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Assessment of Mini-Hydro Power Plant for Improving Output Capacity Generation

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Abstract

Water uncertainty in run-of-river schemes has impacted immensely on existing mini-hydro technology in Malaysia. Since 1980s mini-hydropower plants were operating under difficult conditions due to climate and environmental changes. Power output dwindled to 37% of the total installed capacity of 16,643 kW. Therefore, one of the main contribution of this study is to characterize the factors causing the inconsistency in power output and to suggest ways to improve the system to revive mini-hydropower plants. The methodology will include a two-tiered condition-based assessment and RETScreen Expert Analysis to determine the actual condition of the plants. Hence, the study will propose the area of weakness to focus on in improving output capacity generation to address the insufficient water flow faced by most of the mini-hydros in Malaysia. Power output will be restored to the optimum level of 16,643 kW which will generate an average annual electricity generation of 123,923,778 kWh/year based on a load factor of 0.85%. Additionally, it will contribute positively to efforts in reducing the 40% carbon emission intensity by 2020 from its 1990 levels. The way forward, this concept will recommend the introduction of low-head axial and cross-over turbines. From this assessment it is found that a significant contribution can be impacted with the enhancement of mini-hydropower plants generation into Peninsular Malaysia's electricity grids to help in achieving the national target to increase the penetration of renewable energy generation mix up to 20% by 2025.

1. INTRODUCTION

Mini hydropower plants were constructed and commissioned in the 1970s to electrify primarily the rural areas in Peninsular Malaysia. However, the amount of electricity generated by the plants is site-specific, it is directly related to water quantity and its timing [1]. Mini-hydropower plants use the most cost effective technologies. Today, however, these units are operating under difficult constraints as a result of climate change and river regime, besides the system itself [2]. The challenges faced by the scheme include risk of water scarcity and unexpected water flows in different seasons, climate change and river pollution. Furthermore, the performance of small hydropower is influenced by sedimentation, which reduces the overall efficiency of the power generation system [3]. The global Intergovernmental Panel on Climate Change (IPCC) has highlighted this in its Fifth Assessment Report and the potential impacts on hydropower owing to a reduction in water availability in dry tropical regions of the world [4]. There were efforts in the past to maximize the power output from mini-hydropower plants through various methods such as designing better water intake and penstock, improving the generator and development of turbines suitable for low heads, less than 20 metres or so, but the outcome still remains [5]. The screw turbine has shown good potential to be used for low head micro-hydro-electric installations. This paper reports on a performance analysis based on the experimental data collected from different performance tests carried out on some inclination angle positions of the screw turbine prototype [6]. The US Corps of Engineers initiated an approach in the 1998 under its Repair, Evaluation, Maintenance and Rehabilitation (REMR) research program. The approach, however, met with failure as it had poor procedural setup in vetting results and inconsistent method of data collection and utilization. While classifications may vary from country to country, generally mini-hydropower falls in the category of 100kW to 1MW [7]–[9]. Over the last twenty-five years, mini hydropower plants have been performing inefficiently. Water uncertainty in the mountain streams has caused inconsistency in power output accompanied by frequent unscheduled shutdowns of the power system. In short, the plants have become unreliable. Over time, this has caused the emergence of a gap of 63.15% between total power output of operational plants against the overall total installed capacity. To date, only fourteen (14) plants are operational generating 6,133kW out of the thirty (30) with a total installed capacity of 16,643kW. Five (5) units are under-rehabilitation while eleven (11) units are non-operational.

Climatic and hydrogeological characteristics of run-of-rivers with insufficient water upstream have impacted immensely with inconsistent energy outputs causing frequent outages, plant failures and shutdown especially during dry spells [10]. As the flow determines the level of power production, an assessment of the flow regime in association with intake, turbine and generator is evidently essential. Aging and deterioration of hydroelectric power plant equipment can pose considerable risk to the reliability of generating plants. However, other major contributing factors like climatic change and river regime is also a discernible factor in the loss of power output in mini-hydropower plants [11].

The scope of work will involve the selection of a mini-hydropower plant currently in operation in West Malaysia. It will focus primarily on the statistical assessment of the power plant and equipment. It will introduce an improved design to the existing structure to maintain a constant and continuous water supply for driving the hydraulic turbine. There will be a simulation using RETScreen Expert Software [12] which will evaluate the energy output and verify the CBA evaluation.

2. ASSESSMENT PROCESS OF MINI-HYDROPOWER PLANT

The re-engineering process of mini-hydropower plant to improve its generation capacity consists of different phases of activities. The initial phase of activity is selection of the mini hydropower plant. Sg. Tebing Tinggi MHP was chosen for this project. The second phase of activity involves the categorization of the plant according to operational, non-operational or under rehabilitation. Upon the selection and categorization of the plant, the next stage will entail the collection of data to obtain correct and updated information on the operational problems of the mini hydropower plant. Primary and secondary data will be sought. The data is obtained from readings, journals and internet sources. The other sources include face-to-face meetings with field engineers and executives who are and have been actively involved with mini-hydro schemes. The info of the plant obtained from routine inspection shall be kept in a Routine Inspection Form for assessment. The work and phases of activities are in Figure 1.

The third phase of activity will include a statistical approach to assess the condition of existing mini-hydro plants to identify the frequent power failures and fluctuations that have led to the deterioration in mini-hydropower plant energy output. A standard matrix will be used for each equipment component with the selected metrics of physical condition, age, installed technology, operation restriction and maintenance restriction to calculate the Condition Index or physical condition of the component. The status of the operational condition of the plant will be categorized accordingly as good, fair or poor based on the performance indicators as in the assessment manual. The fourth phase of activity, upon assessment and analysis and the drawing up of the concept design, is to propose the new and improved design. The final phase of activity shall include the verification aspect to compare the power output against the initial installed capacity using RETScreen software.

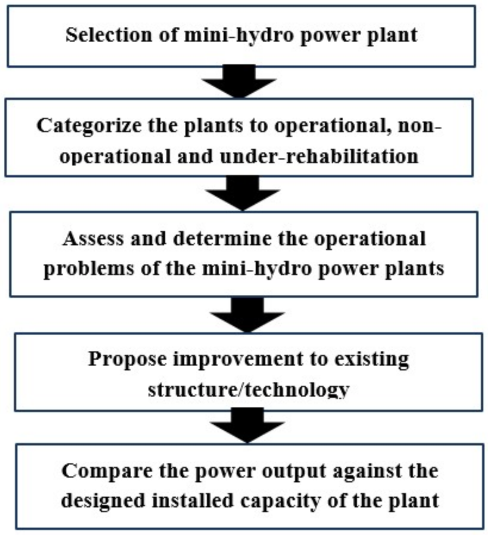

Figure 1. A Flowchart for Site Selection and Process

A. Plant Location

The location of the mini-hydro power plant is near the mainstream of Sg. Tebing Tinggi in Selama, Perak, Malaysia. It is just 12 KM away from Selama town. The estimated terrain elevation above sea level is 472 meters. It is water-retaining run-of-river type of plant situated along a 8 KM long stream. It is operational for over 30 years and its current generating capacity of 152 kW. The plant consists of a power intake, weir structure, penstock, and a powerhouse. Figure 2 shows GPS coordinates whereby the powerhouse station's location is at N 5.16, E 100.89 is shown in Figure 3 and the water catchment/intake station's location is at N 5.16, E 100.89 as shown in Figure 4.

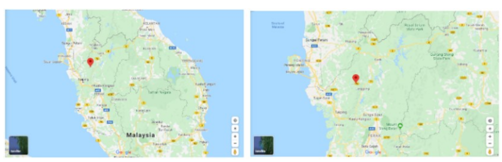

Figure 2. Plant Location – Sg. Tebing Tinggi

Figure 3. Plant Station Location – Sg. Tebing Tinggi

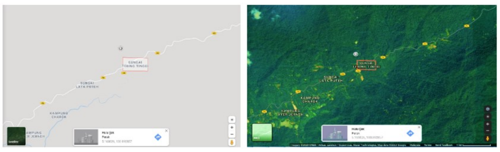

Figure 4. Plant Intake Location – Sg. Tebing Tinggi

B. Plant Climate Data

The software uses satellite information to provide a default climate data location for the selected facility location or physical site location. In this case, Sg. Tebing Tinggi plant is located approximately at N 5.16, E 100.89 of the map coordinate. According to the database, the nearest climate data location is Ipoh, which is located approximately 65 KM from the site location according to the database shown in Figure 5.

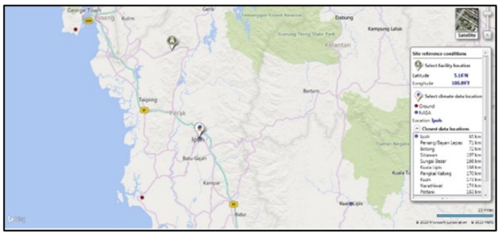

Figure 5. Plant Facility and Climate Data Location – Sg. Tebing Tinggi

Among the climatic data captured include relative humidity (%) and precipitation (mm) of the site location. This information is useful in this study as a verification tool. Figure 6 provides the plant's hydrograph data.

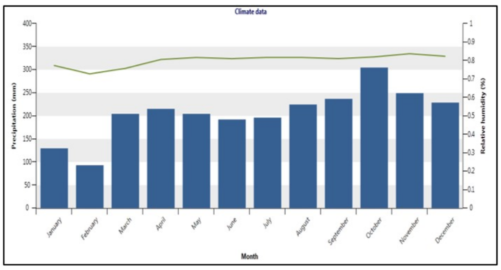

Figure 6. Climate Data and Hydrograph – Sg. Tebing Tinggi

C. Characteristic

Sg. Tebing Tinggi Mini-Hydropower Plant is a run-of-river hydro plant and is located 12 kilometres from Selama town in Perak. It is situated in a granitic hilly terrain. The climate is hot and humid with an average annual rainfall of about 2481 mm and an average annual relative humidity of about 80%. The installed capacity of the plant is 178 kW with a flow rate of 0.17 m^3/s, and this plant has been in operation since 1986. The plant is doing remarkably well and is among the few mini-hydropower plants that are still operational. The plant is generating an average power output of 152 kW to add to the national electricity grid. The factor for its reduced power output as against the installed capacity of 178 kW is the direct result of the uncertainty of the raw water system caused by climatic and river regime. The main features / plant characteristics of the 1981 commissioned Sg. Tebing Tinggi mini hydropower plant is further detailed in Table 1

D. Plant Monthly Flow Data

The monthly flows in Sg. Tebing Tinggi plant is categorized into two (2) different scenarios, which are at installed capacity (1st scenario) and current capacity (2nd scenario). Monthly flow rates from Sg. Tebing Tinggi MHP can be further categorized into three (3) different classifications: high flow, medium flow, and low flow (based on RETScreen precipitation data). The flow rate classification is appended in Table 2.

The average monthly flows showing both scenarios of Sg. Tebing Tinggi are as appended below in Table 3 and Table 4

First Scenario - Energy output at an installed capacity of 178 kW at a head height of 125m. The chart shows an average monthly flow rate (Jan - Dec) of 0.1858 m^3/s at the installation and commissioning equipment efficiency of 78%. There is some variation of high and low flow rates as shown in Table 3:

Second Scenario – Energy output at an average monthly flow rate (Jan - Dec) of 0.1650 m^3/s and equipment efficiency of 75% was 152 kW as shown in Table 4 below:

E. Assessment Model

A model has been identified from among many as the best alternative and most suitable to be used for assessment, and verification, RETScreen Expert Performance Analysis Assessment.

F. RETScreen Expert Performance Analysis Procedural Set-up

Upon completion of the condition assessment, a RETScreen Analysis will verify the findings of the equipment condition assessment. RETScreen Clean Energy Project Analysis Software is a standardized and integrated clean energy project analysis software to identify, assess and optimize the technical and financial viability of potential clean energy projects. The software's energy model platform is widely used for the evaluation of plant capacity and annual energy production of small hydro projects. The software uses both meteorological and product performance data as input to determine the amount of energy that can be delivered by a project. There are seven worksheets namely Energy Model,

Table 1. Sg. Tebing Tinggi Plant's Main Features

Hydrology	
Intake Location	N 5.16 E 100.89
Power Station Location	N 5.16 E 100.89
Elevation Above Sea Level	472 m
Catchment Area	15 km^2
Name of Hydrological Region	Stesen Janakuasa Mini Hidro Sg. Tebing Tinggi
Climate: i) Average Annual Rainfall ii) Average Annual Relative Humidity	 i) 2481.363 mm ii) 80.171 %
Residual Flow	0.05 m^3/s
Rainfall Region	West Malaysia
Climate Zone	1A – Very Hot (Humid)
Geology	Granitic
Physiographic	Hilly and Mountainous
Intake Structures	
Trash Rack	Available
Screening	Available
Gate Valve	Available (1 unit)
Settling Basin	N/A
Overflow weir	N/A
Forebay Tank	Available (45 m after intake)
Surge Tank	Available (1 unit)
Gross Head	125 m
Flow	0.17 m^3/s
Normal Operating Mode	Base Load
Penstock	
Length	467 m ± 10%
Diameter	80 mm
Valve	i) Main Isolating Valve (1 unit) ii) Main Inlet Valve (1 unit) iii) Discharge Valve (1 unit)
Surge Tank	Available (1 unit)
Material	Steel
Power Station	
Location	12 KM from Selama Town
Structure	Reinforced concrete sub-floor structure with a roofed superstructure.
Power house	1 generating unit of 152 kW
Water Turbine Equipment and Auxiliaries	
Turbine	i) Type: Turgo ii) Power: 152 kW iii) Rated Flow: 0.17 m^3/s iv) Speed: 1000 rpm
Generator	i) Type: Synchronous Generator ii) Voltage: 415 V iii) Current: 209 A iv) PF: 0.80 v) Apparent Power: 50 kVA vi) Speed: 1000 rpm
Transformers	Step down transformer complete with auxiliaries and cooling system
Switch Gear Equipment	Switchgear complete with control and protection panels.
Electrical System	
Power connection to grid	The generator 415V terminals are connected to the generator transformer Low Voltage side terminals. The outgoing terminals of the step up transformer (High Voltage) are connected to the 11kV circuit Breaker and to the grid via the 3 phase Aerial Bundled Cable to SJMH Sg. Tebing Tinggi 11kV substation located 20 km away from the power house.

Table 2. Flow Rate Classification based on Monthly Precipitation Level

Monthly Precipitation Level	Flow Rate Classification	Month
> 250 mm (average)	High Flow	Oct
150 – 250 mm	Medium Flow	Mar, Apr. May, Jun, Jul, Aug, Sep, Nov & Dec
< 150 mm	Low Flow	Jan & Feb

Hydrology Analysis and Load Calculation, Equipment Data, Cost Analysis, Greenhouse Gas Emission Reduction Analysis, Financial Summary and Sensitivity and Risk Analysis. However, for this study, we shall focus on the Energy Model and its subsets and the Greenhouse Gas Emission Reduction Analysis only. For run-of-river projects, the required flow duration curve data can be entered either manually or by using the data specific run-off method and data contained in the RETScreen Online Weather Database. Figure 7 shows processes which have been carried out in the RETScreen Expert Performance Analysis.

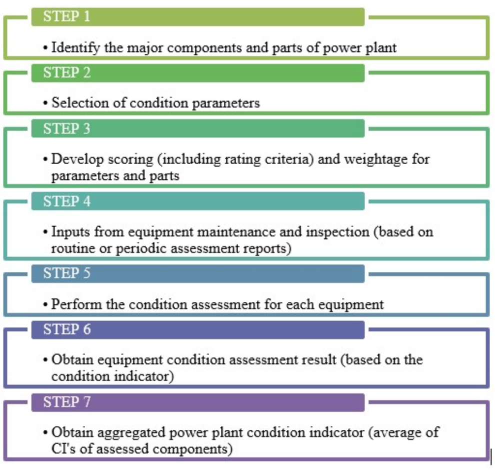

Figure 7. RETScreen Expert Software Assessment Steps

G. Mathematical Calculations

i. Drive-Pipe

The hydraulic ramp pump draws water via the drive pipe from a water source and lift the water through a delivery pipe to the desired height. The rules and principles operation of the ram pump requires the following pipe flow calculation to ensure that the right amount of water is sent to the water storage tank [13]. A general guide for water flow capacity is in the Steel Pipes Schedule 40 – The Engineering Tool Box [14]. The drive pipe flow calculation based on two drive pipes as given in Equation (1).

$$q_1 = A \times V \quad , \quad \left(A = \frac{\pi D^2}{4}\right) \tag{1}$$

where q_1 is average delivery flow rate in m^3/s, A is cross-sectional area of delivery pipe in m^2, V is velocity in m/s ($V = 2.01$), and D is internal diameter of delivery pipe in metres ($D = 0.1016m$).

The delivery pipe can be of any material, preferably galvanized iron, that can withstand the water pressure. The lift of the delivery pipe shall be the sum of the gross head, the vertical fall which is the height from the water source to the ram pump, the vertical height between the upper reservoir and forebay and the calculated head loss. Going by the ratio 1:7, it must be noted that the vertical fall will determine the height that is acceptable, any height higher than that will decrease the flow volume and lifting capacity. The needed flow to meet the requirement is 0.0163 m^3/s.

ii. Average Delivery Pipe Flow Calculation (With Ram Pump Efficiency)

$$q_2 = \frac{Q \times h_1 \times \mu}{H} \quad , \quad (H = h_1 + h_2 + h_3) \tag{2}$$

where q_2 is flow delivered in m^3/s, Q is quantity of water supplied in m/s, H is lift height of the point of use above the ram in metres, μ is efficiency of ram (for commercial models, $\mu = 66\%$), h_1 is vertical fall in metres (from water source to ram pump ($h_1 = 38m$), h_2 is vertical lift in metres ($h_2 = 125m$), h_3 is vertical height in metres ($h_3 = 10m$).

The flow will not be the same. It will be reduced when ram pump efficiency is taken into consideration. This is because the efficiency level of a commercial ram pump is set at 66%. As a result, the flow is 0.0273 m^3/s (meets requirement).

iii. Hazen-Williams Coefficient

The head loss count is calculated using the friction loss calculator which employs the Hazen-Williams equation whereby losses are calculated on the basis of flow rates in circular pipes, the internal diameter of the pipe, the length of the pipe, and the type of pipe [15]. The results obtained show a head loss of 61.35 m.

3. RESULTS AND DISCUSSION

A. RETScreen Expert Software Analysis

A decision-support tool, RETScreen Software, evaluates the performance of the energy and power at the site. The software uses both meteorological and product performance data as inputs to evaluate a plant's capacities and annual energy production. Small hydro turbine efficiency data can be entered manually or can be calculated by RETScreen. Standard turbine efficiency curves have been developed for Kaplan, Francis, Propeller, Pelton, Turgo and Crossflow turbine types. The turbine efficiency curve simulation as shown in Figure 8 is based on rated head, runner diameter, turbine specific speed and the turbine manufacture/design coefficient. The efficiency equations were derived from a large number of manufacturing efficiency curves for different turbine types and head and flow conditions. The turbine

Table 3. First Scenario - Average Monthly Flow Rate in m^3/s

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow rate classification	LF		MF							HF	MF	
Flow rate (m^3/s)	0.15	0.15	0.19	0.19	0.18	0.18	0.19	0.18	0.19	0.24	0.20	0.19

Table 4. Second Scenario – Average Monthly Flow Rate m^3/s

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow rate classification	LF		MF							HF	MF	
Flow rate (m^3/s)	0.13	0.14	0.16	0.15	0.15	0.16	0.18	0.18	0.17	0.20	0.19	0.17

efficiency equations and the number of turbines are used to calculate plant turbine efficiency from 0% to 100% of the design flow at 5% intervals.

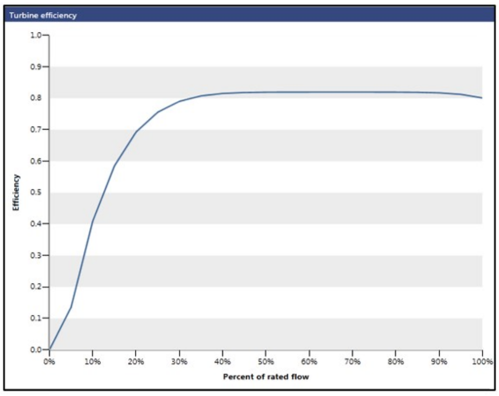

Figure 8. Turbine Efficiency Curve – Sg. Tebing Tinggi

With water uncertainty in the mountain streams and the mini-hydropower plant showing similar low flows, the study zoomed in to gather data for more information on the mean monthly flows of the Sg Tebing Tinggi Mini Hydropower Plant at the time of installation and the current flow to determine the shortfall and to identify the additional flow required by the plants to supplement to meet the installed capacities of the respective plants. A flow duration curve (FDC) is a graph of the historical flow at a site ordered from maximum to minimum flow. It is used to assess the availability of flow over time and the power and energy at the site. The flow-duration curve is specified by twenty-one values $Q_0, Q_5 \ldots Q_{100}$ representing the flow on the flow-duration curve in 5% increments. In other words, Q_n represents the flow that is equal or exceeded n% of the time. RETScreen calculates the power making use of the 21 values of the available flow $Q_0, Q_5 \ldots Q_{100}$ used to define the flow-duration curve, leads to 21 values of available power $P_0, P_5 \ldots P_{100}$defining a power-duration curve. The power duration curve on the graph clearly shows how the power output is directly proportional to the flow at the 5% intervals. The curve usually runs more or less horizontally along with its maximum power output until it reaches the 30% exceedance, upon and after which it descends as the flow rate decreases.

B. Power Output Evaluation

The improved design of upper and lower water tank technology produces an optimum power output, hence bridging the research gap where the low flow has been a significant factor in getting constant and continuous power output. RETScreen simulations indicate that with the supply of additional flow the power outputs of the mini-hydropower plants are revived to run at or run approximately at the initially installed levels

The initial installed capacity of Sg Tebing Tinggi is 178 kW. The current power output, however, is 152kW with an average monthly flow rate of 0.1650 m^3/s. The FDC (blue curve) and PDC (green curve) is as shown in Figure 9.

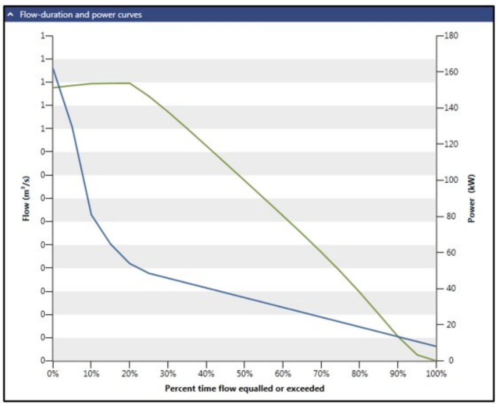

Figure 9. Power Output – Sg. Tebing Tinggi MHP (Existing)

With the supplemented flow from the storage tank, the improved power output of Sg. Tebing Tinggi Mini Hydropower Plant is 177kW at an average monthly flow rate of 0.1925 m^3/s. This output is almost equal to the installed capacity of 178kW at the time of installation and commissioning. The power output is verified via RETScreeen simulation, as in Figure 10.

4. CONCLUSIONS AND RECOMMENDATION FOR FUTURE PROGRESS

Renewable energy is currently a major growth area not only globally but also in Malaysia. From the assessment it is found that there is water uncertainty in the mountain stream of Sg. Tebing Tinggi due to both climatic factors and the river regime. The 1981 commissioned plant is generating

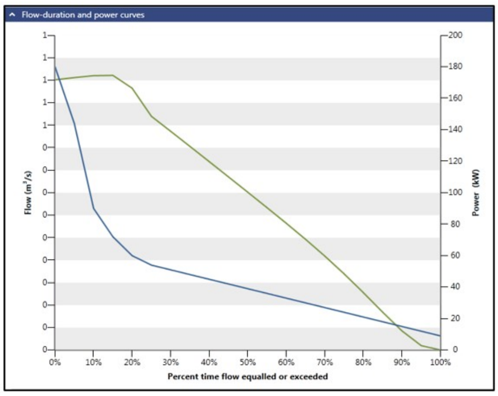

Figure 10. Power Output – Sg. Tebing Tinggi (New)

an average power output of 152 kW to add the national grid against the installed capacity of 178 kW. With the revival of the mini-hydropower plants in Peninsular Malaysia, the total installed capacity will be 16,643 kW which can produce an average annual electricity generation of 123,923,778 kWh/year based on a load factor of 0.85%. Non-operational mini-hydropower plants and those units under rehabilitation will become operational. There will be an increase in power output with consistency in energy generation. This will help to contribute largely to MESTECC's aim to achieve its target to grow the proportion of renewables in the total generation capacity mix from 2% currently to 20% by 2025. The estimated annual GHG emissions reduction will be 4.61 tCO2. With the continuous revival of more mini-hydropower plants, it will help in efforts to reduce further the GHG emission projected to be about 285.73 million tonnes in 2020 as projected in the study on Projection of CO2 Emissions in Malaysia, thereby sharing in reducing 40% carbon emission intensity by 2020 from 1990 levels [16]. This will contribute to environmental sustainability in line with government initiatives.

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