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An evaluation of appropriate hydro pump and turbine systems in generating electricity

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Abstract
With proper supply of wind energy and water resources being available in this particular location. The plan is to harness both sources in an efficient and economically feasible way. Such as a hybrid renewable energy power plant, which will use both wind energy and kinetic energy from water to produce power. The produced will be then supplied to meet local energy demands. One of the major issue with harnessing renewable energy is the inconsistency. As the amount of wind flow is not variable with time, the power output will be inconsistent as well which is not desirable at all. To overcome this issue, this plan includes having a combined wind mill and water turbine station together. As Langkawi is not compatible for building a high rise water damn with natural advantage, a water reservoir will be built and with the extra power produced from the wind turbine will be used to bring water up to the reservoir. In the event of insufficient wind flow, the water turbine will be used to compensate the insufficiency. In this paper, a comprehensive plan regarding this specific scenario is presented with proper data and scholarly material published.

Keywords: turbine, hydro-energy, hydro turbine, solar photovoltaic, wind energy, single-pole double through (SPDT)

Introduction

Energy converted from crude oil, gas and coal powers almost everything around us, hence making these elements the main resource for providing energy for this world. But this heavy use comes with a cost. These energy sources are not renewable and the amount we have is limited. Over a certain period of time, the reserve amount will definitely run out. As it is predicted that with the growth in technological advancement and the increasing rate of fossil fuel consumption it will take 35, 107 and 37 years for oil, coal and gas respectively to deplete completely (Shafiee & Topal, 2009) [7]. Power plants, automotive, aviation, manufacturing plants and in this ongoing list everything is dependent actively or passively on this three resources for power to run on. The strategies to build a sustainable development that involves renewable energy sources such as wind, solar, wave and biomass is to combine them in an efficient manner according to the location it needs to be employed. Such strategies usually require considering aspects such as sustainability of the system, energy savings on the demand side, improvement of efficiency in energy production over time. Therefore, in large scale renewable energy implementation needs to consider strategies on integrating various sources of renewable sources in comprehensible energy systems that focus on energy savings in an efficient manner (Ahammed Sajid, 2021) [1]. In a place like Langkawi island, which has a high potential for few renewable energy sources. As higher wind flow and hydro energy sources. Various methods of harnessing these renewable energy sources are already available. But as has been discussed before, the main challenge is the utilization of these resources in a sustainable and sufficient manner (Kirsch, 2009) [2]. Factors such as wastage of excess power wastage due to less demand is a major concern in this type of systems. Properly designing a system which can utilize this extra produced power into converting or conserving power for future use is the main concern in this design proposal.

Literature Review

The energy storage in the form of potential energy of water is not a new concept. The pumped- hydro energy storage (PHES) is found globally, but mostly on a large scale. This technology has attained the simplicity and commercial maturity along with ease in installation and maintenance. For reducing the residential electricity cost in suburban areas, a grid-connected solar photovoltaic (SPV) system with PHES using a Pico turbine, a pump and the open water source were proposed by some researchers. A similar PHES, but off- grid hybrid system consisting of wind and solar energies with Pico turbine, pump and an open water sources also proposed by some researchers. In both the systems, the water is pumped from the open water source by the excess energy generated and is stored in the upper reservoir in the form of potential energy of water. When the wind speed and solar irradiation are poor, this potential energy of water is used to run the hydro turbine to generate power. (Pali & Vadhera, 2018) [5]

Hydropower facilities may be able to act as a "battery" for wind power by storing water during high-wind periods and increasing output during low- or no-wind periods. Similarly, periods of low water resources or policy pressures on water use can be mitigated by using wind to generate power normally generated by the hydropower systems. (Ahmad Hemami, 2012) [3].

Initiatives was taken to explore the possible synergy between wind and hydropower resources in November 2003 when it sponsored an International Energy Agency (IEA) Topical Expert Meeting on the Integration of Wind and Hydropower Systems. Hosted by the Bonneville Power Administration (BPA) in Portland, Oregon, the meeting drew 28 energy experts from the United States, Canada, Norway, and Sweden. The participants delivered 15 presentations that ranged from high-level national perspectives on wind/hydropower integration to details of specific wind/hydropower projects. The cooperation of federal power management agencies such as BPA and the Western Area Power Administration (WAPA) will be integral to the work. (Rothman, 2016) [6]

The maximum possible energy corresponds to the operation of the windmills at maximum power mode; so, the pitch should be regulated to get the maximum energy at any wind speed condition and connected to an infinite power grid (Pali & Vadhera, 2018) [5].

$$\eta = \frac{E_{Wind\ Produced}}{E_{Wind\ \infty}}$$

In the case of a hybrid wind–hydro power plant installed in a small power system, depending on consumer's demand and wind speed, the hydro energy cannot always be put on line. Both process, energy storage (pumping mode) and the posterior hydraulic energy generation (turbine mode), have losses. The operating efficiency is defined as the direct wind energy put on line plus the hydro energy divided by the maximum energy that the wind farm would have produced in a large power system at maximum power mode (Pali & Vadhera, 2018) [5]

$$\eta = \frac{E_{Wind\ Grid} + E_{Hydro}}{E_{Wind\ \infty}}$$

Methodology

The process started with brainstorming and getting the idea of hydro pump and turbine system. After that need to select the design with system and considering the designing parameter. Then need to calculate the hybrid system and confirm it platform. After that need to finalize the design. Then simulation will be needed to compare the performance. Then can analyze and compare. If the result shows the optimization done, then the aim and objective will be achieved. After that need to fabricate the system. Evaluation can be done by comparing the result achieved by testing and calculation, if output is successful then evaluation will achieve the goal. The flow chart of methodology is given in Figure 1

Design concept

As illustrated in the Figure 2 it is observed that the designed is a simplified design of the proposed project which can elaborate in such a way that the wind firm consist of wind turbines are located at the high elevation in the hills or designated higher elevated places with enough wind supply recorded throughout the year for producing enough power which can distributed to the consumers as well as can be used to pump water to the reservoirs situated at the higher elevations. The power house build at the lower elevation includes three main equipment needed in the project for power generation hydro pump, hydro turbine and generator. More into details of the projects proposes that the wind turbine when produces excess power, the power can be diverted and used tow pump water from the water source which is assumed to be the available sea water surrounding the island. As observed in the design concept the hydro pump is connected with the power supply of the wind turbine, which pumps water to the upper reservoirs. The upper reservoirs consist of over flow pipe and control valve, when the water is fully filled up in the upper reservoir the power used to fill the water from the wind turbine can be cut off and used for distributing the customers or can be stored for future use. During the time of the year when there is less supply of air and wind turbines are less efficient to produce the customer needs the control valves used in the upper reservoirs are open, let it flow towards the hydro turbine, which is also connected with a generator to produce electricity for the consumption. This is a continuous cycle process which have to be maintain efficiently to produce enough electricity to meet customer needs during high demand. Additionally, power storage house with the help of batteries can be built and connect with the supplies can store power when higher electricity has been produced for future consumption. During the design of a wind farm with pumped hydro energy storage project, there are numerous project components that need to be considered. The primary considerations include head, flow rates, waterways, upper and lower reservoirs, pump/turbine selection, and other design issues.

Upper and lower reservoirs

The design of the upper and reservoirs is dependent on a number of factors. First, it depends on whether an existing reservoir is available. Often an existing reservoir or reservoirs may be used. This is attractive because it reduces construction costs and may provide a reliable water source. Second, the layout of reservoirs depends on the topography of the project site and the presence of streams and rivers. Third, the geologic conditions present have a big impact on selecting the location of potential reservoirs and the design of a reservoir lining system. Due to the rapid change in water levels in both the upper and lower reservoirs during reservoir filling and emptying (during pumping and turbine operation) the stability of the reservoir slopes can be greatly impacted; consequently, lining of the reservoir may be required. Seepage losses in the reservoir foundations are also a concern, which may require a grout curtain or lining of the reservoir. This is of particular concern for a closed-system pumped storage hydropower project where conservation of water is important. The sizing of the upper and lower reservoirs depends on the size of the installed units, the operating head, the site characteristics, and the number of hours that operation of the turbines is required. A typical plant is sized to operate between 4 and 20 hours depending on local energy needs. Operational models are used to evaluate the cost-benefit of different reservoir sizing options to refine the design.

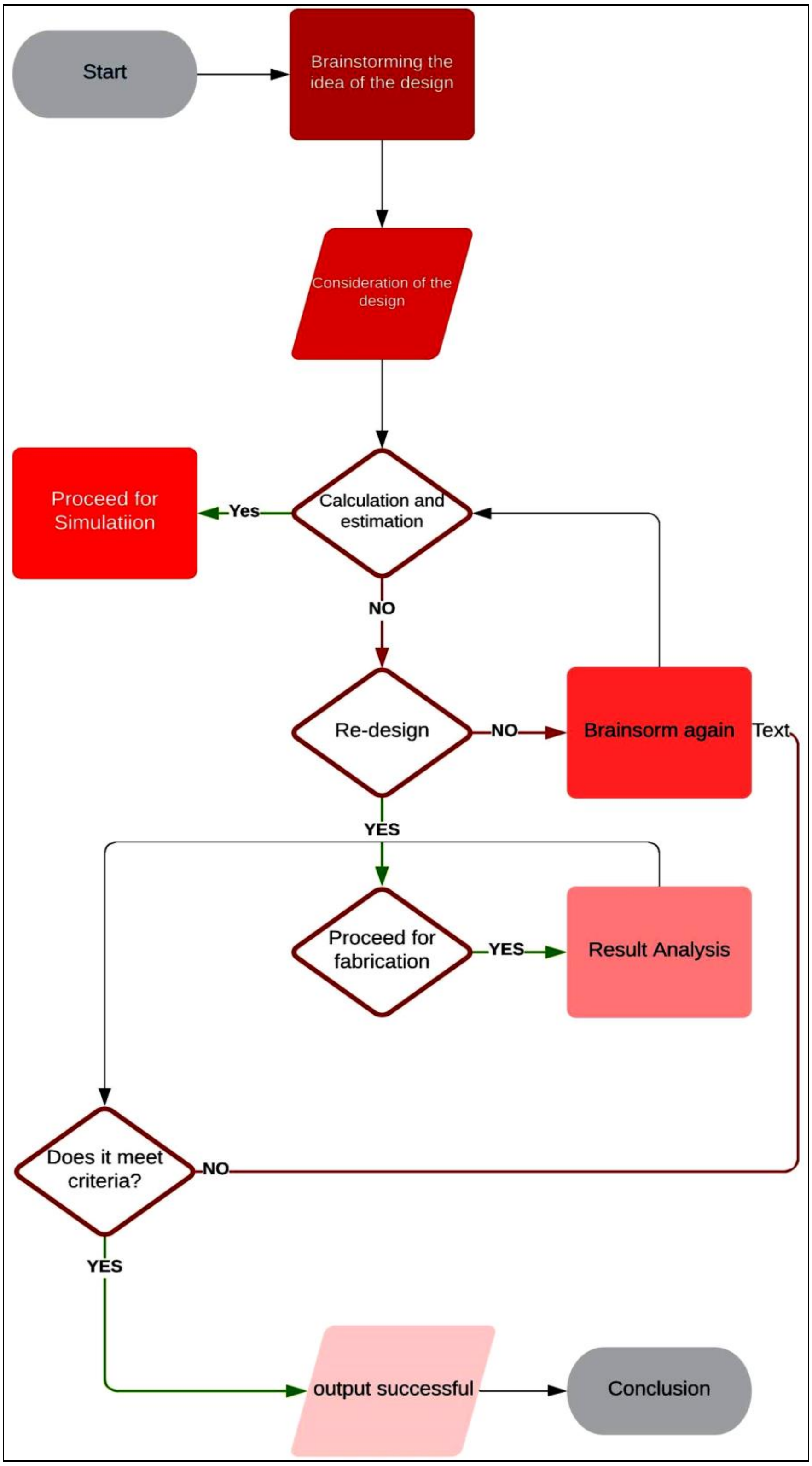

Fig 1: The flow chart of methodology

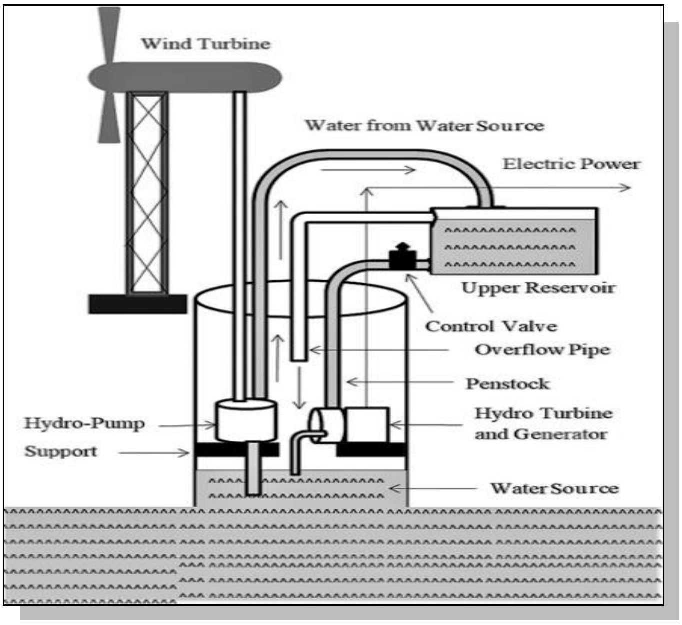

Fig 2: Design concept of the proposed configuration.

Pump and turbine selection

The sizing of pump and turbine units primarily depends on the project economics, site characteristics, and requirements of the power system. Most constructed pumped storage hydropower projects provide between 300 to 2,500 MW, which would suggest that larger scale projects are generally more economically viable. For larger scale projects, and therefore the selection of larger pump/turbine units, sufficient water available, sufficient operating head, and adequately sized upper and lower reservoirs are needed. For projects with low head or limited water available, a smaller scale project is more appropriate. The type of pump and turbine unit, single speed versus adjustable speed or a combination of both, should also be evaluated as part of the design process. While some early pumped storage hydropower projects used separate pump and turbine, most modern project used combined pump/turbine unit. The selection of pump/unit size and type also affects the size and configuration of the powerhouse.

Calculation

Wind turbine

Wind turbine converts the wind power of moving air into the mechanical rotations. The shaft power Pwt extracted by the WT from the wind is expressed as follows:

$$P_{wt} = \frac{1}{2} C_p \rho_a \pi R^2 U^3 \quad \text{for } U_i \leq U < U_o$$

$$= 0 \qquad \text{for } U < U_i \text{ or } U \geq U_o$$

where, 'U' is the wind velocity in m/s; 'R' is the length of each blade of turbine from the centre of the rotor shaft to the blade tip in m; 'Pa' is the air density in kg /m3 (1.29 kg/m3) and 'Cp' is the power coefficient, which depends on tip speed ratio and blade pitch angle. Its value may be in between 35-40%, but for a modern well-designed WT it has been claimed up to 50%. Ui and Uo are the cut-in and cut-out wind speeds of the WT respectively.The power expressed by Php is the net power available at the WT shaft, which can be imparted to the HP. The mechanical power supplied to the HP is less than the shaft power of the WT due to the losses that occurs in power transmission system and can be expressed as: where, 'Php' is the power to the HP supplied by the WT, 'ηts' is the efficiency of the hp P ts mechanical

$$P_{hp} = \eta_{ts}\left(\frac{1}{2} C_p \rho_a \pi R^2 U^3\right)$$

$$= \eta_{ts} P_{wt}$$

Transmission system which supplies power from WT to HP and converts the rotational speed of WT into the rated speed of HP.

Hydraulic pump

The power available by the HP from the WT as given by is utilized to store water in the UR. Hence using (2), the potential energy of water stored per second in the reservoir can be expressed as

$$\rho_w g H_{av} Q_{hp} = \eta_{hp} (P_{hp})$$

$$= \eta_{hp} (\eta_{ts} P_{wt})$$

where, ‘ηhp’ is the overall efficiency of the hydraulic pump ‘*P*hp ’ is the density of water in kg/m3 (1000 kg/m3); ‘g’ is the acceleration due to gravity in m/s2 (9.81 m/s2) and ‘hp’ is the average HP water head in m. The average flow rate of the water sucked from the water source ‘Qhp’ in m/s which hp Q is equal to the water discharge rate into the UR, is expressed as:

$$Q_{hp} = \frac{\eta_{hp}(\eta_{ts} P_{wt})}{\rho_w g H_{av}}$$

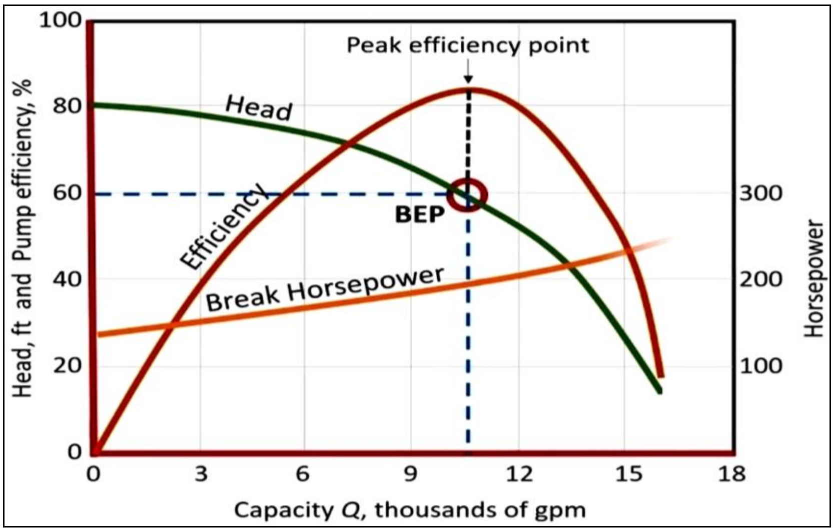

Fig 3: Diagram of hydraulic pump working parameter.

Hydraulic turbine-generator

The electric power output of the pico-hydro turbine-generator set is given by:

$$P_o = \eta_{ht} \eta_{eg} \rho_w g H Q_{ht}$$

where, ‘ηht’ is the efficiency of PHT; ‘ηeg’ is the efficiency of the electric generator and ‘Qht’ is the water flow rate of PHT. If the overall efficiency of the PHT and the ht Q electric generator is ‘ηht’, then

$$\eta_{tg} = \eta_{ht} \eta_{eg}$$

$$P_o = \eta_{tg} \rho_w g H Q_{ht}$$

And output power is given byAssuming the resistive load, the output voltage ‘Vo’ can be expressed as:

$V_o = f\ (P_o R_L)$

Where, ‘R_L’ is the load resistance.

Water head

In any time period of one-hour interval, the water head ‘H’ at ‘T’ seconds after the starting of the interval having initial head at start of the interval can be expressed in H as:

$$H = H_{in} + (Q_{hp} - Q_{ht})\frac{T}{A_{UR}}$$

Where, ‘Aur’ is the area of the upper reservoir in m2 and ‘Qhp’ is the pump discharge rate UR A hp Q at the average wind speed in that period of one hour. In order to assure reliability of continuous operation of the system, the water head should always remain within the desired limit of PHT. Therefore, the UR must be allowed to be filled completely with water before the starting of the PHT. As the power generation starts, the water level depends upon the average input and output flows of the UR. Therefore, the water level in the UR and hence the water head would remain constant, if

Qhp=Qht

The HP discharge ‘Qhp’ depends upon the wind velocity. Therefore, if Qhp< Qht, the water level in the UR starts to come down and when the whole water is exhausted, the power generation is stopped and output power is zero. On the other hand, if Qhp>Qht, the water starts to be accumulated in the UR and when the UR fills completely with water, the water starts to flow back into the water source through the overflow pipe.

Internal height of upper reservoir
In the proposed wind-PHES system, the maximum variation in water head Hvar(max) is expressed as:

$$H_{var(max)} = H_{max} - H_{min}$$

where, ‘Hmax ' is the maximum value of the PHT head and is equal to the head available due to the difference in the height of the upper level of UR from the PHT blades ‘Hmin ' is the minimum value of the PHT head and is equal to the head available due to min H the difference in the height of the lower level of the UR from the PHT blades.

Hand calculation

1. **Wind turbine**

Let,

Wind velocity, U= 8m/s

Length of blade, R= 70m

Air density, P_0= 1.23 kg/m^3

N=22.5

a) **Turbine output power,**

$P= \frac{1}{2}\pi r^2 PU^3$= 3.1416×70^2×0.5×1.23×8^3

=4847212.339 =4.85MW

b) **Output Torque,**

$P=\tau\tilde{\omega}$ $[\tilde{\omega}== \frac{22.5x2\pi}{60}=2.35]$

$\tau= \frac{22.5x2\pi4847212.339}{2.35}$=2062656.3Nm

c) [Let assume the turbine’s estimated production in 6MW]

$C_p=\frac{Pout}{Pin}=\frac{6000KW}{4850KW}$ =1.25

d) **The shaft power**

P_{wt}= 0.5$C_p P_a \pi R^2$

=0.5×1.25×3.1416×1.23×70^2×8^3

=6.2MW [Can produce the estimated power]

2. **Pump**

Let’s assume,

η_{hp}=60%=0.6

water density P_w= 100kg/m^3

g=9.82m/s^2

H_{av}=57m

η_{ts}=1

R_L=0.0025(Stand-alone generator)

Water discharge rate

$Q_{hp}=\frac{\eta hp(\eta tsxPwt)}{PwgHav}=\frac{0.6x1x6.05M}{1000x9.81x57}$

=6.49m^3/s

3. **Hydro-turbine generator**

Power output, $P_0 = \eta_{tg} P_w gHQ_{ht}$

=1×1000×9.81×57×6.49= 3.62MW

Then output voltage $V_0=\sqrt{Po}$RL

= $\sqrt{32.62MWx0.0025}$

=300.83V

4. **Water Head**

H=Hin +(Qhp-Qht) $\frac{T}{Aur}$ =57m

$H_{var(max)}=H_{max}-H_{min}$ = 57m-15m

=42m

Fig 4

Discussion

In the period when there is no wind or its speed is less than the cut-in or more than the cut-out speed of the wind turbine, the wind turbine stops and hence the HP remains inoperative and no water flows into the reservoir. During this period, the PHT operates till the water in the UR gets exhausted, but, if the wind retains its velocity in operating range of WT before the water is exhausted, then the PHT remains in continuous operation. Therefore, it is very essential to study the wind pattern of the area of previous years very carefully for determining the length of maximum durations in which the wind velocity remained continuously in the inoperative range of the WT used. The average of these maximum durations may be chosen as the inoperative period of the WT. In order to maintain the persistent and reliable operation of the system for rated power generation even when the wind speed is not in the operating range of the WT, the important aspect is to design the inside volume of the UR more than the volume needed to store the water sufficient to operate the PHT for the inoperative period as determined above. Thus, a properly designed inside volume of UR can easily maintain the continuity in power generation. Here the pump operation depends upon the wind speed and that of PHT on the water head available. The operation of the model, which is quite simple, begins when the UR is completely filled with water. The changes in the water head due to variable wind may not be more than the internal height of the UR. It reads the system data, gets the input power from the wind and generates the signals to operate the WT, HP and control the water head to operate the PHT and generator.

Water source

An appropriate open section in the ocean is considered as lower reservoir, for which a particular section is selected after studying its depth and the seasonal variations in its water level (WL). The seasonal variation in WL will affect the water depth and hence the HP head. Consequently, the HP discharge rate and the filling rate of the UR may be changed. However, if the proper HP selection is done after taking due care of the change in HP head because of WL variation, the change in HP discharge and so in UR filling rate will be negligible. But, the PHT head and so the power generated and the system performance will not be affected by the WL variation. Even then, for reliable and smooth HP operation, the selected area should have minimum WL variation. Therefore, the WL depth should match the requirement of the HP head for the desired PHES installation all the time in all the seasons.

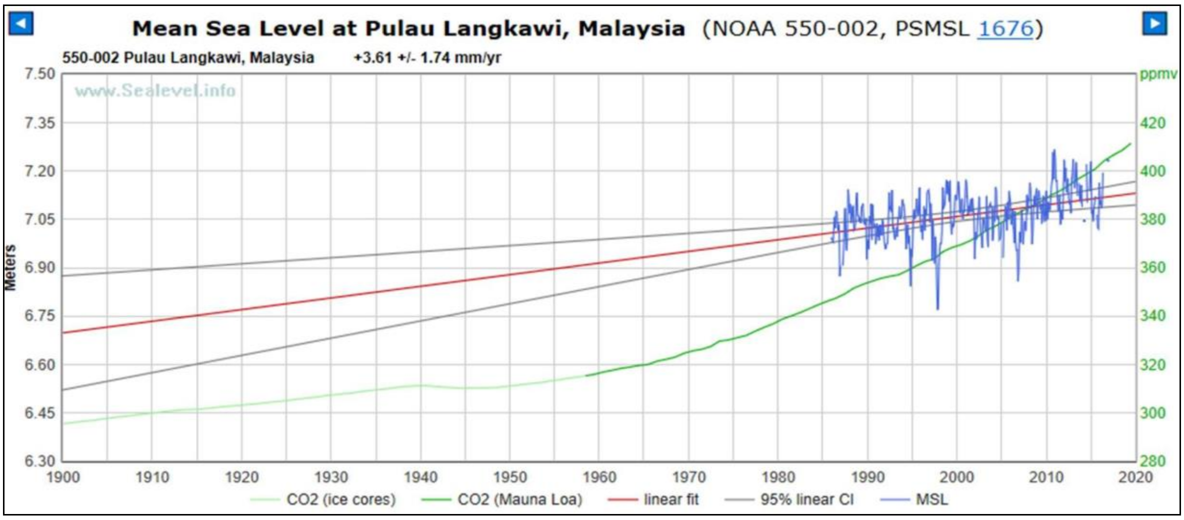

Fig 5: History of mean sea level in Pulau Langkawi (Sunarya, Ibrahim, Apribowo, Pramono, & Sulistyo, 2020).

Hydro turbine and generator

In the proposed PHES system the water head is either low or medium. For such low and medium head applications the single-jet Turgo turbine is a nice option. Some commercially available single-jet Turgo turbines and Pico-hydro generators with their technical characteristics are shown in Table 1 and Table 2 respectively, from which the suitable Turgo turbine generator can be opted according to the power requirement.

Table 1: Hydro turbine generator model data.

Model	Rated Head, M	Rated Flow Litre/s	Output, W	Pipe diameter, mm
XJ14-0.2DCT4-Z	10-14	3-4	200	50
XJ14-0.3DCT4-Z	12-14	3-5	300	50
XJ18-0.5DCT4-Z	12-18	5-7	500	50-75
XJ18-0.75DCT4-Z	14-18	5-8	750	75
XJ22-1.1DCT4-Z	16-22	8-10	1100	100

Table 2: Hydro turbine model specifications.

Model	SF 0.3-4	SF 0.5-4	SF 0.75-4
Rated head, m	12-14	12-18	14-18
Rated flow, 1/s	3-5	5-7	5-8
Output power, W	300	500	750
Output voltage, V	230	230	230
Phase	Single	Single	Single
Frequency, Hz	50	50	50
Efficiency	70	70	70
Turbine runner	Turgo	Turgo	Turgo
Rotary Speed, rpm	1500	1500	1500

Hydraulic pump

Once the value of the water head and flow rate of the hydraulic turbine are known from its specifications, then the rated HP discharge can be chosen as the average of the PHT discharge and the HP head is taken more than the average of PHT head, but not less than the distance between the WL of the water source and the UR. The variation in HP head due to seasonal variations in WL depth should also be taken into consideration in HP selection for reliable and smooth operation. Using these parameters, the pump power can be computed from. In this paper, the simulation is carried out using a centrifugal pump, but this pump can only be utilized if it is compatible with WT output power, for which, the speed range of satisfactory operation of HP should match with the cut-out and cut-in speed of the WT. Another important point for satisfactory pump operation as well as for stable operation of the system is that its frequent starts-stops limit should be reasonably more than the expected frequent cut-in and cut-out of the WT determined on the basis of expected wind pattern. In case, if the average wind speed is low and the fluctuations are high, the use of reciprocating pump may be a better option for low power generation.

Wind turbine

The WT should have adequate ability to extract power from the available wind for meeting the HP power requirement satisfactorily. Therefore, in order to have minimum rotor radius, its power coefficient should be higher as far as possible. For example, in the design problem of this paper, at Cp = 0.35, the rotor radius computed, is 3.5 m for the given wind pattern. On the other hand, if the WT selected has Cp = 0.5, then, the radius would be 2.9 m for the same wind pattern. In the same way, at Cp = 0.5, the WT rotor radius would be 1.7 m and 0.98 m for the wind speeds of 7 m/s and 10 m/s respectively. Therefore, once the pump power is known, the WT shaft power can be computed from (2). Then, after knowing the WT power coefficient, its rotor radius can be found from (1) at the average wind velocity of the place of installation.

Power balance

In order to maintain the power balance, the active power generation must be equal to the load demand at all the time, but the load may not be constant at all the time. Therefore, for maintaining the load balance, the dummy load is quite effective for the proposed system.

A simple, easy and without any controlling complexity, a dummy load scheme suitable for the system is described here. In the scheme one resistive dummy load is connected separately with each and every actual load by a single-pole double through (SPDT). The power rating of the dummy load is equal to the corresponding load. When the actual load is required to be switched- off, the power is disconnected from the actual load and is connected to the dummy load with the help of SPDT switch. The vice-versa operation can also be performed by the SPDT switch. Hence the generator experiences the constant load. Consequently, the generation remain continuous at constant voltage and frequency.

Similarly, the proposed system is evaluated when there is no wind or the wind speed is too low to rotate the hydraulic pump. Therefore, the wind speed can be assumed zero and consequently the WT and the HP powers are equal to zero. Hence the pump discharge is also zero and no water is added into the UR, but the water flow rate from the UR remains same and continuous due to the remaining water which maintains the continuous operation of the PHT to generate power at constant voltage till water exists. If the UR is completely filled with water, the proposed system can operate up to 3 hours 43 minutes without wind. In the same figure the time of system operation at other speeds is also shown.

It is quite certain that the wind speed will not remain same for the entire time periods. If the wind speed increases, the HP will discharge more water to the UR, which will enhance the operating time of the system accordingly and if the water discharge of the pump becomes more than the turbine discharge, the water again starts to be accumulated in the reservoir. On the other hand, if the water discharge of HP is lesser than that of PHT due to decrease in wind speed, the water stored in the UR begins to reduce. But, the UR volume is designed according to wind pattern so the water stored in the UR is quite enough and will not exhaust before the wind regains higher speed due to which, water accumulation is again started and the proposed wind-PHES system will generate power continuously at constant voltage.

Conclusion

The proposed system in the study is suitable for rural electrification in isolated and remote locations. The innovative features of the designed system, maintains a continuity of power generation at constant voltage irrespective of changes in wind power due to variations in its speed. The water stored in the upper reservoir is able to maintain the continuity of power generation operation to generate power even when there is no wind or its speed is too slow to run the turbine generator. The proposed system is different from all other existing system in such a way that, in this system, both the water storage in upper reservoir through the wind power and the power generation through the hydro power can take place simultaneously and continuously. Moreover, the proposed system utilizes locally available renewable energy sources to facilitate the rural and remote areas with continuous, reliable and quality power.

Similarly, the proposed system can be evaluated when there is no wind or the wind speed is too low to rotate the hydraulic pump. Therefore, the wind speed can be assumed zero consequently, the wind turbine and the hydraulic pump powers are equal to zero. It is quite certain that the wind speed will not remain same for the entire time periods, if the wind speed increases, the hydraulic pump will discharge more water to the upper reservoir, which will enhance the operating time of the system accordingly.

In this study the fundamental variable values are estimated to calculate the output power generation for the proposed designed. For the wind turbine, the wind velocity is assumed to be 8m/s, length of each blade is considered 70m, where by air density is 1.23 kg/m^3 and power coefficient is 1.62.

The turbine out power is evaluated 4.85MW and the output torque is 2062656.3 Nm. The shaft power is calculated 6.05MW and the power transmission is generated 4.06MW. For the pump section water discharge rate of 6.49m^3/s, power output of 3.62901 MW and output voltage of around 300V is estimated, the output voltage is calculated with a value resistance load of 0.025ohm for standard generator. For the water head calculation maximum height of 57m and minimum 15m is estimated.

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