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Feasibility Study of Seawater Pumped Hydro Energy Storage Plant for Sri Lanka

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Abstract: Methods of peak shaving are required for the countries where the daily load curve is dominated by the domestic loads. Using energy storage devices is often the solution for levelling the daily load curve. Pumped Hydro Energy Storage Plants are widely used in most of the countries for the peak leveling purposes. This study proposes to construct a seawater pump hydro energy storage plant for the Sri Lankan power system. The study identifies Trincomalee as the one of suitable locations for the Seawater Pumped Hydro Energy Storage Plant. The data of the Sri Lankan Survey Department and Google Earth data of the locations have been used for the collection of details of the location. The volume of the upper reservoir was calculated within the study and found to be 868,750 m^3. Detailed calculations were carried out to determine the net head for both generating and pumping modes and presented. The results of the calculations show that the suitable time duration of the plant in generation mode is 3.5 hours and the operation of the plant in pumping mode is 5.64 hours. This research study concludes that it is feasible to construct a 49 MW Seawater Pumped Hydro Energy Storage plant in Trincomalee.

Keywords: Daily load curve, Flow rate, Generating mode, Net head, Peak shaving, Pumping mode

1. Introduction

Sri Lanka's energy landscape is currently facing challenges due to increase in energy demand, especially in domestic sector, with the population growth and increase of electrical appliances for people's day to day activities. At present, the country's energy mix relies heavily on fossil fuels, with hydro energy making a significant contribution [1]. In the meantime, inflation and dollar deficits are hindering the import of fossil fuels for power generation, resulting in high costs. Sri Lanka has targeted to achieve 70% of its energy requirement from renewables and become carbon neutral by 2050 [2]. The country also has a target to reduce carbon emissions by 4% in 2030 [2]. To achieve the above targets more and more renewable energy-based power plants need to be integrated into the Sri Lankan power system. The focus is mainly on wind and solar energy sources. One of the major problems with both these energy sources is intermittency. In the past, hydropower plants shared the major portion of total energy generation. At present, hydropower plants share 43% of the total generation [2]. Hydropower plants are located at different locations, especially in the hill areas of the country. Their locations mainly depend on the ability to water storage in large amounts and the creation of required head. At present, most of the suitable locations in the country have been utilized for the construction of large capacity hydropower plants. Consequently, the country needs new options for electricity generation to meet the growing demand using renewable energy sources.

The daily load curve of the Sri Lankan power system experiences two distinct peaks: morning peak from 05:30 h to 07:30 h and evening peak from 18:00 h to 22:00 h. This results in a low load factor (LF). These sharp peaks increase the unit cost of energy, as meeting this peak demand, which lasts only a few hours each day, often necessitates the construction of new power plants, requiring significant capital investment. Meanwhile, the growing contribution of renewable energy sources, such as solar and wind, can lead to excess energy generation especially during the off-peak time.

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This surplus energy needs to be stored to use during peak hours through Energy Storage Devices (ESDs). At the distribution level, battery energy storage systems are becoming popular as ESDs. However, high-capacity battery systems for grid-level applications are still at the developmental stage. Traditionally, Pumped Hydro Energy Storage Plants (PHESP) have been implemented in many countries as an effective energy storage method to balance supply and demand fluctuations [3].

Inland Pumped Hydropower Storage Plants (PHSPs) consist of two reservoirs: upper reservoir and a lower reservoir. The principle of PHESPs is to pump water to the upper reservoir during off-peak hours, consuming electrical energy, and then generate electricity by releasing water back to the lower reservoir during peak-hours. This process allows PHESPs to store excess power and release it during peak demand by optimizing energy usage between off-peak and peak periods [4]. PHESPs require specific locations since they need two reservoirs. In Sri Lanka, several hydropower plants have been constructed with reservoirs along the Mahaweli River. The reservoirs of these plants are arranged in cascade and serve two main purposes: providing water for irrigation and generating electricity. However, as Hewavisenthi (1992) noted, converting these plants to PHESPs is highly challenging due to the complexities of water management [5]. The investment cost for PHESPs is substantial, as they require the construction of two reservoirs and installing pumps to facilitate water movement to the upper reservoir. Studies by Wickramarathna (2015) and Dilrukshi et al. (2018), also explore the feasibility of PHESPs, highlighting the growing need for grid-scale energy storage solutions, especially with the increased integration of renewable energy sources [6].

The requirement for two reservoirs can be avoided if one of them is naturally available. As a solution, the sea serves as the lower reservoir, while high land or mountainous areas near the coastline are used to construct the upper reservoir. Such pumped hydro energy storage facilities are referred to as Seawater Pumped Hydro Energy Storage Plants (SPHESPs). The world's first SPHESP, having a capacity of 30 MW, is currently operational in Japan [8,9]. Additionally, several other countries, including Korea, Denmark, and Estonia, are planning to construct SPHESPs. A notable project, with a 300 MW solar-plus-SPHESP facility, is being executed in Chile [10]. This current study includes location identification, plant capacity determination, and an energy cost assessment.

As an island in the Indian Ocean, Sri Lanka is surrounded by the sea, making it a possible candidate for SPHESP. Therefore, the objective of this study is to carry out a feasibility study of establishing a SPHESP in the country. One of the most challenging tasks in establishing a SPHESP is the identification of a suitable location. Hydropower plants require land that can provide sufficient head and is also appropriate for reservoir construction. Such land must be situated away from residential areas. Additionally, preventing corrosion due to seawater poses another significant challenge. Most of the plant's equipment will be exposed to seawater, necessitating the use of special materials and technologies to minimize equipment deterioration from corrosion. The high cost of such specialized equipment can significantly impact the unit cost of energy generated from SPHESPs.

One of the major advantages of SPHESPs is the elimination of the need for a lower reservoir, as seawater is available year around. This significantly reduces the overall cost of the plant. Density of the seawater is slightly greater than that of fresh water. This can have some positive effect on the efficiency and capacity of the plant. The increased energy density may also contribute to lower maintenance and operating costs. Therefore, SPHESP presents a more efficient and cost-effective alternative to traditional pumped storage hydropower. Waxing and waning of the moon cause the high and low tides in the sea. This can cause different head heights at different time periods and a more detailed study is necessary to assess the level of this effect. Furthermore, climate dynamics significantly affect hydropower operations, with global warming influencing water cycles and output variability [11]. Typically, pumped storage systems exhibit a global efficiency ranging from 75% to 80% [12]. SPHESPs can be designed with various configurations, and a popular and cost-effective option is the binary set, which consists of a reversible Francis pump/turbine paired with a single synchronous motor/generator. Both the turbine and generator must be engineered to withstand the corrosive effects of seawater. The rotor windings of the generator receive DC excitation current through slip rings, while the stator windings connect to three-phase AC at grid frequency.

2. Location Identification

Hydropower plants are located in areas where sufficient head is available. Additionally, there should be a suitable land area for the construction of a reservoir. The reservoirs can be either natural or artificial. In the case of SPHESP, meeting both the above requirements (sufficient head and suitable land area for reservoir) is challenging. This is because highlands or mountains in proximity to the sea are not commonly available in most of the coastal areas in the country. In addition, there should be sufficient land area at the top of such highlands for the upper reservoir which is used to store the sufficient amount of seawater. In addition, grid access availability, proximity to the load centres also is considered in identifying a suitable location for any PHES plants.

To identify a suitable location, contour maps available in the Sri Lanka Survey Department, Google Earth maps, Topographic Maps and other technologies [13] were used. After going through these maps, a location in Trincomalee has been identified as one of the suitable locations for the proposed SPHESP. As per the topography, the location is situated in a mountainous area, which is relatively rare among lands close to the sea. This location is shown in Figure 1. In Figure 1, the area shown in red colour is at the altitude of 85-90 m. This area is proposed for the upper reservoir. The coordinate of this location is 8.54675^{0} N and 81.242719^{0} E. These coordinates point to Sri Lanka near the northeastern cost in Trincomalee district. This location is close to the Sri Lanka Navy Museum, Elephant Point Beach, Coral Cove Beach, and the area around Chapel Beach. This site meets many of the requirements needed for constructing SPHESP. The location is in proximity to the coast and at a suitable elevation.

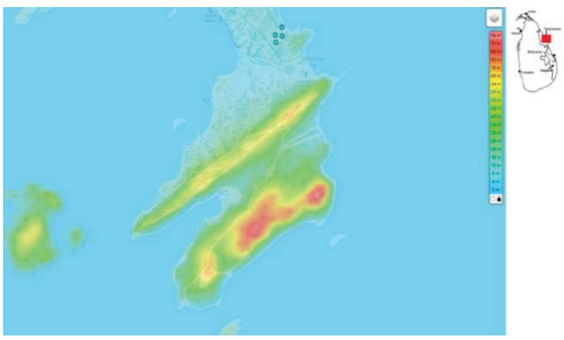

Figure 1 - Location for the proposed SPHESP (https://en-in.topographic-map.com/map-14j3q/Sri-Lanka.)

Figure 2 illustrates the contour map of the location and the site location with the proposed area for the upper reservoir (marked in red colour). The elevation of the upper reservoir is about 93 m above sea level. Unlike other highland regions near the sea such as Galle, Kalutara, Negombo, and Jaffna, which are expanded upon urban developments or flat lands or even deal with a lack of suitable heights, the location in Trincomalee provides the required height differential which makes energy storage effective.

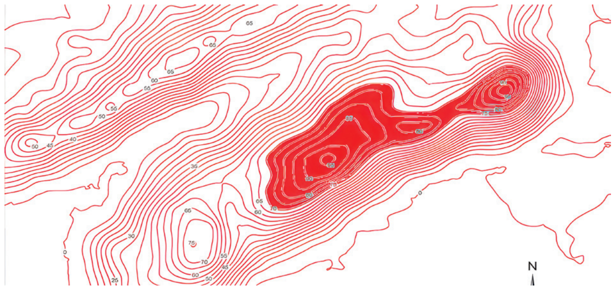

Figure 2 - Contour map of the site location for the proposed SPHESP

Figure 3 shows the bird's-eye view of the proposed upper reservoir area. The location for the upper reservoir extends from the summit of the high mountain down the slope.

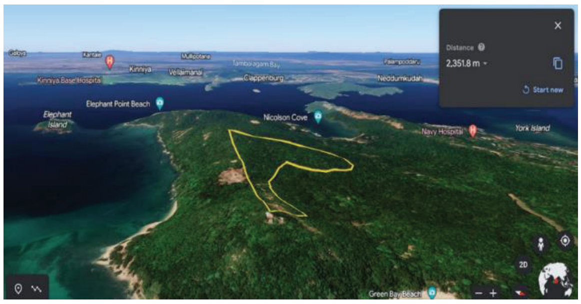

Figure 3 - Bird's-eye view of the proposed upper reservoir location in Trincomalee (https://earth.google.com)

3. Upper Reservoir and Dam

The upper reservoir is designed with the consideration of the highland's topography. Based on the landscape at the summit of the mountain, it is proposed to construct a dam with the configuration shown in Figure 4. Since the surface on the mountain is not a flat land it is proposed to construct a pond which will have a different height from the ground level. For example, the dam on the right side is built along the contour line of 70 m and the maximum water level is expected to reach 90 m.

The upper reservoir has an upper limit 93 m with dam-wall and lower limit of 70 m. On the seashore side (left side) the height of the dam is only 3 m, and it has an abrupt slope. On the landward side (right side) it reaches a height of 23 m, and the slop gradually decreases. The lowest water level in upper reservoir should be at the contour line of 71.5 m for the prevention of air into the pipe.

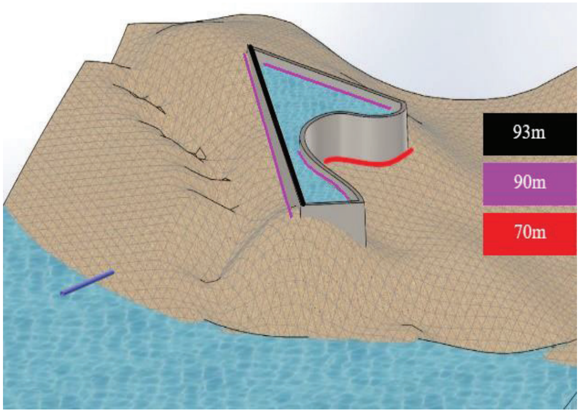

Figure 4 - Configuration of the proposed dam for the Upper Reservoir

3.1 Tunnel, tailrace and penstock

Figure 5 illustrates the schematic arrangement of the upper reservoir, penstock, valve house, powerhouse, and lower reservoir (sea).

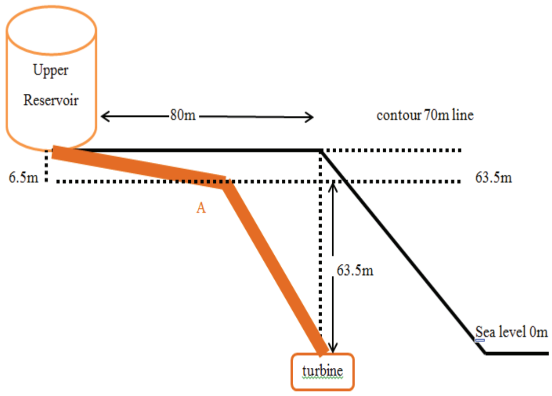

Figure 5 - length of penstock and head of the plant

In preliminary studies, the length-to-height (LH) ratio (where L represents the waterway length from the intake structure to the tailrace and H represents the head available for electricity generation) is used to assess the initial viability of a pumped storage plant. In this specific location, the bottom of the upper reservoir terminates at the 70 m contour line. The distance from the intake screen to the top of the mountain, where the slope begins, is 80 m. To achieve maximum velocity of the seawater while it flows through the penstock from the valve house (A) to the turbine, it is most efficient to maintain a 45^0 angle with the horizontal. Considering the diameter of the penstock and assuming a minimum depth of 6.5 m from the intake screen to the valve house, we calculated the lengths of the penstock segments. When the penstock makes an angle of 45^0, the horizontal distance from value house (point A) to the top of the mountain becomes 63.5 m. The length of the penstock from the valve house (A) to the turbine is 89.8 m, resulting in an L:H ratio of 1.41 (89.8:63.5). The length of the penstock from the valve house to the upper reservoir intake screen is 17.73 m, bringing the total length of the pipe to 107.53 m. Consequently, the overall L:H ratio is 1.344 (107.53:80). Sites with an L ratio of less than 10 are considered suitable for pumped hydropower storage plants; thus, the proposed site meets this requirement.

4. Power Calculation

SPHESP must deliver its stored energy during the peak load time. Since the peak load continues for several hours a day, seven options for the plant's generator mode were considered: 5 h, 4 h, 3.5 h, 3 h, 2.5 h, 2 h, and 1 h. Out of these options, the best option for the generating mode SPHSP must be selected.
The possible power (P (kW)) of the hydropower plant is calculated using equation (1) [14,15].

$$P = \rho \times g \times h \times Q \times \eta \qquad \dots (1)$$

where:

ρ-desity of water (kgm^{-3})
g- acceleration due to gravity (m^2s^{-1})
h- head (m)
Q- rate of discharge (flow rate) (m^3s^{-1})
η-efficiency of the turbine and generator

Power, P (kW), mainly depends on the possible gross head between upper and lower reservoirs that is limited by the topography of the area considered.

4.1 Volume of the upper reservoir

In the proposed upper reservoir, the height of the dam gradually changes while moving across the contour lines. Therefore, the volume of the upper reservoir (Vu) is calculated using the Prismodial rule as given in equation (2) [15].

$$Vu = D/3 \left[(A1+A5) +4(A2+A4) +2(A3)\right] \qquad \dots (2)$$

where:
A1, A2, A3, A4, A5 – areas between 70-75, 75-80, 80-85, 85-90 m and 90-95m contour lines, respectively,
D - height of adjacent contour lines (5 m).

As per the equation, the volume of the upper reservoir (Vu) becomes equal to 868,750 m^3.

4.2 Penstock

Function of the penstock is to release seawater from the upper reservoir to the sea and pump the seawater back to the upper reservoir. Considering high pressures, penstocks made of steel are used in hydroelectric projects. But, in the case of SPHESP, such penstocks are used since they are prone to corrosion due the seawater. Therefore, the penstocks made of Fibre Reinforced Plastic (FRP) are used in SPHESP. These FRP penstocks are non-degradable in seawater.
There should be at least 1.5 m of water level from the bottom of the reservoir to prevent air from entering the pipe. Hence the lowest water level of the upper reservoir should be maintained at the 71.5 m contour line. As per equation (2), the corresponding volume of the water of this height is 7500 m^3. Then, the volume of water available for electricity generation becomes 861,250 m^3. The use of large-diameter penstock is impractical for this plant. Considering penstock diameters used in most of the hydropower plants in Sri Lanka [16] the penstock diameter is selected as 3.2 m. It must be noted that in more precise calculations, the penstock diameter must be selected to keep the head loss less than 5%.

4.3 Operation of SPHESP in the generation mode

The available gross head at a hydro power plant is the difference between the water level in the reservoir and behind the dam and water level in the sea where the tailrace is located. Therefore, the gross head can be taken as 90 m, and the upper reservoir volume remains fixed at 861,250 m^3. SPHESP generates electricity during peak time by releasing the water from the upper reservoir to the sea.

4.4 Flowrate calculation

Flowrate is calculated considering the time during which the plant is expected to generate electrical power by releasing the water from the upper reservoir to the lower reservoir (sea) for the seven options of peak time. Flow rate (Q m^3/s) calculation was done using the equation (3).

$$Q = Ve / tpeak \times 3600 \qquad \dots (3)$$

where:
Ve - usable volume of the upper reservoir (861,250 m^3)
tpeak - peak time (h) during which seawater discharges from upper reservoir to the lower reservoir

5. Net Head Calculation

Net power generated by the plant can be determined using the net head of the plant. The net head differs from the gross head due to various losses and inefficiencies that occur in the hydro system. These losses include friction losses in pipes, losses due to bends and fittings, losses at the entrance and exit of the pipes, and turbines.
Equations (4) and (5) give net head for pumping (Hp net) and generating (Hg net) modes.

$$\text{Hp net} = \text{Gross Head} + \text{Head Loss (Hd)} \qquad \dots (4)$$

$$\text{Hg net} = \text{Gross Head} - \text{Head Loss (Hd)} \qquad \dots (5)$$

5.1 Head loss calculation

Head loss (Hd) is calculated using equation (6).

$$Hd = (KV^2)/2g \qquad \dots (6)$$

where:
V- Water velocity in the penstock (ms^{-1})
K- Loss coefficient

Loss coefficient K is the sum of two coefficients: Kpipe and Kfitting as given in equation (7)

$$K = Kpipe + Kfitting(elbow) \qquad \dots (7)$$

where:
Kfitting(elbow) - 0.2 for 45° elbow [17,18]
Kpipe is determined using equation (8)

$$Kpipe = fL/D \qquad \dots (8)$$

where:
D- pipe diameter
L- length of the pipe which is sum of tunnel length (Lt) and penstock length (Lp) (L = Lt + Lp)
f- friction coefficient

The friction coefficient (f) [19] is determined using the formula given in equation (9).

$$f = \frac{0.25}{\log\left\{\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right\}^2} \qquad (9)$$

where:

$\mathcal{E}$ - roughness factor (1.5 x 10^{-6}m)

Re -Reynolds number

Reynolds number (Re) is calculated using equation (10) [20].

$$Re = \rho VD/\mu \quad \ldots (10)$$

where:

μ kinematic viscosity

ρ - Sea water density 1026 kg/m³)

V- seawater velocity in the penstock

The kinematic viscosity of the seawater mainly depends on the temperature. Since the annual average temperature of the seawater in Trincomalee is 29^0 C (32, μ is taken as 8.6014 x 10-7 m²/s.) (Figure 6) [21].

Seawater velocity (V) in the penstock is determined using equation (11)

$$V = Q / A \quad \ldots (11)$$

where:

A- Cross sectional area of the penstock (A=πD2/4)

The flowrate (Q) depends on the duration of the time during which the seawater is released through the penstock (equation 3). Accordingly, seawater velocity (equation 12) also changes. This has an impact on loss coefficient and therefore the head loss. The results of the calculations (equations 6 -11) for different peak time options are given in Table 1.

6. Pumping Mode of Operation

It is proposed to use reversible Fracis turbine for both generating and pumping mode.

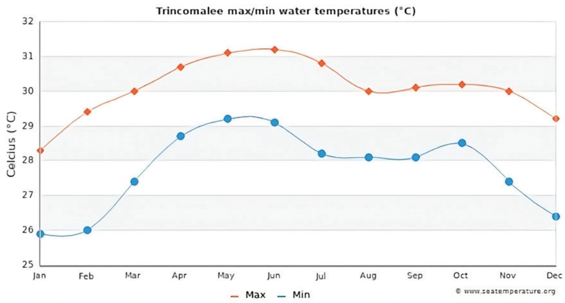

Figure 6 - Trincomalee water temperature chart (https://www.seatemperature.org/asia/sri-lanka,)

Therefore, the power generated during the generation is equal to the power consumed by the plant during the pumping mode (Pg=Pp). This enables to determine flowrate using equation (1) for the pumping mode. This is given in equation (12).

$$Qp = Pp / (\rho \times g \times Hp\ net) \quad \ldots (12)$$

Pumping time is determined using equation (3) for the pumping mode. Then, the time for pumping the seawater back to the upper reservoir is expressed as given in equation (13).

$$tp = Ve / (Qp \times 3600) \quad \ldots (13)$$

Annual generation of electrical energy (Eg) by the plant and energy consumption during the off-peak hours (Ep) are given in equations (14) and (15),

Eg = Pg × hours of generation per day × number of working days … (14)

Ep = Pp × hours of pumping per day × number of working days … (15)

Table 1 - Results of the net head calculation for different time peak time (penstock diameter 3.2m)

$t_{peak\ (h)}$	5	4	3.5	3	2.5	2	1
Q(m³/s)	47.84	59.8	68.35	79.75	95.69	119.62	239.24
V(m/s)	5.94	7.34	8.5	9.91	11.89	14.87	29.73
Re	2.27×10^{10}	2.84×10^{10}	3.241×10^{10}	3.78×10^{10}	4.54×10^{10}	5.67×10^{10}	1.13×10^{10}
f	0.0052	0.00527	0.00523	0.00526	0.0052	0.00523	0.00256
K_{pipe}	0.37	0.377	0.3769	0.03769	0.377	0.379	0.3769
K	0.17	0.177	0.1769	0.1769	0.177	0.1768	0.1769
Hp net(m)	90.51	91.0618	91.386	91.8871	92.7171	94.2449	106.676
Hg net(m)	89.48	88.9382	88.6134	88.1129	87.2829	85.755	73.0249

6.1 Determination of the best option for generation and pumping modes and the plant capacity

As discussed above, seven possible options of the peak time duration (tpeak) which the plant can operate in generating mode were calculated and the results are given in Table 2. The objective of this calculation is to determine the best time duration for the operation of the plant. The table also provides annual energy generated and consumed by the plant for the considered peak time durations. It also gives pumping time for the respective peak time. The efficiency given in the table indicates the amount of energy generated from the energy consumed for pumping.

SPHESP experiences increase of head losses and reduced efficiency as flow rates rise. At the same time, the gross head remains constant at 90 m; higher discharges as in Option 7 result in significant head and energy losses due to friction and turbulence. The efficiency declines from 63% (Option 1) to 43.69% (Option 7), reflecting higher mechanical and hydraulic losses. Optimizing flow rates and operational parameters is essential to minimize losses and improve system efficiency.

The most suitable option among the options is selected based on the pumping time and the sea water velocity in the penstock. Pumping seawater back to the upper reservoir should be carried out only during off-peak hours. As per the daily load curve shown in Figure 7, off-peak time is between 11:00 h to 05:45 h which means the pumping time should be less than 6 hours. On the other hand, the velocity of the seawater in the penstock should be less than 10 ms^{-1}. This is because the penstock used in SPHESP is made of fibre reinforce plastics that cannot withstand higher velocities [18]. Considering both these factors, option 3 has been identified as the best option for SPHESP operation. The plant capacity reference to the option 3 is 49 MW. Therefore, the suitable capacity of this plant is 49 MW.

Proposed time duration of the plant in generating and pumping modes are indicated in Figure 7.

7. Economic Feasibility

This study does not include a detailed economic analysis. However, based on the existing cost of energy in Sri Lanka, integrating a SPHESP can be financially viable. Peak load energy demand is typically covered by plants with short start-up times; apart from hydropower, diesel and gas turbine plants are often used to meet peak loads. According to the data of the Public utilities Commission of Sri Lanka, unit generation cost for diesel power plants at present is approximately Rs. 64.71 per kWh, while gas turbine plants cost around Rs. 18.00 per kWh. These costs fluctuate with fuel prices on a monthly or yearly basis. In comparison, the unit cost for hydroelectric generation is Rs. 4.81 per kWh. Although the unit cost for SPHESP is higher due to the specialized materials required for the water conduit systems, electrical equipment, generators, motors, and turbines, it could be lower than conventional PHESP, since it operates with a single reservoir. In India, the cost of SPHESP is around Rs. 19 per kWh.

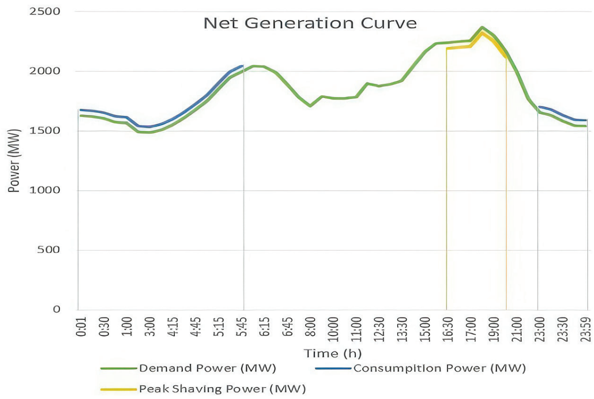

Figure 7 - System daily load curve with possible peak power reduction due to operation of SPHESP

Table 2 - Power generated by the plant for possible peak time durations

Option	$t_{peak(h)}$	Qp(m3/s)	$t_{off\text{-}peak(h)}$	Eg(Gwh)	Ep(Gwh)	Efficiency(%)	Pg=Pp(MW)
Option 1	5	30.16	7.9	62.8	99.6	63	34.4
Option 2	4	37.39	6.4	62.53	100.04	62.51	42.83
Option 3	3.5	42.42	5.64	62.31	100.4	62.06	48.78
Option 4	3	48.94	4.89	61.95	100.95	61.37	56.58
Option 5	2.5	57.65	4.15	61.37	101.86	60.25	67.25
Option 6	2	88.56	3.43	60.3	103.54	58.23	82.6
Option 7	1	104.52	2.29	51.35	117.53	43.69	140.7

Based on these estimates, the unit generation cost for the proposed SPHESP is expected to be between Rs. 10 and 15 per kWh [22]. Considering the volatility of oil and gas prices in the global market, SPHESP is likely to remain economically feasible. Additionally, unlike conventional Pumped Hydropower Storage Plants (PHSP), SPHESP can operate continuously without interruptions due to water shortages during dry seasons.

8. Environment Impact

The project site is in a bio-valuable forest area within the Trincomalee district, which is home to diverse wildlife and ecologically significant plant species. It is crucial to prioritize the protection of this habitat while implementing the project. To achieve this, a portion of the animal's habitat should be allocated within the project area, ensuring their continued presence, while the remaining part will be carefully designed to provide a suitable environment for their survival.

However, it is important to address potential environmental concerns associated with sea breeze and seawater vapour. Research reports on the SPHESP have proposed various measures to mitigate these conditions [23]. One such suggestion includes planting vegetation that can absorb seawater vapour around the upper reservoir, effectively reducing the potential damage caused by the mixture of sea breeze and seawater.

By implementing these measures and considering the unique ecological characteristics of the project site, it is possible to strike a balance between harnessing the benefits of the project and preserving the valuable biodiversity of the area.

9. Conclusions

Energy storage methods are important for both leveling of load curve and effective integration of renewable energy source into the grid. The results and analysis of the SPHESP in proposed location have shown that such plant is very appropriate in Trincomalee. Operation of the plant at the rated capacity of 49 MW during peak hours can cover the part of the peak demand. It also enables to reduce the stress to the power system during the peak hours and positively affect the unit cost of generation. The evaporation of seawater from the upper reservoir can be identified as one of the constrains in this type of the plant. It can be proposed to install floating solar panels on the reservoir to minimize the evaporation. The location selection has been carried out without considering the soil testing of the location and the geological expert opinion on the section. These details need to be looked after at the next step of this study. Since in the study cost benefit analysis has not been discussed in detail such analysis needs to be carried out in the future work.

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