Evaluation of the wind pumped hydropower storage integrated flood mitigation system

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Abstract. As Wind Pumped Hydropower Storage (WPHS) need high cost to construct, it is important to study their impacts on economic and environmental aspects. Thus, this research aims to evaluate their economic and environmental performances. First, Hybrid Optimization Model for Electric Renewable (HOMER) was used to simulate power generation system with and without the flood reservoir. Next, the total amount of emitted air pollutant was used to evaluate the environmental impacts. It was found the wind-diesel with reservoir storage system (A-III) will have much lower NPC than other systems that do not include reservoir for flood mitigation when the cost of flood losses are included in the total Net Present Cost (NPC). The NPC for system A-III was RM 1.52 million and for diesel standalone system (A-I) is RM 10.8 million when the cost of flood losses are included in the total NPC. Between both energy systems, the amount of pollutants emitted by the A-III system was only 408 kg-CO_2/year which is much less than the A-I system which is 99, 754 kg of carbon dioxide per year. To conclude, the WPHS integrated with flood mitigation system seems promising in the aspects of economic and environment.

1. Introduction

Pumped hydropower storage (PHS) is a powerful form of energy storage on the electric grid today. At the moment, it is the most affordable form of bulk energy storage available. Integrating wind energy with pumped hydro energy storage (WPHS) can overcome the intermittency of wind by consuming energy during low-demand periods and supplying energy during high demand. PHS is a proven, low-risk technology with a great track record in their efficiency, has longer facility lifetimes, adjustable and can quickly respond to the fluctuations of electricity [1]. Although WPHS is clean, renewable and can store excess energy during non-peak times but the problem with this storage facility is that they can be expensive to construct [2]. Therefore, other aspects should be included as the added value of WPHS, to make it worth to construct this storage facility. The reservoirs of WPHS can store huge amounts of water. If the reservoir is designed in the similar mechanism of flood reservoir it may capable to mitigate flood during extreme hydrological events. When the effect of a flood can be avoided or at least reduced, there will be a lot of advantages can be gain, especially in the term of economic aspects. Due to the feasibility of WPHS reservoir in flood mitigation and the high cost of those projects, a study should be conducted to evaluate the feasibility of the proposed WPHS integrated with flood mitigation system. Through the evaluation, the economic and environmental aspects of the proposed power system can also be assessed.

2. Methodology

2.1. System description and specification

In this research, the residential at Kuala Pahang was selected as a targeted study area. It was estimated that this sub division of Pekan district has the total population about 7,936 peoples with 6 villages and consists of 1,133 households. Each village was estimated to have 180 households. Approximately the total electricity usage is 25,290 kWh per month. The daily load profile in Kuala Pahang is shown in Figure 1 and it shows that highest demand of electricity occurs at night.

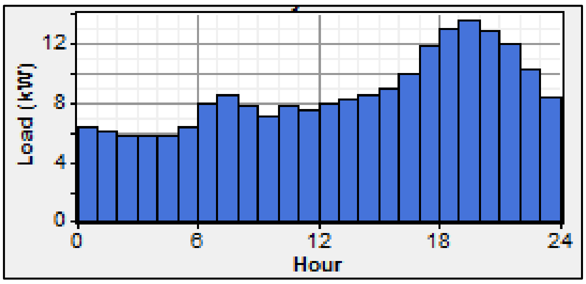

Figure 1. Daily load profile in Kuala Pahang.

In this study, there was three power generation system studied. First is the diesel standalone system as A-I in Figure 2, the second system is wind-diesel without reservoir storage as A-II in Figure 3, the third system is the wind-diesel with pumped hydropower storage as A-III in Figure 4. The proposed PHS system not only will exploit the excess energy from intermittent renewable energy but also can be effectively used for flood mitigation by holding the excess runoff in the reservoirs during annual flood seasons. The storage space of the lower reservoir is kept low for a huge discharge of excess runoff during extreme hydrological events or monsoon seasons.

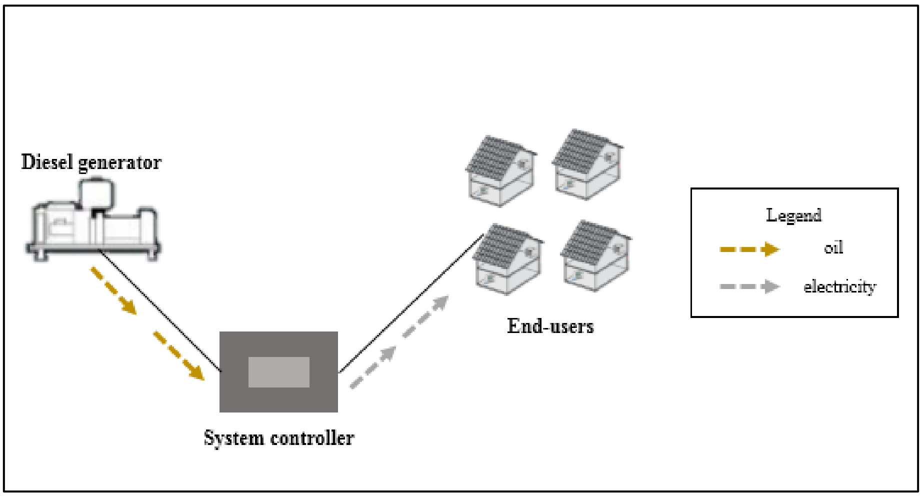

Figure 2. Diesel standalone system as A-I.

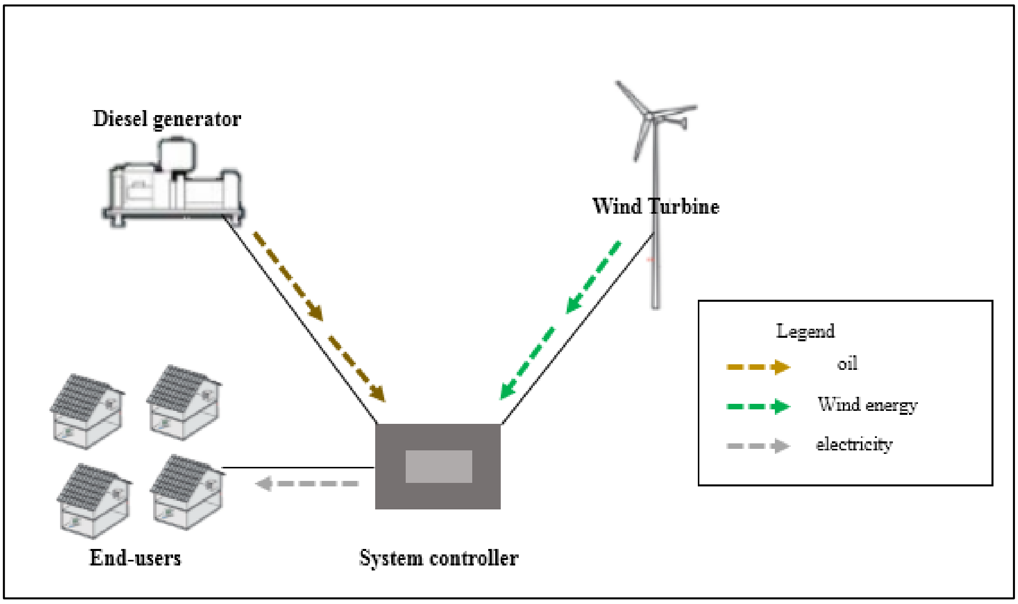

Figure 3. Wind-diesel without reservoir storage as A-II.

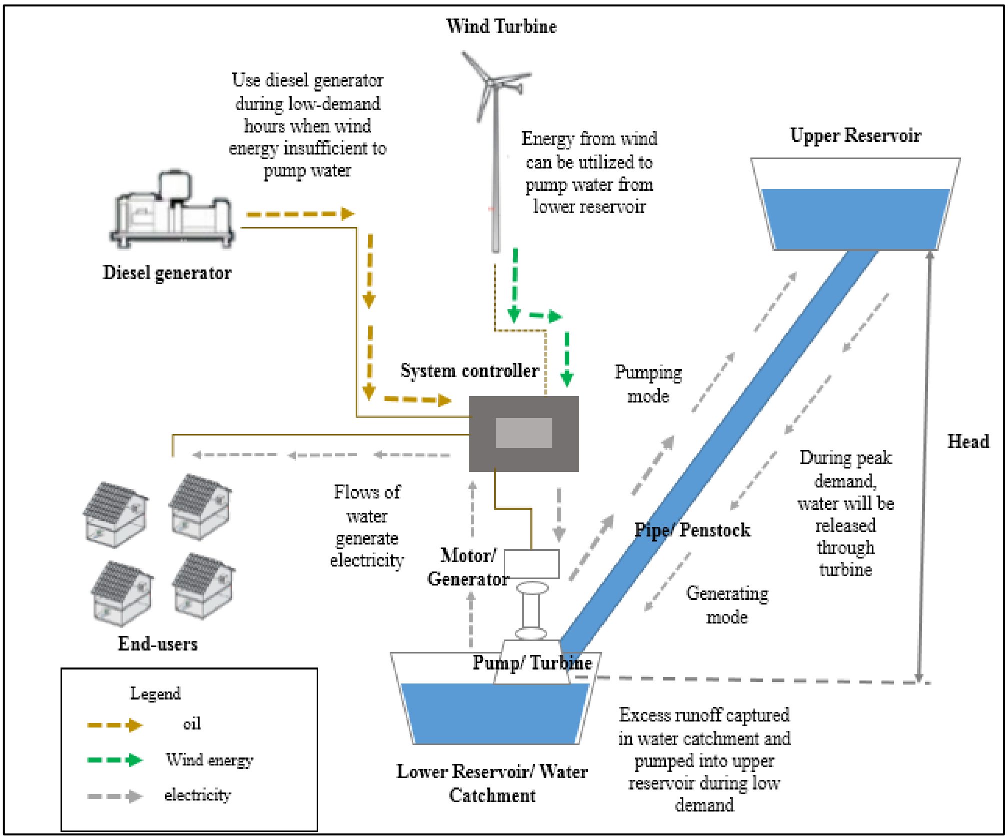

Figure 4. Wind-diesel with pumped hydropower storage as A-III.

The integrated wind–diesel system consists of four main components which include a diesel generator, wind turbines, batteries as water reservoir and converters units. The technical specification of the energy system for the generator, wind turbine, inverter and battery bank, as simulated in Hybrid Optimization Model for Electric Renewable (HOMER) was described in Table 1.

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Table 1. Data of selected system component.

Description	Data
Reservoir	
Nominal voltage	240 V
Nominal capacity	2,161,254 Ah
Lifetime throughput	1,471,210,496 kWh
Wind turbine	
Model	Fuhrländer 30
Cut in wind speed	2.5 m/s
Rated wind speed	8 m/s
Cut out wind speed	25 m/s
Lifetime	20 years
Hub height	30 m
Inverter	
Model	Solectria PVI-80kW-480V
Size (step size 50 kW)	0 - 500 kW
Lifetime	15 years
Generator	
Model	Cummins
Size (step size 50 kW)	0 – 500 kW
Rated power	80 kW
Minimum running hours	15,000hr
Minimum load ratio	25%

2.2. Modelling pumped storage hydropower in Hybrid Optimization Model for Electric Renewable (HOMER).

Canales and Beluco had discussed the steps to model pumped hydropower storage (PHS) with a few modification in HOMER [3]. In HOMER, a battery was created as equivalent to electrical storage mechanism of PHS with particular capacity and roundup efficiency. The connection between the battery created and PHS was explained further in next sub-section.

2.2.1. Battery representing the reservoir. The battery is capable of storing excess energy and supply when there is a demand which has the similar capability of PHS reservoirs. The properties of battery modelled in HOMER was assumed to remain the same during its lifespan. Based on explanation by Canales and Beluco [3], the total stored energy in the volume of reservoir can be described as in equation (1).

$$E_S = \frac{9.81\ x\ \eta_{hyd}\ x\ H\ x\ Vol}{3600} \quad (1)$$

Where, E_S is the total stored energy [kWh], H is the gross head [m], η_{hyd} is the efficiency in turbine mode [%] and Vol is the volume of reservoir [m^3]. The discharge current of the battery with a fixed voltage and capacity is considered independent, and the stored energy can be expressed as in equation (2).

$$E_S = \frac{V \, x \, C_B}{1000} \tag{2}$$

Where, E_S is the stored energy [kWh], V is the voltage [V] and C_B is the capacity [A.h]. The power produced by the battery is corresponding to the value of current when the voltage is assumed to be constant and can be calculated as in equation (3).

$$P_{bat} = \frac{V \, x \, I}{100} \tag{3}$$

Where, P_{bat} is the power [kW], V is the voltage [V] and I is the current [A]. According to Canales and Beluco, there are three steps to model PHS in HOMER. The first step is to set a reference voltage of the equivalent of the battery and estimate the capacity of the equivalent battery which proportional to the reservoir volume. The battery also must be set in DC bu. This important to make sure that inputs and outputs of the battery will represent the flow rate of water being stored or leaving the PHS reservoir. The second step is to create an equivalent battery with a selected reference voltage and capacity decided earlier. The round trip efficiency should be set at 100% and 0 % for the minimum state of charge. The third step is to include the converter component, which will represent the various options for hydropower plant capacity. This component can be used to control the conversion efficiency in either pump or turbine modes.

2.3. Environmental analysis

To estimate the amount of emission produced, the emission factors [kg/kWh] used for estimating emission in power plants is identified first as in Table 2 [4]. Then, the emission factor of air pollutants was multiplied by the total amount of electricity generated as in order to get the amount of emission release to the environment.

Table 2. Emission factors [kg/kWh] used for estimating amount of emission produced.

Fuel type	CO_2	NO_X	SO_X	CO
Generator	0.85	0.0025	0.0164	0.0002

3. Result and discussion

Figure 5 shows the configuration of proposed system as designed in HOMER. The components of the system consist of a wind turbine, batteries or reservoir, a power converter and generator. The simulated peak demand of primary load was 16 MW and the total energy consumption was 206 kWh/day.

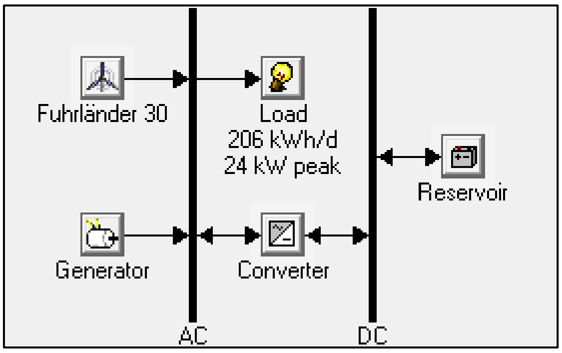


Figure 5. Schematic diagram of the wind-diesel pumped hydropower with generator system.

All possible system configurations are listed in ascending order in the HOMER output. Figure 6 shows the simulation results of the annual production of electrical energy by each system. The production value is the annual energy output of each electrical energy-producing component in the system added to the total electrical production. As in Figure 6, the combination of generator/wind turbine systems (A-II) has the highest production of electricity which was 88,165 kWh/year. Out of this, 77,032 kWh/year comes from the generator component and 11,133 kWh/year produced by the wind turbine (WT). The second highest electricity production is from the standalone generator system (A-I) which was 81,453 kWh/year. Meanwhile, the combination of generator/wind turbines/reservoir system (A-III) produces about 78,233 kWh/year, 77,933 kWh/year comes from the WT and 300 kWh/year produced by generator component. The analysis showed that equipping the energy system with reservoir improves the penetration of renewable sources. Without reservoir storage for the generator/wind turbine system, the penetration of wind was only 12.6 %. But, with the addition of reservoir in the system, the penetration of wind energy was almost 100 %.

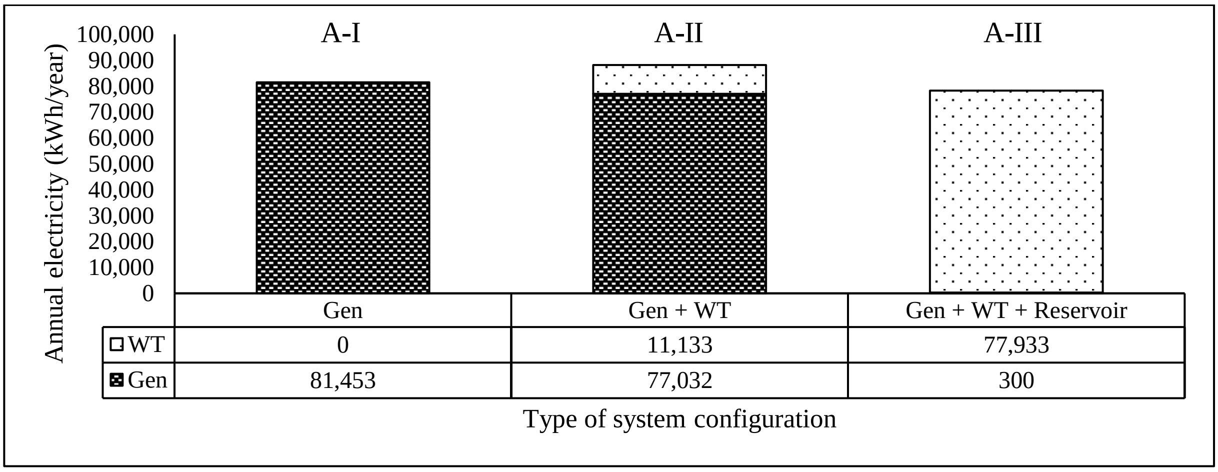
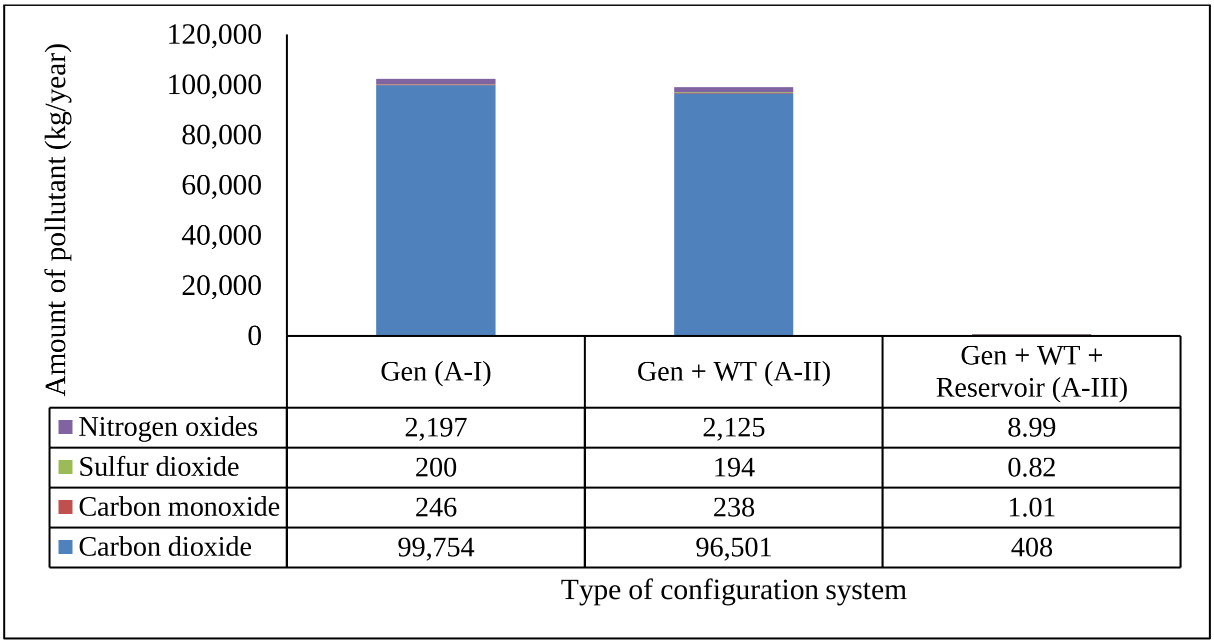


Figure 6. Comparison electricity production for different configuration system.

As expected, there were significant amounts of reduction in emission where the generator system is mixed with renewable energy sources as compared to diesel standalone system. Basically, when less energy produced from combustion of diesel, the less emission of the pollutant is. The reduction of emission for generator/wind turbines/reservoir system (A-III) was reduced by 99.6 % compared to the diesel standalone system (A-I). The emissions from A-III system was low compared to the other systems due to more participant of wind energy in their electricity production as shown in Figure 7. 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, NOx, CO, and PM10 can be avoided from releasing to the atmosphere [5]. If the PHS is awarded 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 assumes the price range to be US$ 3-10 per tonne of CO_2 [6].



	Gen (A-I)	Gen + WT (A-II)	Gen + WT + Reservoir (A-III)
Nitrogen oxides	2,197	2,125	8.99
Sulfur dioxide	200	194	0.82
Carbon monoxide	246	238	1.01
Carbon dioxide	99,754	96,501	408

Figure 7. Amount of pollutants produced by different power system (kg/year).

Figure 8 shows the data on the amount of pollutants produced and Levelized Cost of Energy (LCOE) in a graph. The type of pollutants emitted as listed in Figure 7 which included CO_2, CO, SO_X, and NO_X. The emission of the pollutants into the environment not only causing harmful effects on human health but also the one of the main contributor to the global warming phenomenon [7]. Meanwhile, the LCOE is interpreted by HOMER as the mean cost per kWh of electrical energy unit produced by the system. The LCOE can be a useful tool for comparison of various energy systems. If a system has a reasonably low LCOE, it implies that the electricity is being produced at a low cost. Thus, for the investors, they will have a higher chance of returns with low cost of electricity production [8]. As can be seen in Figure 8, the system such as the generator standalone system (A-I) has the lowest LCOE among all systems. Meanwhile, generator/wind turbine systems (A-II) and generator/wind turbines/reservoir system (A-III) had higher LCOE than average rate of the electricity tariff in Malaysia which is RM 0.38/kWh [9]. But, in term of environmental aspects, generator/wind turbines/reservoir system (A-III) had the least emission of pollutants to the environment. However, A-III system which included reservoir as their storage device in their system had significantly increased the LCOE and the Net Present Cost (NPC) as compared to other systems. The inclusion of reservoir in the proposed system is important for flood mitigation during annual monsoon seasons and also can act as an energy storage device for intermittent renewable energy sources.

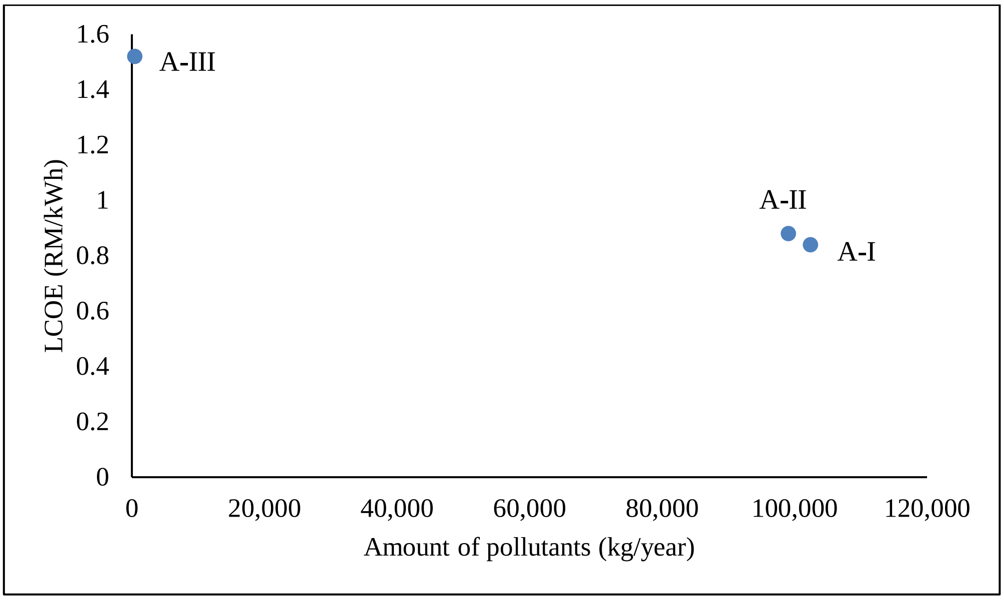


Figure 8. Summary of difference configuration system.

Figure 9 shows the comparison when the cost for flood losses was added into the total NPC of configuration systems without reservoir for flood mitigation. The Figure 9 (a) shows the total NPC without flood losses included in each system and meanwhile Figure 9 (b) shows the total NPC with flood losses included in the overall cost. Only system A-III had included the reservoir in their configuration which may help prevent floods, so the total NPC does not change. The total loss due to floods recorded in 2014 in the Pekan district alone is almost RM 10 million and this cost has been included to the total NPC of the power system that does not have a reservoir in their system.

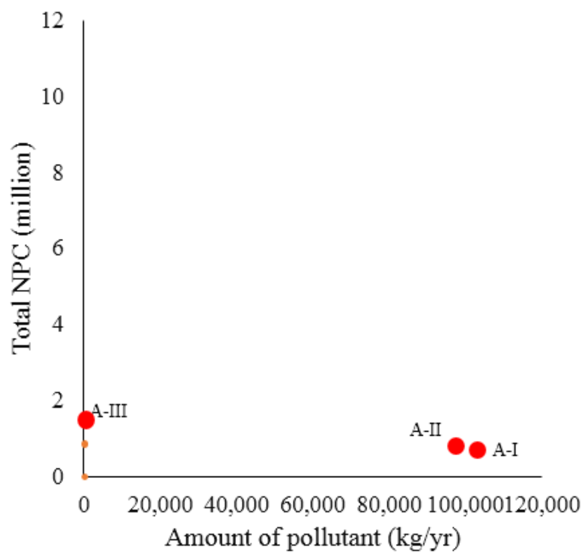


Figure 9 (a)

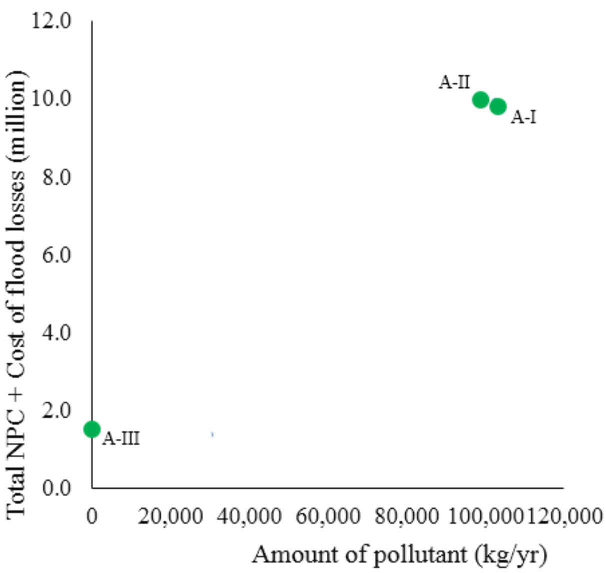


Figure 9 (b)

A total of RM610 million in losses was recorded in the year 2014 flood event that hit Pahang which leads to the destruction of property, agricultural produce, and infrastructure. It is the worst flood disaster after 1971, RM348.5 million losses had been recorded from infrastructure damage involving roads, bridges and public utilities in the state. For the agriculture sector, Pahang had lost over RM65.1 million and 219 houses in seven districts including Jerantut, Kuantan, Lipis, Pekan, and Temerloh were destroyed in the disaster [10]. The cost of flood damage is high as compared to the costs required to construct projects such as A-III system that include reservoirs to overcome floods. The NPC for system A-III is RM 1.52 million which much lower than another system when the cost of flood losses are included in the total NPC. It is better to allocate a small budget to implement projects which can mitigate floods rather than to bear high costs due to flood losses as in the year 2014.

4. Conclusion

The analysis has shown that when the cost of flood losses are included in the total Net Present Cost (NPC), the wind-diesel with reservoir storage system (A-III) will have much lower NPC than other systems that do not include the reservoir for flood mitigation. The addition of reservoir as a storage device in the power generation system has significantly raised the value of NPC and also the levelized COE of the system. But, the inclusion of the reservoir in the proposed system is important for flood mitigation during annual monsoon seasons and at the same time, it can act as energy storage device for intermittent renewable energy sources. Thus, the pumped hydropower storage integrated flood mitigation system offers benefits in both economic and environmental aspects.

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