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Feasibility of pumped hydro storage for energy production and flood mitigation in Pekan

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ABSTRACT

The purpose of this paper is to study the feasibility of flood water catchment integrated with pumped hydro storage plant for energy production and new flood mitigation in Pekan, Pahang. The application of pumped hydro storage basically is to improve the peak power scenario by storing electric energy in the form of hydraulic potential energy, but in this study the lower reservoir is designed to capture and store the excess water from the flood event to reduce the peak discharge at the downstream. The water collected in the lower reservoir will be pumped into the upper reservoir for production of energy. The study on this paper comprises on estimation of required storage volume for flood attenuation, description of proposed pumped system and operation principle, estimation of power output and power input and also the capabilities and environmental benefits of the power plant. The proposed power plant was estimated to support 37.8 % of energy demand in the flood prone areas with a mean value of the power output is 19.3 MW and power input is 34.3 MW. As estimated, 33 200 tonnes of avoided carbon dioxide emission can be translated into carbon credits and can be further translated into monetary value which equivalent to US$ 99 600 - US$ 332 000 or RM 419 420 - RM 1.4 million can be generated per year. From the results, a new concept of sustainable flood mitigation can be adapted to turn the problematic floods into a sustainable source of energy.

1. Introduction

One of the most potential energy resources apart from fossil fuels, solar, wind, geothermal and nuclear are hydro resource. The hydro resource can be categorized as sustainable and renewable energy system as it is can be obtained freely from the environment. One of the alternative hydro sources that can be harvested for energy generation is from excess water during flood events (Ramos et al., 2013). According to the facts, floods would occur whenever expected amount of excess water comes into an area. In recent years, impacts of extreme flood events in Malaysia have gained much attention. For example, in December 2007, 2013 and 2014, some parts of Malaysia were badly hit by flooding which caused tremendous losses to the victims and as well to public properties. As reported by the Department of Irrigation and Drainage (DID), it is estimated that the damage to be about RM 915 million, involved more than 4.82 million people and about 29 000 km^2 areas are affected by flooding annually (Talchbhadel, 2011). Thus, the overflow of a large amount of excess water can be captured in a catchment as there is potential energy in the flowing water and at the same time it can be sustainable flood mitigation. Regard to this issue, this paper aims to study the feasibility of flood water catchment integrated with pumped hydro storage (PHS) plant for energy production and as well as a new flood mitigation. This new strategy of sustainable flood mitigation will be planned not only to solve the floods issue of flood prone areas but also can be an opportunity to utilize the potential of hydropower.

The fundamental development of PHS plants is generally to improve the peak power scenario by storing electric energy in the form of hydraulic potential energy (Deane and Gallachóir, 2015). As the most widely used for massive energy storage in the world, PHS plant account for about 129 GW or 99% of the total installed capacity worldwide (Luo et al., 2015). The energy is stored by pumping water from one reservoir to another at a higher elevation during off-peak periods and when electricity is needed the water is released back from the upper reservoir through a hydroelectric turbine to generate electricity during peak periods (Deane et al., 2010). In this study, the lower reservoir of PHS is designed as a water catchment for flood mitigation.

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The lower reservoir will capture and store the excess water from the flood event to reduce the peak discharge at the downstream. Later, the water collected will be pumped into the upper reservoir for the production of energy. As a means of evaluating this approach, a feasibility study has been completed on the Sungai Mentiga at Pekan watershed in Pahang, Malaysia. Hydrological modeling software, HEC-HMS which has been used in several studies for flood estimation (Feldman, 2000; Hasan et al., 2009; Razi et al., 2010) was run with the rainfall data in order to provide a water discharge level evaluation entering a catchment on the Pahang River. The results of this study are presented, which starts with estimation storage volume to attenuate flood, proposed system description and operation principle and potential energy generated. The results of the study are then presented and discussed.

2. Methodology

2.1. Estimation of required storage volume for flood attenuation

The research is conducted based on data sourced from the catchment area of Sungai Mentiga at Jambatan Chini 1 along Sungai Pahang, located at Pekan, Pahang. The data to be analyzed are from flood event on year 2014 and these readings are acquired from the telemetry station at Kampung Batu Gong at Pekan. Pekan is a district which located 50 km south of Kuantan City and is the royal town of Pahang, a state in Malaysia. It is a district that can be categorized as predominantly rural with low population density from the regional point of view. There are approximately 103, 000 residents in this district. Although Pekan experienced flood almost every year, the population of the town has increased more than 2%. The increase population concentration has dramatically altered the urban landscape along it's edged in flood prone areas. Pahang River flowing through this royal town nears the coast before discharging into the South China Sea. As the discharge point, the Pekan town is vulnerable to experience flooding almost each year. A disastrous flood had hit Pekan town in the year 2007 for about 2 weeks. The highest level of flood waters reached was 2.5 meters along the Pahang River and about 0.5 meters in the town center, which hugely affected all forms of business and caused thousands of residents were moved to relief centers (Ghani et al., 2012).

Urban Hydrology for Watersheds, TR-55 contains a simple method for estimating the volume of a reservoir for peak flow attenuation. The storage volume required to attenuate peak inflow can be determined by knowing the runoff volume, peak flow and peak outflow (Cronshey et al., 1986). The relationship between the peak inflow and peak outflow to the required storage and runoff volume is shown in Chart 1 (Fig. 1).

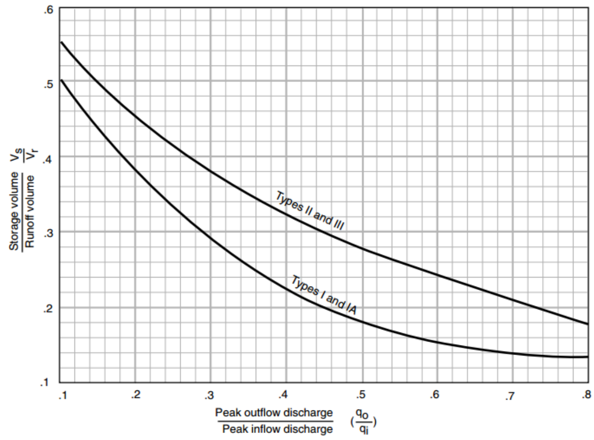

Fig. 1: Approximate detention basin routing for rainfall types I, IA, II, and III

The runoff volume of the study area is computed using Initial and Constant-rate loss model in Hydrological Modelling System (HEC-HMS) software to be 41331.65 acre-feet and the peak inflow is 17 976.7 cfs. The storage volume (V_s) can be calculated by multiplying the volume of runoff (V_r) with the ratio peak outflow discharge (q_0) to peak inflow discharge (q_i).

Peak inflow discharge, q_i = 17976.7 cfs
Peak outflow discharge, q_0= 12583.7 cfs
The ratio of outflow to inflow= 0.215
(From the graph, used a ratio of storage volume to runoff volume)
Required storage volume= Vr x (V_s/V_r)
= 41331.65 ac-ft x 0.215
= 8886.3 ac-ft
= 10 961 073.3 m^3

2.2. Proposed pumped hydro storage system and operation principle

Fig. 2 shown the schematic diagram illustrating the principle operation of proposed PHS that is designed based on the described in studies of "Optimal operation and hydro storage sizing of a wind–hydro power plant" by Castronuovo et al. (2004). The system proposed of wind turbines used in conjunction with the PHS and connected to the grid. The operating principle of the proposed system can be described as follows: The water from lower reservoir or water catchment is pumped to the upper reservoir using the wind turbine output during low demand of electricity. The pumped water in upper reservoir is then released through the turbine and driving a generator to produce enough energy during high demand for electricity. During hydrological extreme events or flood seasons, the storage space of lower reservoir is needed to keep an empty space for huge discharge of excess water. In order to regulate the level of river at the downstream of the dam, the water reservoir only needs to temporarily store the excess water and can slowly release it after the flood event or when the river water return to normal level.

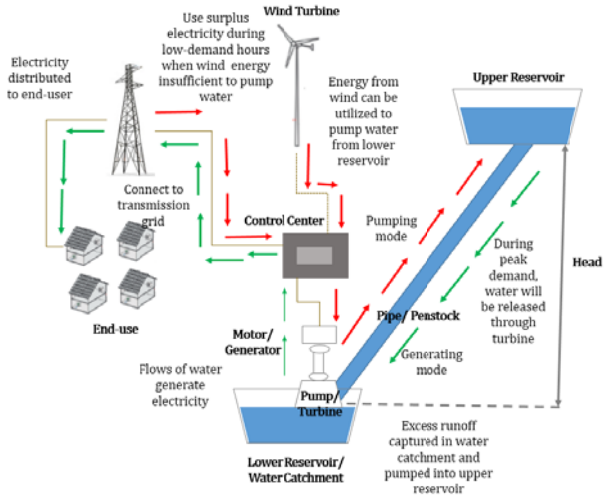

Fig. 2: Proposed system layout

2.3. Generating mode

When there is high demand of energy, water from the upper reservoir is used to operate the turbine driving the hydro generator. The generation of energy from the turbine, E_T can be expressed as in Eq. 1.

$$E_T = \rho \; x \; g \; x \; h \; x \; Q_T \; x \; \eta_T \qquad (1)$$

Where η_T is the overall efficiency of generating mode; ρ is the density of water (kg/m^3); h is the net pumping head in meters (m); g is the acceleration due to gravity (9.81 m/s^2); and Q_T is the water flow rate from the upper reservoir onto the turbine in cubic meter per second (m^3/s). According to the engineering practice and manufacturers' specifications, the estimated efficiency of the turbine and generator are 75% (Ramos et al., 2014).

2.4. Pumping mode

The energy required to pump water, E_P from the lower reservoir up to the upper reservoir can be expressed as Eq. 2.

$$E_P = \frac{\rho_W \; x \; g \; x \; h \; x \; Q_P}{\eta_P} \qquad (2)$$

Where, E_p is the charging power required to pump water up in Watts (W); Q_p is the water flow rate from the pump in cubic meter per second (m^3/s); and η_p is the overall efficiency of pumping mode. Only a portion of water stored in the upper reservoir from the total volume of flood required to attenuate flood event (Punys et al., 2013).

3. Results and discussions

3.1. Calculation for pumped hydro storage

1. Time to empty reservoir (t) = 72000 sec,
2. Discharge through penstock, Q x t = (Area x Height) m^3 = Vm^3
3. Thus, Q = 97.2 m^3/s
4. Velocity at the penstock inlet (v) = $\sqrt{2gh}$ = 9.9 m/s
5. Head loss due to friction in penstock (h_f) = $\frac{fLv^2}{2gD}$,
6. f = frictional factor, h_f = 23 meter
7. Plant net head (H) = 50 m – 23 m = 27 m

Then, power generated during generation mode and power input during pumping mode,

$$E_t = \left(1000\frac{kg}{m^3}\right) x \left(9.81\frac{m}{s^2}\right) x \; (27\; m) x \left(97.2\frac{m^3}{s}\right) x \; 0.75 = 19.3 \text{ MW}$$

$$E_P = \frac{\left[\left(1000\frac{kg}{m^3}\right) x \left(9.81\frac{m}{s^2}\right) x \; (27\; m) x \left(97.2\frac{m^3}{s}\right)\right]}{0.75} = 34.3 \text{ MW}$$

The mean value of power output is 19.3 MW and the power input is 34.3 MW. The power generated during the total period of plant running varies from the maximum and minimum value as the output relies on water head, velocity of flowing water, discharge, etc. As shown in Fig. 3, a graph of the data set of generation mode and pumping mode is prepared based on the mean value of power output and input. Assumed the proposed PHS runs for 18 hours per day, 13 hours is allocated for power generation and 5 hours for pumping of water into upper reservoir (Table 1).

Table 1: Specification of pump hydro storage

Parameter	Value
Volume of water available in upper reservoir (V)	7 000 000 m^3
Upper reservoir height	50 m
Length of penstock (L)	80 meter
Average water head in upper reservoir (h)	5 meter
Time required to empty reservoir (t)	20 hours = 72000 seconds
Diameter of penstock (D)	0.8 m

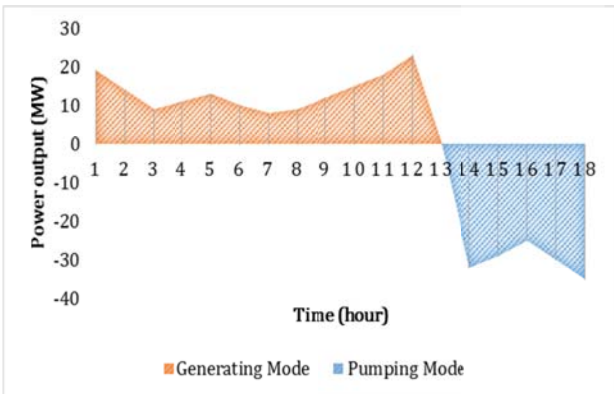

Fig. 3: Data set of proposed PHS

The upper area under the graph in Fig. 3 representing the total amount of generated whereas the lower area under graph indicating the input power required pumping water up into upper reservoir. If the power plant operates throughout the year, about 91.6 GWh of energy can be produced for community consumption. Based on the data by Tenaga Nasional Berhad, average power usage by Malaysian household is around 10.1 MWh per year.

Then, this PHS has the capability to support 9114 households or 37.8% of total house in Pekan community. Besides that, in order to generate the equivalent amount of energy, 29 599.1 tonnes of coal (energy content of coal is 8142 kWh/tonne with 0.38 energy efficiency) are required in coal-burning power plant (Fig. 4).

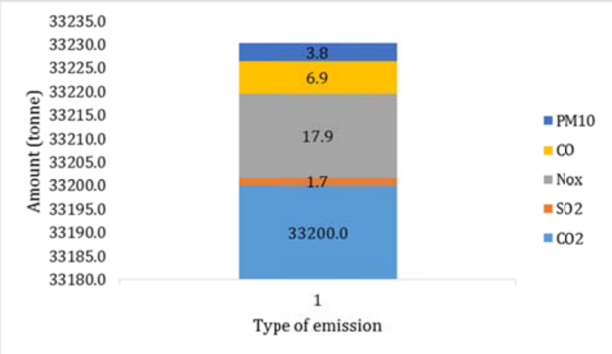

Fig. 4: Amount of emission avoidance

Conventional power plants operate on fossil fuels, which produce huge amount of air pollutants. When the proposed PHS is integrated with renewable resources such as wind energy for energy input, tonnes of harmful emission such as CO_2, SO_2, NO_x, CO and PM^{10} can be avoided from releasing to the atmosphere (Strachan and Farrell, 2006). If the PHS is awarded with Certified Emission Reductions by the United Nation Executive Board of Clean Development Mechanism, tonnes of avoided carbon dioxide can be translated into carbon credits and can be further translated into monetary value. One carbon credit is equivalent to one metric tonne of carbon dioxide and the Malaysian Energy Centre (PTM) assumes the price range to be US$ 3-10 per tonne of CO_2 (Lim et al., 2013). Therefore, as shown in Chart 3, the estimated amount of CO_2 can be avoided is 33 200 tonnes, which equivalent to US$ 99 600 - US$ 332 000 or RM 419 420 - RM 1.4 million can be generated per year.

4. Conclusions

This study proposed flood water catchment integrated with pumped hydro storage plant for energy production and at the same time acts as sustainable flood mitigation. The results reveal that the system capabilities to support 37.8 % of energy demand at the flood prone areas and the study also indicates the positive environmental benefits of the plant by avoiding a huge amount of air pollutant emission and also can generate monetary value. It is expected from this new propose system, a new concept sustainable flood mitigation can be applied by management to turned the problematic floods into a sustainable source of energy.

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