d h_g \ (1 - (h_{hydr} + h_{tail})) e_{t,Qd} e_g (1) - l_{trans}) * (1 - l_{para}) \qquad (9)$$

where$e_{t@(Qd)} =$ turbine efficiency at the design flow rate = 86.23%
e_g = generator efficiecny = 95% , Hydrauliclossesh_{hydr} = 7%, Transformer losses l_{trans} = 2%, Parasiticelectricitylossesl_{para} = 3%, andtailracelossesh_{tail} = 7% are assumed for this case.

Table 2 shows the summary of the turbine parameters as the gross head varies. The analysis was done to estimate the gross head for the selected river to satisfy the peak load required by the area.

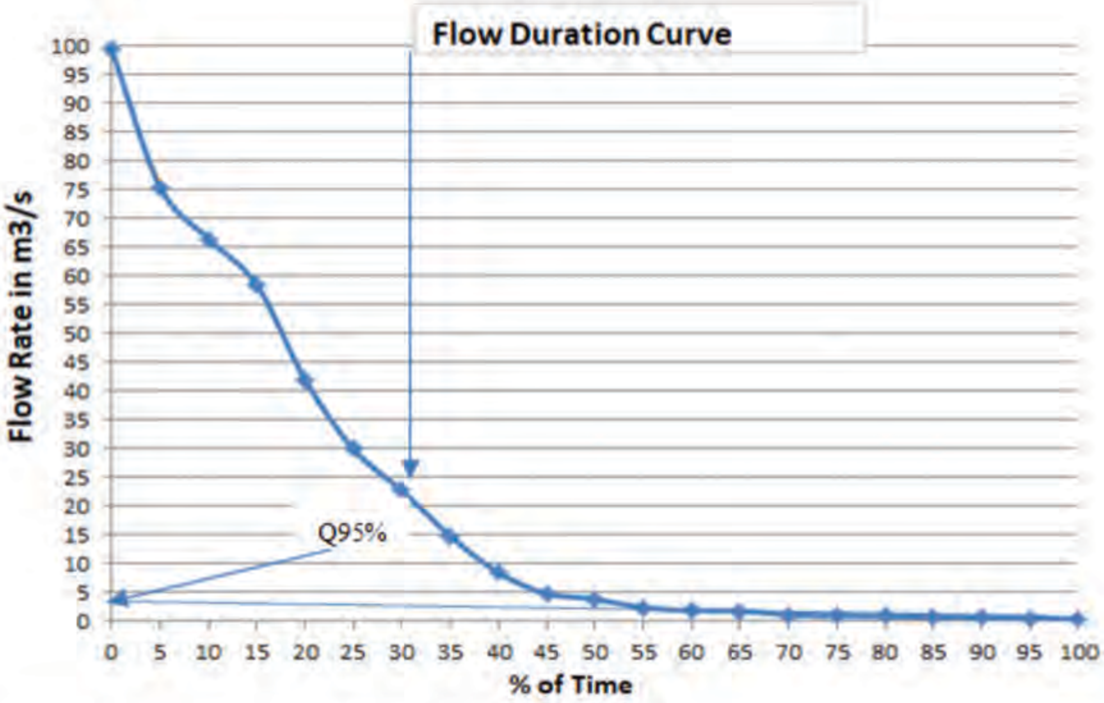

***Figure 3** Flow Duration Curve of Temecha River*

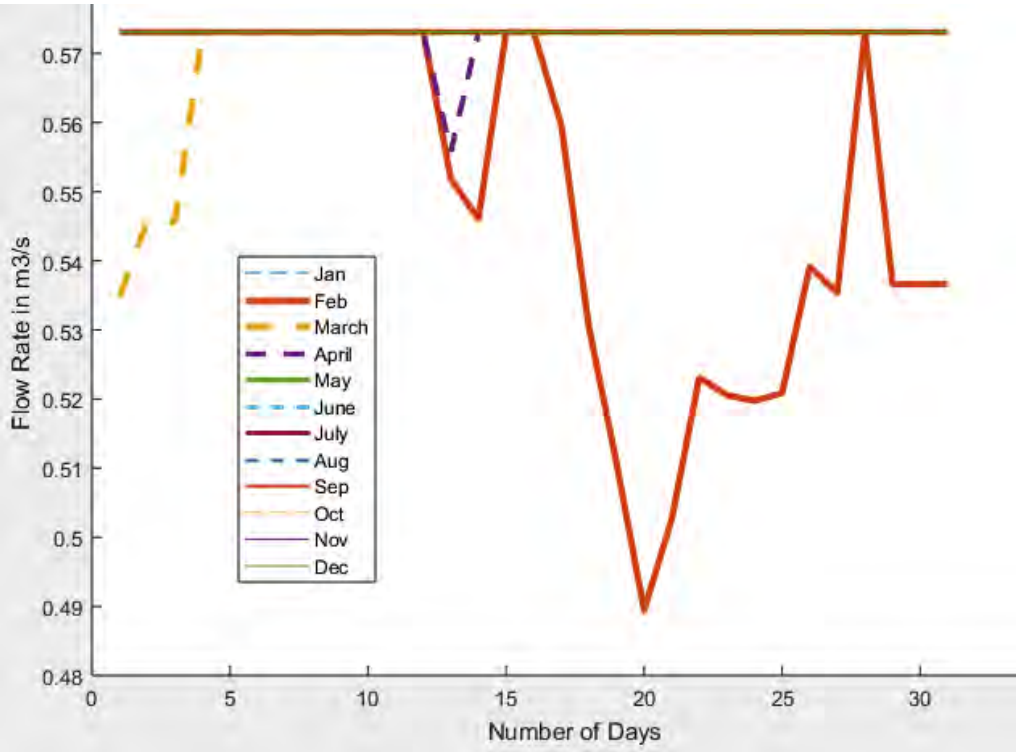

Figure 4 Flow duration curve in the penstock

Table 1 Turbine parameter analysis at variable gross head

Gross head, Hg (m)	Net head, Hn (m)	Turbine runner size, d (m)	Specific speed, nq	Turbine Speed, n (r.p.m)	Specific speed adjustment to peak efficiency ($\hat{e}_{nq}$)	Runner size adjustment to peak efficiency ($\hat{e}_{d}$)	Turbine peak efficiency (e_p)	Peak efficiency flow, (Q_p), (m^3/s)	Available power at the design flow rate, Pd (kW)	MHP System Available Power in kW
10	8.6	0.354	273	616	0.0216	0.0033	0.879	0.403	42.5	38.4
12	10.32	0.354	249	642	0.0127	0.0031	0.887	0.403	51.5	46.5
14	12.04	0.354	231	665	0.0075	0.0029	0.892	0.403	60.4	54.6
16	13.76	0.354	216	687	0.0043	0.0028	0.896	0.403	69.3	62.6
18	15.48	0.354	203	706	0.0023	0.0028	0.898	0.403	78.1	70.5
19	**16.34**	**0.354**	**198**	**716**	**0.0016**	**0.0028**	**0.898**	**0.403**	**82.5**	**74.5**
20	17.2	0.354	193	725	0.0011	0.0027	0.899	0.403	86.9	78.5

As expressed in the demand analysis, the peak load was 72.72 kW. As seen in Table 2, the turbine design parameters that satisfies this peak load requirement has 19m gross head and 0.5731m^3/s of design flow rate. Therefore, based on the above analysis for this case, a net head value of 16.34mwas considered.

3.4.Selection of Standard Components

3.4.1. Selection of Turbine

The parameters values used for the selection of turbines are design flow rate, Q_d=0.5731m^3/s and net head up to 16.34m. Therefore, from turbine selection chart shown in Figure 5, the type of turbines may be Cross flow, Kaplan, and Propeller. For this case, Kaplan turbine was selected, an axial flow reaction turbine suitable for low heads. It was selected as it can handle the variation of flow efficiently and since it is more efficient than propeller and bulb turbines.

3.4.2. Selection of Generator

Generator in hydropower system is used to convert the mechanical energy produced by the hydraulic turbine into electricity. Two types of generators are used for hydropower systems [13]. These are synchronous and asynchronous generators. Synchronous generators are used for large hydropower system capacities more than 10Mw, whereas Induction generators are used for low power capacities less than 10MW.

Srpčič, G. [15] states that, in Hydropower system either the induction or synchronous generators are used. In small hydro power systems like MHP plant, induction generators are recommended and the size of the generator is determined by the output power of the turbine [15]. Since this research has a MHP system with capacity power less than 10MW, which is 74.5KW, induction generator type that has a capacity of 75kw is selected for this system.

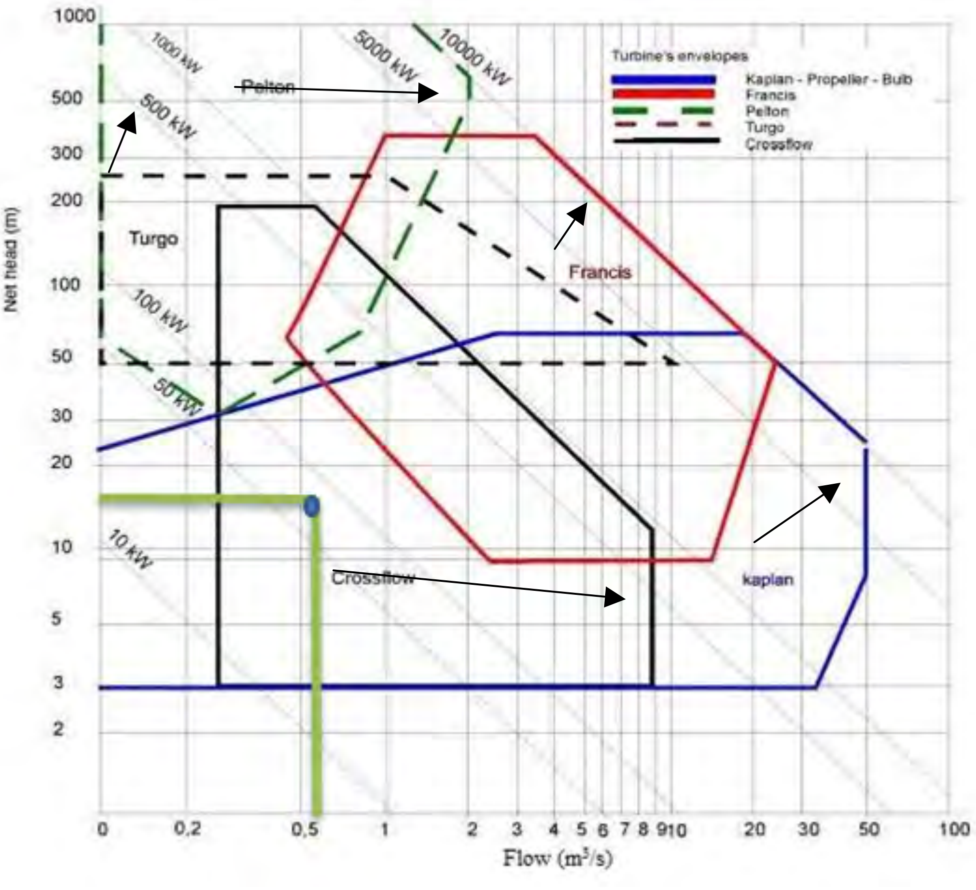

Figure 5 Turbine selection chart based on net head and flow rate [14]

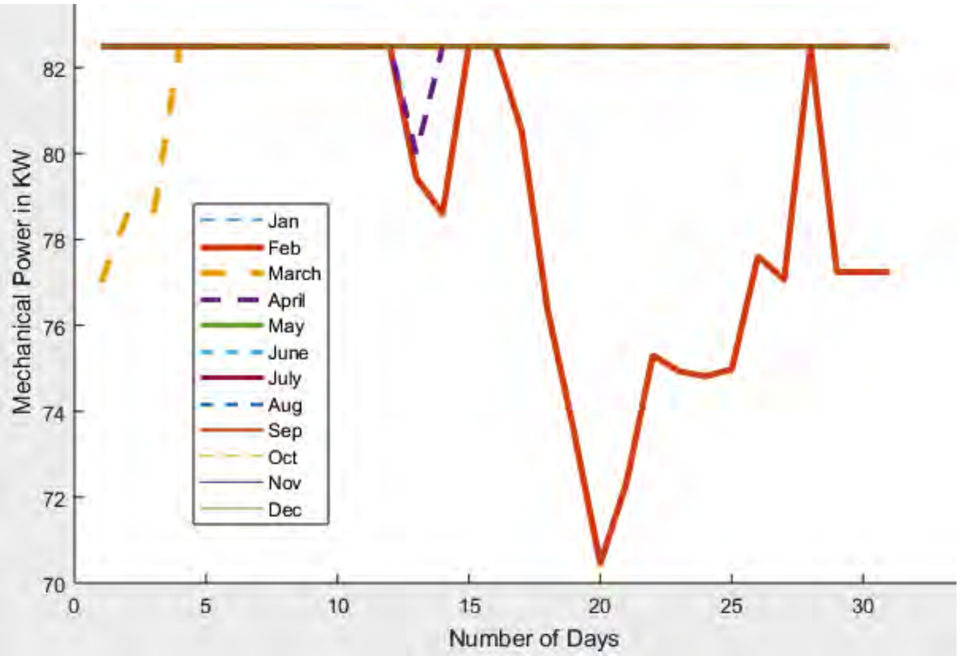

Figure 6 Turbine mechanical power output curve (mechanical power vs. number of days

3.5. Mechanical Power Curve

As shown in Figure 6, the mechanical power output from the Kaplan turbine was around 82.5 kW, which was represented by the horizontal line and below it for around 20 days of the year. For example, the mechanical power produced during the month of February was less than the maximum one for 16days. This was because the flow rate of this month was less than that of the design flow rate. On the other hand, for March, the mechanical power produced was around 82.5 kW for 27 days and less than that for the remaining 3 days. For April, the turbine output was 82.5 kW for 29 days and less than that for 1 day of the month. Generally, the above variation of the turbine output power was caused due to the flow rate variation around the year.

Figure 7 shows the variation of mechanical power with the number of days at different values of the gross head. Obviously, one can see that the mechanical power increases as the flow head increases.

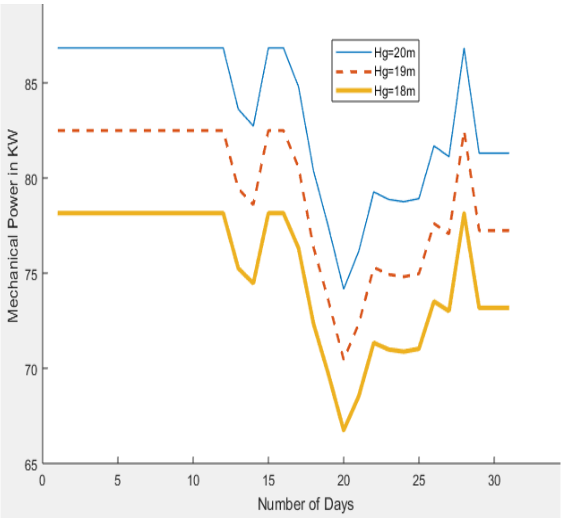

Figure 7 Mechanical power vs number of days for February month at different values of Gross Head

3.6. MHP System Power Curve

Figure 8 shows that the MHP system output power versus the number of days of the year for each month. As seen in the same figure, the maximum power output of the system was found to be 74.5 kW. This numerical value was constant for 11 months of the year.

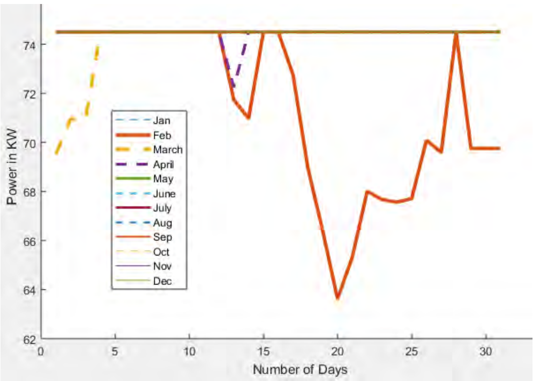

Figure 8 MHP system output power curve

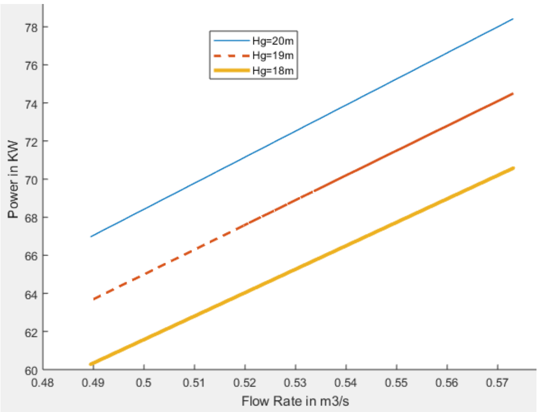

Figure 9 Final system output power versus flow rate of February at different values of Gross Head

For the months of February, March and April, the output power was below the maximum for 16, 3 and 1 days, respectively as the river flow rate was less than the design value in these days. Generally, the system satisfies the demand amount for 346 days of the year.

Thus, if the monthly energy requirements are greater than that could be generated by this system, then the consumption need to be reduced so that it at least matches the available energy but, in some cases, electronic load controller connected to the generator can be used to give the balance.

Figure 9 shows the MHP System power output versus flow rate at different flow head values of the site.

The result shows that as the flow rate increases, the power output also does. And also, as the flow head value increases, the power output also does. Therefore, the system power, flow rate, and flow head have a direct relationship with each other.

4. CONCLUSIONS

MHP system solves rural electrification problems in remote areas. Therefore, the main objective of this research was to model and simulate the MHP system in the case of the *Temecha* River.

The uniqueness of this research from previous works was summarized below.

As seen in the simulation result, Figure-8 shows that with a 16.34m net head and 0.5731m^3/s design flow rate, the electricity produced is up to 74.5 kW of power, which is enough to be more than current demand of 72.72 kW of electricity for the site.

From these results, one can conclude that by implementing this MHP system, 74.5 kW electricity can be produced for around 346 days of the year. In general, by implementing such an MHP system, around 1200 families can get electricity access for lighting, mill machine and mobile phones.

As the population and their economic activities increased, the researcher recommends the society to implement such additional Micro Hydropower systems with in a small distance of the original one.

Most importantly, a general awareness and technical understanding of successful Micro-hydro power technology can be developed and fostered at the local and regional levels so that rural electrification projects can be implemented effectively. Finally, this study recommends capacity building in Micro hydro power technology, transformation of research findings into real products to solve rural electrification problems.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

ACKNOWLEDGMENTS

The authors acknowledge the Ethiopian Basins Development Authority, for supplying the river flow data of both *Temecha* and *Gudla* River.

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