An Optimization Model for the Design of an Off-Grid Micro-Hydro Power Plant

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Abstract

It is estimated that around 1.3 billion people globally still have either limited or no access at all to electricity. These, in turn, have directed greater focus on affordable, accessible, and environmental-friendly renewable energy systems. In countries like the Philippines with numerous unelectrified remote communities, there is even greater need to incorporate affordable renewable energy technologies because the cost of investing in national grid extensions proves to be very costly. Micro hydroelectric power is a clean and efficient source of energy that has been used for the electrification of rural off-grid communities around the world. In this paper, an optimization model for the design of an off grid micro hydro power plant is developed. The proposed model is able to provide the necessary technical specifications given certain parameters such as details on the site location and requirements of the small rural community. Additionally, the model is also able to provide the minimum cost needed to invest in the micro hydro power plant. Finally, the model is then compared with current cost equations to see how the model compares with current studies.

Keywords
Micro-hydro, optimization, renewable energy, design model, integer programming

1. Introduction

Electricity is a good that is essential for the promotion of education, health, transportation, and infrastructure which in turn, improves the standards of living of a community (Nasir 2014). However, the world is currently faced with diminishing sources of fossil fuels and environmental pollution. Furthermore, accessibility to electricity continues to be a problem around the world, particularly in developing countries. It is estimated that around 1.3 billion people globally still have either limited or no access at all to electricity (The outlook for energy: A view to 2040 2014). These, in turn, have directed greater focus on affordable, accessible, and environmentally-friendly renewable energy systems. In countries like the Philippines with numerous unelectrified remote communities, there is even greater need to incorporate affordable renewable energy technologies because the cost of investing in national grid extensions proves to be very costly (Roxas and Santiago 2016). According to the Philippine Institute for Development Studies (2013), about 16 million Filipinos still do not have access to electricity and such problem persists in nearby countries like Indonesia (63 million) and in Myanmar (26 million).

Micro hydro is a well-established technology that has been implemented for rural electrification around the world. It a run-of-river system, which means it does not require a dam or a storage facility to be constructed. It diverts water from a stream or river, channels it into a valley and then it drops into a turbine through a pipeline (Bracken et. al 2014). It can provide clean affordable renewable energy to remote communities and can be operated without a connection to the grid. The comparative advantages of micro hydro include the following: relatively lower cost of maintenance and operations, can be locally managed and operated, and it has minimal environmental effects. The characteristics for potential sites conducive for micro hydro implementation include the following: situated close to a running body of water, has enough demand for electricity, and isolated from the grid (Centre for Rural Technology, Nepal 2005).

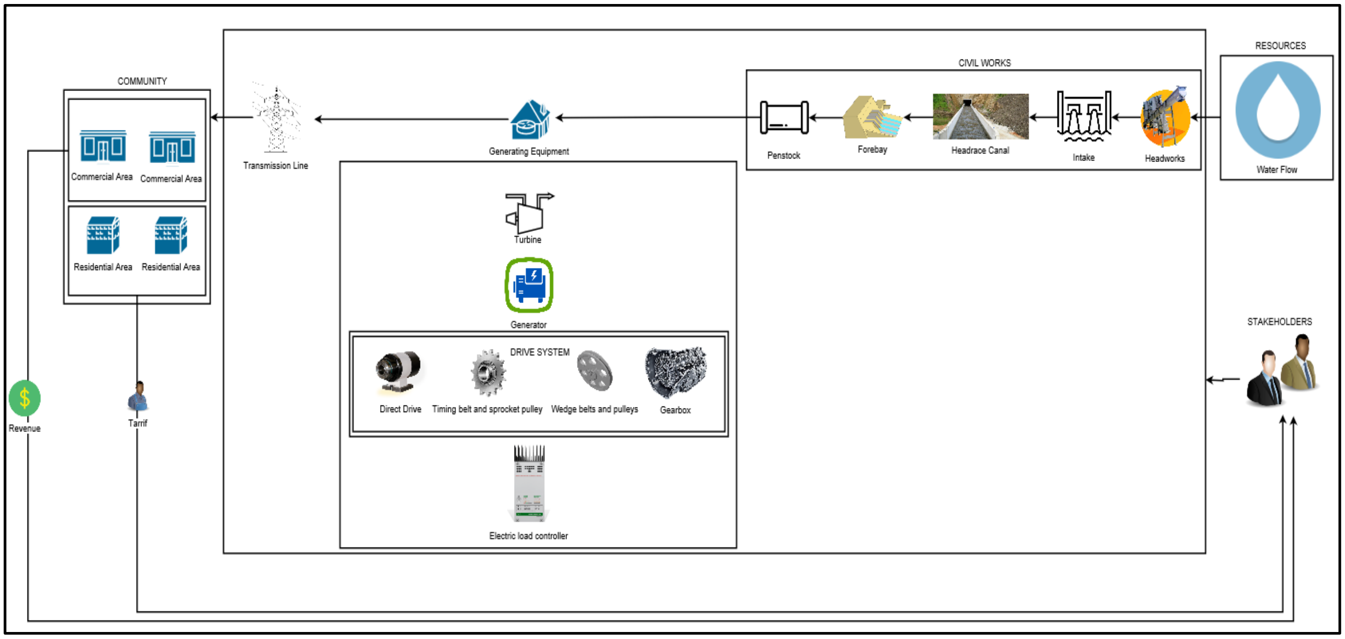

Figure 1: Rural off-grid micro-hydro power plants

While micro hydro power plant, as shown in Figure 1, are characterized by relatively low running costs in the form of repairs, maintenance, labor, and depreciation, they require high capital costs. This means that "entry costs" are likely to be beyond the reach of poor communities that may need such, despite its lifetime costs being relatively lower than other alternatives. (Khennas & Barnett, 2000). More often than not, this results to communities requiring the aid of an external investor in order to establish a micro hydro power plant. However, the relative neglect of investors in micro hydro can be attributed to not having a proper understanding of under what circumstances can the investment be financially profitable or sustainable (Centre for Rural Technology 2005). On one hand, micro hydro investments are considered to be social infrastructures, similar to the provision of health services, schools, and roads. As such, there has been a lack of information on the profitability of such investments (Khennas and Barnett, 2000). The sustainability of micro hydropower plants in South and Southeast Asia has been a major issue due to plants experiencing weak cash-flow performance sometimes resulting to shutdowns of plants. This indicates that although operational and maintenance cost for micro hydro are relatively low as compared to other power plants, weak cash-flow could still be a problem that affects the sustainability of the plant. This can be attributed to the poor utilization of micro hydro power plants, with usage limited to domestic lighting in the evening. (Sibol ng Agham at Teknolohiya, Inc. 2015). In Nepal, around 30% of total micro hydro installations in the country have failed and are no longer operating. The failure of these installations were identified to be caused by the following factors: poor site selection, poor installation, faulty equipment, uneconomic canal length and design, wrong estimation of materials and demand, lack of productive end-use possibilities, and wrong sizing (undersizing/oversizing) of the plant (Earth Consult 1998). Additionally, the low utilization of the plants results to the plant failures as well. For example, the Salleri Electricity Utilization project (SCECO) plant's peak power demand per consumer is one of the highest for isolated rural grid system (360 watts per consumer), and yet the load factor is 33%. (Vaidya, n.d.). While this can mean that the power is used for a productive enterprise, the costs involved with the plant itself significantly increase. Therefore, load management is then needed in order to address this problem in the demand side. (Roy et. al 2017). These causes show a pressing problem on both the design and management of micro hydro power plants.

As micro hydro power plants continue to face issues in its sustainability, there are three identified opportunities to be addressed: first is the optimization of the micro hydro power plant's different design elements given the tradeoffs present in the maximization of power production and ensuring the cost effectiveness of the investment while considering an actual demand from a rural off-grid community. Furthermore, the variability of the streamflow will be considered in order to better model the system's actual behavior. Second is the prospect of introducing productive end usage as it presents itself as an opportunity for micro hydro plants to be sustainable. Last is the incorporation of load management strategies to address the issues of costly underutilization for micro hydro power plants. With this, a design model that capitalizes on the aforementioned opportunities is established.

This study introduces a design model that is directly applicable to micro hydro power plants with the unique inclusion of productive end usage for the plants, as no literature has yet to integrate such in their model. Furthermore, these researchers will consider electrical demand from a community to be fulfilled by the micro hydro power plant as another unique component of this study.

2. Micro Hydro System

In the system, there are many decisions to be considered when designing the optimal micro hydro power plant. Each component of the system would be built with specific specifications that would all have tradeoffs and costs. A micro-hydro power system can be divided into three sequential segments or components, namely: civil works components, powerhouse components, and transmission network component. (Natural Resources Canada 2004).

2.1 Civil Works

There are many possible configurations for a micro-hydro power scheme each with varying head distances and penstock lengths (Harvey 1993). The components included in the civil works would control the water that is the source of power for the MHP. It is important therefore to locate these in suitable sites and design these with optimum performance and stability in mind (Natural Resources Canada 2004).

2.2 Electro-Mechanical Equipment

In order to determine which turbine type to use, the head measurement and the flow rate must be determined. The mechanical energy that the turbine produces gets transferred to the generator to generate electrical energy. Moreover, since there are load variations which cause damage in the system, a controller is vital to balance the consumption and electricity produced. This controller will help minimize the deterioration of the turbine and generator from runaway speed. Runaway speed is the speed of the water turbine at the system's full flow which is caused by load clearing (Pasalli and Rehiara 2014).

There are different types of turbines that must be considered before choosing the best turbine for for the study. The selection of such turbine depends on factors in the installation site such as the length of the head, and the flow of the river. It is important to properly select the suitable turbine because each turbine type has a range of inflows, and outside this range significantly decreases the electrical power it can generate.

There are four different turbine types that can be categorized into two: impulse and reaction turbine. Kaplan and Francis are reaction turbines, whereas Pelton and Crossflow are impulse turbines. The reaction turbine can only accommodate smaller loads but can produce higher efficiencies at a full load. They also require smaller heads as compared to impulse turbines. On the other hand, impulse turbines are the ones which can obtain high efficiencies at low loads (Yildiz 2015).

2.3 Transmission/Distribution Network

The use of overhead transmission lines is the most common way to distribute the electricity. Depending on the amount of electrical power to be transmitted and the voltage, the size and type of the electric cables would vary. It should be noted that there are transmission losses that are needed to be taken into account when setting up the lines as these can be great in magnitude. Usually, the transmission distance of micro-hydro systems would range not more than 1 km in distance as this is the most economic configuration available for the system (HS Dynamic Energy 2017).

3. Model Development

The model is initially designed to minimize the cost of the micro-hydro power plant components. These would consist of the materials to be used for the weir intake, the penstock dimensions, the thickness of the wiring, and the turbine type to be used according to its efficiency. The main tradeoffs to be considered in the model would be from cost and efficiency. There would be a target efficiency to be established beforehand. The system diagram of the model can be seen in Figure 2 where the inputs and outputs are clearly defined. Together with the civil works cost components, the community demand, target efficiency, and site characteristics would be inputted to the model. The model would then determine the optimal combination of components based on the given inputs and the demand of the community.

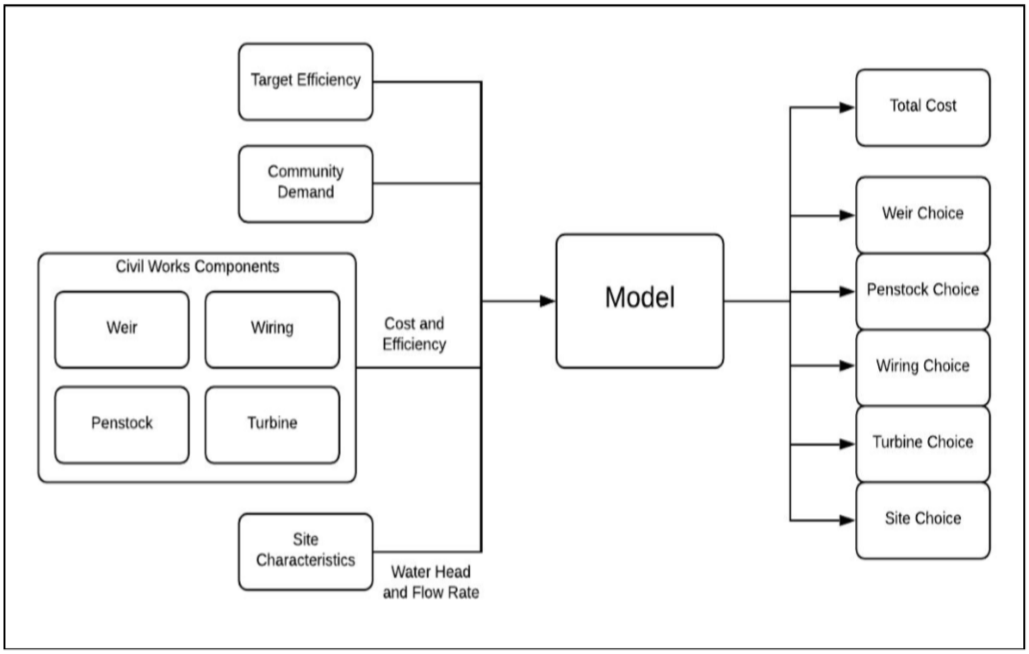

Figure 2: System diagram of the model

The objective function aims to minimize the costs associated with the establishment of the micro-hydro power plant as seen in Equation 1:

$$Minimize\ cost\ = \sum(C_{pen} * b_{pen}) + \sum(C_{wer} * b_{wer}) + \sum(C_{tur} * b_{tur}) + \sum(C_{wir} * b_{wir}) \quad (1)$$

Moving on to the constraints, the model would have to ensure that the demand is met. This is important for rural electrification since no one would have other means to electricity other than the installed micro-hydro power plant. Therefore, the demand is set as a hard constraint based on the power equation of hydro power:

$$PQ * b_{sit} * eff * 9.8 \geq Dem \quad (2)$$

Furthermore, the micro-hydro power system would have to be able to reach a target efficiency in order to for the system to perform sustainably. This would be done by equating the combined efficiency factors of the components of the micro-hydro system to a target efficiency.

$$E_{tur} * b_{tur} - (E_{pen} * b_{pen} + E_{wer} * b_{wer} + E_{wir} * b * wir) \geq eff \quad (3)$$

The remaining constraints would be the binary constraints in order to force the model into choosing only one choice per component.

$$\sum(b_{sit}) == 1) \quad (4)$$
$$\sum(b_{tur}) == 1) \quad (5)$$
$$\sum(b_{pen}) == 1) \quad (6)$$
$$\sum(b_{wir}) == 1) \quad (7)$$
$$\sum(b_{wer}) == 1) \quad (8)$$

4. Results and Discussion

The software used for the validation of the model is MATLAB using IBM's CPLEX solver together with ROME for the optimization functions to be used. All nonlinear relationships are linearized in order for the model to run in the program.

4.1 Input Parameters

There are four input parameters considered: site characteristics, demand, efficiency, and the civil work components.

(1) Site Characteristics - Five (5) sites were set for the model to choose from for both the head and the flow rate. They are as follows:

Table 1: Site characteristics

Site	Head (in meters)	Flow Rate (in m^3/s)
Barangay Parina, Apayao	16.5	0.095
Hink River, Indonesia (Pasalli and Rehiara, 2013)	8.6	0.3
KEMKEN, Cameroon (Signe et. al 2017)	10.5	9.3
SIBAT, Philippines	52	20
India (Michael and Jawahar 2017)	12	0.072

(2) Demand - The demand was set at 15 KW, based on the demand of Sitio Parina, with a consumption of 153 watts/household with a total of 98 households. This is to capture the demand of a typical micro hydro community set up.

(3) Efficiency - A conservative approach was taken, with target efficiency only set at 0.5 (50%).

(4) Civil Work Components - The civil work components are comprised of the weir, penstock, wiring, and turbine.

Weir
Table 2 shows the costs of the materials used for the weir construction along with its corresponding efficiency losses were used. It must be noted that the option of using the site's own characteristics as the weir yields no cost but incurs a much higher efficiency loss relative to the other costlier options.

Table 2: Weir material cost and efficiencies

Weir Cost	Efficiency Loss
0	0.2
10	0.15
22	0.11
40	0.1

Penstock

The penstock is seen as the most expensive component of the whole micro hydro power plant. Table 3 shows that as the material improves as well as its thickness, the cost of the penstock goes significantly higher as well. However, with improved material and improved thickness, the efficiency losses are significantly reduced as well.

Table 3: Penstock material cost and efficiencies

Penstock Cost	Efficiency Loss
120	0.15
300	0.1
450	0.05
700	0.01
1000	0.005

Wiring

The wiring is associated with the transmission system of the micro hydro power plant. Similar to the other civil works components, the increase in costs correspond with decreasing efficiency losses.

Table 4: Wiring material cost and efficiencies

Wiring Cost	Efficiency Loss
50	0.13
57	0.01
85	0.08
100	0.05

Turbine

Four types of turbines are considered: Crossflow, Pelton, Francis, and Kaplan. Each turbine’s effect is demonstrated through efficiency gain, as compared to the previous civil works components which are expressed through efficiency losses.

Table 5: Turbine type cost and efficiencies

Turbine	Turbine Cost	Efficiency Gain
Crossflow	600	0.8
Pelton	670	0.87
Francis	980	0.89
Kaplan	910	0.91

4.2 Base Run Results

The base run resulted to choosing the optimal component choices based on the target efficiency and required demand of the community. Seen below is the table of the component choices with a resulting total cost of Php 799,000. It was also able to meet the target efficiency with a system efficiency of 0.53.

Table 6: Civil works components cost and efficiency

Component	Cost	Efficiency
Weir	22	0.11
Penstock	120	0.15
Wiring	57	0.01
Turbine	600	0.8
Total	**799**	**0.53**

On the other hand, the optimal site characteristic is determined as the one with a head of 16.5 meters and a flow rate of 1 m^3/s. To further validate the results, a comparison with the cost estimate equation of $C_p(\$/kW) = 566.9H^{0.01218}P^{0.1452}$ formulated by Zhang et. al (2012) is used. The total cost of the model together with the input data derived from actual data sites resulted to around Php 799k. Dividing this by the community demand and converting it to dollar would yield to a unit cost of $1,183.70/kW. Compared to the total cost coming from the equation, the model was able to determine a savings of Php 212.4k.

5.. Conclusions

A model was developed through MATLAB that was able to determine the optimal micro hydro power plant components to be chosen with the least cost, given a community's energy demand and the site conditions. This model can be useful as a rapid assessment tool for micro hydro power plant planning

The existing model can be improved by analyzing more technical components of the micro hydro power plant such as penstock thickness, penstock diameter, specific speed, and rotation speed. Furthermore, incorporating productive end usage as another demand stream can improve the model as it can show the possible profitability of a micro hydro power plant investment.

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