Economic Evaluation of Pumped Storage Power Plant Complexes and Comparison with other Candidate Pumped Storage Power Plants Proposed for Sri Lanka

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Abstract

The daily electricity demand in Sri Lanka varies significantly with the time. The maximum demand occurs between 0630pm to 0930pm and the lowest demand occurs between 0030am to 0430am. The maximum demand is more than twice the lowest demand. According to the Ceylon Electricity Board (CEB) Long Term Generation Plan 2013~2032, sixteen coal power plants amounting to 4,700MW capacity will be added to the Sri Lanka power system in future. For economic operation of coal power plants in a power system which has significantly varying load throughout the day, energy storage mechanisms such as Pumped Storage Power Plant (PSPP) are required.

The studies reveal that Sri Lanka has several attractive natural sites for Pumped Storage Power Plants, among them two sites can be developed as Pumped Storage Power Plant Complexes (PSPPC). This paper present the economic evaluation of possible sites and the findings shows that developing 1,000MW Maha Pumped Storage Power Plant Complex would be the most economical candidate site when considering the capacity requirement with the time.

Calculation Method

The calculations were done by the measured values based on layouts done on 1:10,000 scale topographical maps and formulae based on the quantities of existing facilities. These formulae used were developed in Japan for the purpose of the hydropower potential studies. They are prepared for each facility considering factors such as intake weir, intake, and headrace etc. The quantities of civil works are calculated for main work items such as excavation, concrete, embankment, reinforcement bars, gates, screens, and steel conduits.

Following symbols and units are used in the calculation. V_e :(Excavation volume in m^3), V_c :(Concrete volume in m^3), V_f :(Dam embankment volume for fill dam in m^3), W_r :(Weight of

reinforcement bars in ton), W_g :(Weight of gate in ton), W_p :(Weight of steel conduit in ton), W_s :(Weight of screen in ton).

Quantities of work items other than main work items are not calculated. However, their costs are calculated as "others" in a lump-sum at a certain ratio against the total cost of main work items. Quantities of works of headrace tunnels and penstock are calculated based on their inner diameters.

Conditions for Construction Cost Estimate

Construction costs calculations are described in Table 5 for Maha PSPPC. In the preparatory works, costs of access roads, camp & facilities are calculated based on quantity of civil works, and the percentage cost are calculated making reference to actual costs of similar projects. For access road as 5% for pumped storage type of the total cost of civil works is estimated. While camp & facility cost as 3% and Environment mitigation cost as 3%. The cost of civil works and hydraulic equipment are calculated by multiplying the quantity of main items of works by unit cost which is described in Table 3 and Table 4 for Maha PSPPC. The work quantity is obtained from tables, diagrams and numerical formula. In this evaluation, the main work items of structures of civil works are excavation, concrete, embankment, and reinforcement bars and those of hydraulic equipment are gate, screen, and steel pipe. The costs of rest of the items of work, other than the main items, are calculated as "Others" in a lump-sum at a certain ratio against the total cost of the main work items. Unit costs are obtained by making reference to the latest data of similar works in Sri Lanka's Upper Kotmale Hydropower Project.

The construction costs of turbines, generators, control devices and main transformers, etc. are appropriated in a lump-sum in "Electro-mechanical equipment". There is a relationship that it is almost a straight line on logarithmic paper between electro-mechanical equipment cost

according to each turbine type and $P / \sqrt{He}$ (P : maximum output in kW), He (effective head in meters), as shown in the example in Figure 1 and escalated as required.

In this paper, the construction cost of transmission lines is not considered. The following are included in the costs of "administration", "engineering service", "contingencies", which are calculated by multiplying the direct construction cost by an appropriate ratio. The administration cost includes personnel expense and expenses to maintain the construction office. The engineering service cost includes expenses related to technical services such as design work and construction supervision conducted by consultants. In this evaluation, 15% of the direct construction cost is appropriated as the cost of administration and engineering service. The contingency includes physical contingency which is the increase of quantities of work, and 10% of the direct construction cost is appropriated for the contingencies. Interest during construction is calculated based on the following conditions.

Figure 1 - Example of Electro-Mechanical Equipment Cost

Weighted average interest rate (i) is calculated taking into account the ratio of local currency and foreign currency. For example, if the local and foreign currency portions are 25% and 75% respectively the calculation is as follow.

$$i = i_1 \times 0.25 + i_2 \times 0.75 = 6.05\%$$

i_1 : Interest rate for local currency = 20 %

i_2 : Interest rate for foreign currency = 1.4 %

Interest during construction

= (cost of preparatory works + cost of

environmental mitigation + cost of civil works + cost of hydraulic equipment + cost of electro mechanical equipment + cost of administration and engineering service + contingency) $\times 0.4 \times i \times T$, where,

T : Construction period (years) = 5 years

The value of 0.4 is a cash flow coefficient which is an empirical value for existing projects.

Quantities of work for Maha Pumped Storage Power Plant Complex

Uduwella Pumped Storage Power Plant

Uduwella PSPP -Upper Dam

(1) Structural Design

Rock fill type dam is adopted because of the following reasons.

Environment friendly type to harmonize with the estate (integration with nature, gentle inclination with nature rock), Catchment area is narrow, Possible to utilize the excavated material, Difficult to transport concrete

Dam specifications are determined as below.

Crest Elevation: 719 m; Crest Length: 340 m; Dam Height (H_d): 32 m

Data such as Creager's curve should be used to calculate the design flood discharge if available. In case such data are not available, it is estimated by using annual rainfall, and the following simplified formula should be used as reference.

$$Q_f = q \times A$$

$$q = a \times A^{(A^{-0.05} - 1)}$$

Q_f : Design flood discharge (m^3/s); q : Specific discharge ($m^3/s/km^2$); a : Region coefficient = 100; A : Catchment area (km^2) : 4.8754 km^2

$$Q_f = 432 m^3/s$$

(2) Quantity of work

i) Rock fill dam

Excavation and filling volume of dam are obtained by the following equations.

$$V_e = 10.0 \times H_d \times L$$

$$V_c = \frac{1}{6} \times (m + n) \times H_d^2 \times (L + 2 \times B) + \frac{W}{2} \times H_d \times (L + B)$$

H_d : Dam height (m): 32 m; L : Dam crest length (m): 340 m; B : River bed width (m): 60 m; W : Crest width : 10m; m : Upstream slope of dam ($m=2.0$ in this Manual); n : Downstream slope of dam ($n=1.8$ in this Manual)

$$V_e = 108,800 \text{ m}^3; V_c = 362,325 \text{ m}^3$$

Cost of other items of works such as grouting not included in the main items described above is estimated at 20% of the cost of the main items.

ii) Spillway

In the case of a fill type dam, the quantity of work of the spillway is calculated by the design flood discharge.

The excavation volume, concrete volume, weight of reinforcement bars, and weight of gates are calculated according to the following equations.

$$V_e = 84 \times \sqrt{Q_f} \times H_d$$

$$V_c = 13 \times \sqrt{Q_f} \times H_d$$

$$W_r = 0.02 \times V_c$$

$$W_g = 0.22 \times Q_f$$

Q_f : Design flood discharge (m³/s) : 432 m³/s

H_d : Dam height (m) : 32m

$$V_e = 55,878 \text{ m}^3; V_c = 8,648 \text{ m}^3; W_r = 173 \text{ ton};$$

$$W_g = 95 \text{ ton}$$

Cost of other items of works which is not included in the main items described above is estimated at 20% of the cost of the main items.

Allugolla PSPP - Upper Dam

(1) Structural Design

Concrete gravity type dam is adopted because of the following reasons.

Possible to obtain the sound rock for the dam foundation, River span is narrow, Easy to overflow during the flood period, Easy to transport concrete.

Dam specifications are determined as below.

Crest Elevation: 819 m; Crest Length: 260 m; Dam

Height (H_d): 41 m

$$Q_f = 259.467 \text{ m}^3/\text{s}$$

(2) Quantity of work

Excavation volume and volume of dam is obtained by the following equations.

$$V_e = 10.0 \times H_d^2 \times L$$

$$\text{In the case : } H_d^2 \times L > 100 \times 10^3$$

$$V_c = 0.34 \times (H_d^2 \times L) \quad (B/L = 0.5)$$

$$V_c = 0.30 \times (H_d^2 \times L) \quad (B/L = 0.4)$$

$$V_c = 0.27 \times (H_d^2 \times L) \quad (B/L = 0.3)$$

$$V_c = 0.21 \times (H_d^2 \times L) \quad (B/L = 0.2)$$

$$V_c = 0.16 \times (H_d^2 \times L) \quad (B/L = 0.1)$$

$$W_g = 0.13 \times Q_f$$

B : River bed width (m) : 35 m; L : Crest length (m) : 260 m; Q_f : Design flood discharge : 259.5 m³/s; H_d : Dam height (m) : 41m

$$V_e \approx 106,600.00 \text{ m}^3$$

$$V_c \approx 69,929.60 \text{ m}^3$$

$$W_g \approx 33.7 \text{ ton}$$

Cost of other items of civil works such as grouting and coffering not included in the main items above, is estimated at 20% of the main items.

Lower Dam - Arama Lower Dam

(1) Structural Design

Concrete gravity type dam is adopted.

Dam specifications are determined as below.

Crest Elevation: 305 m; Crest Length: 350 m; Dam

Height (H_d): 57 m

$$Q_f = 1206 \text{ m}^3/\text{s}$$

B : River bed width (m) : 45 m; L : Crest length (m) : 350 m; Q_f : Design flood discharge : 1206 m³/s; H_d : Dam height (m)

$$V_e \approx 199,500 \text{ m}^3$$

$$V_c \approx 181,944 \text{ m}^3$$

$$W_g \approx 156.8 \text{ ton}$$

Cost of other items of civil works such as grouting and coffering not included in the main items above, is estimated at 20% of the main items.

Uduwella PSPP - Intake

(1) Structural Design

A pressure type is adopted. The inner diameter of waterway is obtained from Figure 2. by using the maximum plant discharge.

Inner Diameter: 6.9 m

Maximum plant discharge: 152 m³/s

Figure 2 - Inner Diameter of Waterway

(2) Quantity of work

The excavation volume, concrete volume, weights of reinforcement bars, gate and screen are calculated by the following equations.

$$V_e = 130 \times \left[\{(h_a + D) \times Q\}^{1/2} \times n^{1/3} \right]^{1.27}$$

$$V_c = 56.5 \times \left[\{(h_a + D) \times Q\}^{1/2} \times n^{1/3} \right]^{1.23}$$

$$W_r = 0.04 \times V_c$$

$$W_g = 0.9 \times \{(h_a \times D)^{1/9}\} \times Q$$

$$W_s = 0.5 \times \{(h_a \times D)^{1/9}\} \times Q$$

h_a : Available drawdown (m) : 19.55 m;

Q : Maximum plant discharge (m³/s) : 152 m³/s

D : Inner diameter of waterway : 6.9 m

n : Number of waterway channels : 1

V_e =25,273 m³; V_c =9,304 m³; W_r =372 ton;

W_g = 236 ton; W_s =131 ton

Cost of other items of works such as coffering and trash rack, rake, etc. not included in the main items above are estimated at 25% of the main items.

Uduwella PSPP - Headrace

(1) Structural Design

A circular fully lined pressure tunnel is adopted. Diameter of tunnel is calculated assuming that a flow velocity in the tunnel is 6.0 m/s.

$$Diameter = (4 \times \frac{Q_{max}}{6\pi})^{0.5} = 5.7m$$

(2) Quantity of work

The excavation volume of the pressure tunnel, concrete volume and weight of reinforcement bars are calculated by the following equations.

$$V_e = 3.2 \times (R + t_0)^2 \times L \times n$$

$$V_c = \{3.2 \times (R + t_0)^2 - \pi R^2\} \times L \times n$$

$$W_r = 0.04 \times V_c$$

R : Tunnel radius (m) = 2.85m; t_0 : Lining concrete thickness (m) = 55cm ; L : Total length of waterway channels (m) = 1850m; N : Number of waterway channels =1

V_e =68,435

V_c =21,250

W_r =850

Cost of other items of works such as grouting, adit, ect. Not included in the main items stated above is estimated at 15% of the cost of the main items.

Uduwella PSPP-Headrace Surge Tank

(1) Structural Design

Surge tank shall be provided to protect the headrace tunnel against the pressure of water hammer.

(2) Quantity of work

The excavation volume, concrete volume, and weight of reinforcement bars are calculated in accordance with the following equations.

$$V_e = 38 \times q \times (h_a + L)^{1/4} \times n$$

$$V_c = 11 \times q \times (h_a + L)^{1/4} \times n$$

$$W_r = 0.05 \times V_c$$

q : Design discharge (m³/s) = 152 m³/s; L : Total length of waterway (m) = 1850 m; a : Available drawdown of regulating pond or reservoir (m) = 19.55 m; n : Number of waterway channels = 1

V_e = 37,980 m³

V_c =10,994 m³

W_r =550 ton

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

Uduwella PSPP - Penstock

(1) Structural Design

A circular fully steel lined pressure tunnel is adopted. The inner diameter of penstock is calculated assuming that a flow velocity in the penstock is 10 m/sec.

$$Diameter : (4 \times Q_{max} / 10\pi)^{0.5} = 4.4 m$$

(2) Quantity of work

For embedded type of penstock, excavation volume and concrete volume are obtained by the following equation, assuming constant thickness of backfill concrete of 60 cm.

$$V_e = \frac{\pi}{4} (D_m + 2t)^2 \times L$$

$$V_c = \frac{\pi}{4} \{(D_m + 2t)^2 - D_m^2\} \times L$$

D_m : Average inner diameter of steel pipe (m) = 4.4 m; t : Thickness of backfill concrete (m) = 0.6 m; L : Total length of penstock (m) :2400 m

V_e = 59,082 m³

V_c = 22,608 m³

Cost of other items of works such as grouting, audit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

The weight of the steel conduit is obtained by the following equations for embedded type in tunnel.

$$W_p = 7.85 \times \pi \times D_m \times t_m \times 1.1 \times L$$

$$t_m = 0.0270H \times D_m + 2$$

W_p : Weight of steel conduit (ton)

t_m : Average thickness of steel conduit (mm)

H : Design head (m) (high water level - tailwater level) = 387.6 m

$$W_p = 13,743 \text{ ton}$$

$$t_m = 48 \text{ mm}$$

Uduwella PSPP -Underground Powerhouse

(1) Structural Design

Underground type is adopted for Powerhouse.

(2) Quantity of work

The excavation volume, concrete volume, and weight of reinforcement bars are obtained by the following equations.

$$V_e = 27 \times A + 1.3 \times A \times d$$

$$V_c = 15 \times A$$

$$W_r = 0.6 \times A$$

Provided that,

$$A = 1,798 \text{ m}^2$$

Q : Maximum plant discharge (m^3/s) = $152 \text{ m}^3/\text{s}$;

H_e : Effective head (m) = 387.6 m;

A : Area of powerhouse (m^2) = $1,798 \text{ m}^2$;

d : Height of powerhouse (m) = 40m

$$V_e = 142,027 \text{ m}^3$$

$$V_c = 26,967 \text{ m}^3$$

$$W_r = 1,079 \text{ ton}$$

The cost of powerhouse building and transformer chamber is included in 50% of "Others".

Uduwella PSPP -Tailrace Tunnel

(1) Structural Design

A circular fully lined pressure tunnel is adopted.

Diameter of tunnel is calculated assuming that a flow velocity in the tunnel is 6.0 m/sec. Diameter:

$$(4 \times Q_{\max} / 6.0\pi)^{0.5} = (4 \times 152 / 6.0\pi)^{0.5} = 5.7 \text{ m}$$

(2) Quantity of work

The excavation volume of the pressure tunnel, concrete volume, and weight of reinforcement bars are calculated by the following equations.

$$V_e = 3.2 \times (R + t_0)^2 \times L \times n$$

$$V_c = \{3.2 \times (R + t_0)^2 - \pi R^2\} \times L \times n$$

$$W_r = 0.04 \times V_c$$

R : Tunnel radius (m) = 2.85 m; t_0 : Lining concrete thickness (m) = 55cm; L : Total length of waterway channels (m) = 200 m; n : Number of waterway channels = 1

$$V_e = 7,398 \text{ m}^3$$

$$V_c = 2,297 \text{ m}^3$$

$$W_r = 92 \text{ ton}$$

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

Figure 3 - Relationship between Inner Diameter of Tunnel and Lining Concrete Thickness

(2) Quantity of work

The excavation volume, concrete volume, and weight of reinforcement bars are calculated in accordance with the following equations.

$$V_e = 38 \times q \times (h_a + L)^{1/4} \times n$$

$$V_c = 11 \times q \times (h_a + L)^{1/4} \times n$$

$$W_r = 0.05 \times V_c$$

q : Design discharge (m^3/s) = $152 \text{ m}^3/\text{s}$; L : Total length of waterway (m) = 200 m; h_a : Available drawdown of regulating pond or reservoir (m) = 33 m; n : Number of waterway channels = 1

$$V_e = 22,566 \text{ m}^3$$

$$V_c = 6,532 \text{ m}^3$$

$$W_r = 327 \text{ ton}$$

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

Uduwella PSPP -Tailrace Outlet

(1) Structural Design

A pressure type is adopted same as the intake.

(2) Quantity of work

During pumping operation the tailrace outlet becomes an intake, therefore, calculation method of quantity of work for intake is adopted.

$$V_e = 130 \times (((33 + 5.7) \times 152)^{1/2} \times 1^{1/3})^{1.27} = 32,182 \text{ m}^3$$

$$V_c = 56.5 \times (((33 + 5.7) \times 152)^{1/2} \times 1^{1/3})^{1.23} = 11,758 \text{ m}^3$$

$$W_r = 0.04 \times 11,758 = 470 \text{ ton}$$

$$W_g = 0.9 \times (33 \times 5.7)^{1/9} \times 152 = 245 \text{ ton}$$

$$W_s = 0.5 \times (33 \times 5.7)^{1/9} \times 152 = 136 \text{ ton}$$

Cost of other items of works such as coffering and trash rack, rake, etc. not included in the main items obtained above is estimated at 25% of the cost of the main items.

Uduwella PSPP – Access Tunnel to Powerhouse

(1) Quantity of work

Excavation volume, concrete volume, and weight of reinforcement bars of the access tunnel are obtained by the following equations. The maximum gradient of the access tunnel is 1:10.

$$V_e = 45 \times L \text{ (m}^3\text{)}$$

$$V_c = 10 \times L \text{ (m}^3\text{)}$$

$$W_r = 0.03 \times V_c \text{ (ton)}$$

T : thickness of overburden at Powerhouse = 70 m;

L : Length of access tunnel (m) = 30m

$$V_e = 1,350 \text{ m}^3$$

$$V_c = 300 \text{ m}^3$$

$$W_r = 9 \text{ ton}$$

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

Uduwella PSPP –Miscellaneous Works

Cost of miscellaneous works such as the disposal area and landscaping work is estimated at 10% of the total civil work cost.

Alugolla PSPP - Intake

Inner Diameter : 6.4 m

(1) Quantity of work

$$V_e = 26,310 \text{ m}^3$$

$$V_c = 9,674 \text{ m}^3$$

$$W_r = 387 \text{ ton}$$

$$W_g = 194 \text{ ton}$$

$$W_s = 108 \text{ ton}$$

Cost of other items of works such as coffering and trash rack, rake, etc. not included in the main items above are estimated at 25% of the main items.

Alugolla PSPP - Headrace

(1) Structural Design

Diameter = 5.0m

(2) Quantity of work

$$V_e = 67,680$$

$$V_c = 21,561$$

$$W_r = 862$$

Cost of other items of works such as grouting, adit, etc. Not included in the main items stated above is estimated at 15% of the cost of the main items.

Alugolla PSPP – Headrace Surge Tank

(1) Structural Design

$$V_e = 32,112 \text{ m}^3$$

$$V_c = 9,295 \text{ m}^3$$

$$W_r = 465 \text{ ton}$$

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

Alugolla PSPP – Penstock

(1) Structural Design

Diameter : = 3.9 m

(2) Quantity of work

$$V_e = 29,951 \text{ m}^3$$

$$V_c = 11,191 \text{ m}^3$$

$$W_p = 7,398 \text{ ton}$$

$$t_m = 53 \text{ mm}$$

Alugolla PSPP- Underground Powerhouse

(1) Structural Design

Underground type is adopted for Powerhouse.

(2) Quantity of work

Q : Maximum plant discharge (m³/s) = 121 m³/s

$$V_e = 136,570 \text{ m}^3$$

$$V_c = 25,931 \text{ m}^3$$

$$W_r = 1,037 \text{ ton}$$

The cost of powerhouse building and transformer chamber is included in 50% of "Others".

Alugolla PSPP – Tailrace Tunnel

(1) Structural Design

Diameter: $(4 \times Q_{\max} / 6.0\pi)^{0.5} = 5.1 \text{ m}$

(2) Quantity of work

$$V_e = 12,800 \text{ m}^3$$

$$V_c = 4,020 \text{ m}^3$$

$$W_r = 161 \text{ ton}$$

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

Alugolla PSPP- Tailrace Surge Tank

(1) Structural Design

$$V_e = 21,329 \text{ m}^3$$

$$V_c = 6,174 \text{ m}^3$$

$$W_r = 309 \text{ ton}$$

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

Alugolla PSPP – Tailrace Outlet

(1) Structural Design

A pressure type is adopted same as the intake.

(2) Quantity of work

$$V_e = 27,568 \text{ m}^3$$

$$V_c = 10,121 \text{ m}^3$$

$W_r = 405$ ton

$W_g = 192$ ton

$W_s = 107$ ton

Cost of other items of works such as coffering and trashrack, rake, etc. not included in the main items obtained above is estimated at 25% of the cost of the main items.

Alugolla PSPP - Access Tunnel to powerhouse

(1) Quantity of work

$V_e = 2,250$ m³

$V_c = 500$ m³

$W_r = 15$ ton

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

Alugolla PSPP -Miscellaneous Works

Cost of miscellaneous works such as the disposal area and landscaping work is estimated at 10% of the total civil work cost.

Economic Analysis

Benefit-Cost Method (B/C Method)

The economics of the project is analyzed on the basis of maximum output, energy output and the construction cost obtained.

Methodology of Analysis

An economic analysis of the hydro power project is made by a method to compare its benefit (B) and cost (C). The benefit of a hydro power project is the avoided cost of an alternative thermal power that supplies electric power equivalent to the hydro power project, and the cost is derived from the construction cost of the hydro power project. In the case of benefit cost ratio (B/C) is 1.0 or over, hydro power is economically better than the alternative thermal power. It is also possible to judge that a certain hydro power project is economically attractive if the B/C value is outstanding among a number of hydro power projects that are compared. Yet another method is to use the latter method and calculate the Economic Internal Rate of Return (EIRR).

Selection of Alternative Thermal Power

The alternative thermal power plants are gas turbine, coal fired, oil fired, liquefied gas fired, combined cycle, and diesel power plants.

(1) Standard Thermal Power

One method is to select the power source most commonly used in the electric power system. This is defined as the "standard thermal power". This method is suitable to compare the economic viability of a number of hydro power sites according to the same criteria, and this method is used for hydro power potential survey, master plan studies, etc. For example, in the case of an electric power system consisting mainly of coal fired thermal power plants or new coal fired plants are scheduled to be constructed, coal fired plants are selected as the standard thermal power.

(2) Alternative Thermal Power Equivalent to Hydropower

The other method is to select an alternative thermal power which is equivalent to the planned hydro power project, to evaluate its position as the source of supply in the electric power system. For instance, a gas turbine plant is often selected as the alternate thermal power for the reservoir type, pondage type and pumped storage type power plants that are designed to supply power for peak.

Benefit and Cost of Conventional Hydropower Projects

Benefit

Annual benefit (B) of a hydro power project is obtained in accordance with the following formula, based on the fixed cost (mainly the equipment cost) and variable cost (mainly the fuel cost) of the alternative thermal power selected.

$$B = B_1 + B_2$$

$$B_1 = Ph \times b_1$$

$$B_2 = E \times b_2$$

Where,

B: Annual benefit of hydro power plant (monetary unit)

B_1 : kW benefit (monetary unit/kW)

B_2 : kWh benefit (monetary unit/kWh)

Ph: Effective output (kW), maximum output is used in the case of pumped storage type

E: Annual energy generation (kWh) at 2190 hours operation in a year (6hours per day)

b_1 : kW value (also called capacity value), which is the fixed cost per kW for alternative thermal power (monetary unit/kW)

b_2 : kWh value (also called energy value), which is mainly the fuel cost and is the variable cost per kWh for alternative thermal power (monetary unit/kWh)

Loss rate and Outage rate is omitted.

Calculation of kW Value (b_1) and kWh Value (b_2)

The kW value and kWh value are calculated from the following equations for the selected power source.

$$b_1 = Ct \times \beta \times \alpha$$

$$b_2 = \text{Heat rate (kcal/kWh)} \times \text{fuel price (monetary unit/kcal)} \times 860 \text{ (kcal/kWh)/thermal efficiency} \times \text{Fuel price (monetary unit/kcal)}$$

Ct: Unit construction cost of thermal power (monetary unit/kW)

α = Annual cost factor of thermal power

β = kW adjustment factor; correction factor due to the difference in reliability (station use, forced outage, scheduled outage) between hydro power and thermal power.

The annual factor and thermal efficiency for gas turbine plant is shown below.

Table 1 - The Annual Factor and Thermal Efficiency for Gas Turbine Plant

	Gas Turbine
Annual cost factor	Approx. 18%
Thermal Efficiency	Approx. 30%
Service life	20 years

The following equation is used to calculate more detailed annual factor.

Annual cost factor (α) = Capacity Recovery Factor (CRF) + Operation & Maintenance cost (OM: fuel cost excluded)

$$\alpha = CRF + OM = \frac{i(1+i)^n}{(1+i)^n - 1} + 0.03$$

Where,

i: Interest rate

n: Service life (years) (hydro power=50years)

Economic Analysis results for Maha pumped storage power plant complex are shown in Table 6.

Conclusion

The nature has blessed Sri Lanka with several natural locations which are suitable for developing Pumped Storage Power Plants. Few sites can be developed as Pumped Storage Power Plant Complexes which, further improve their economic viability. These will reduce the transmission costs which was not considered in this study.

Results (Table 7) show that 500 MW Maha-Alugolla Pumped Storage Power Plant is the most economical plant while 1,000MW Maha Pumped Storage Power Plant Complex is the next lowest.

The future load curve trends showed that there will be about 1,000MW PSPP capacity requirement by year 2021[3]. By considering the economic evaluation results and PSPP capacity requirement forecasted for the future, it can be concluded that the "Maha" Pumped Storage Power Plant Complex will be the best candidate plant to be installed in Sri Lanka.

References

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Note: This paper was presented in the Energy Symposium Sri Lanka 2015.

Economic Evaluation Summary

	Construction Cost (Civil) (USD)	Construction Cost (Hydro-mechanical Equipment Cost) (USD)	Construction Cost (Electro-mechanical Equipment Cost) (USD)	Total Cost (USD)	Capacity (MW)	Design Discharge Q (m ³ /s)	Effective Head (m)	L/H	Project cost per kW (USD/kW)	ERR (%)	Benefit /Cost
Maha-Alugolla PSPP	205,189,962	62,140,374	151,768,750	664,702,542	500	121	485.2	7.84	1,329	39.90%	2.65
Maha PSPPC	556,830,901	172,045,045	273,702,618	1,600,091,621	Udu. / 500 / Alu. 500	Udu. / 152 / Alu. 121	Udu. / 387.6 / Alu. 485.2	Udu. / 10.64 / Alu. 7.84	1,600	34%	2.4
Puna-Kotmale PSPP	279,501,762	102,958,931	158,254,594	859,822,180	500	88	666.5	9.4	1,720	34%	2.4
Maha-Uduwella PSPP	358,266,582	111,385,988	121,933,868	948,648,602	500	152	387.6	10.64	1,897	29.10%	2.14
KM PSPP	215,730,430	57,751,710	76,532,960	561,841,272	250	80.2	366.7	11.6	2,247	24.81%	1.91
Dambagastalawa PSPP	334,948,441	32,165,864	93,396,154	746,936,019	300	79	445.8	6	2,490	23%	1.8
Agra PSPP	382,574,211	26,241,954	90,801,816	813,267,607	300	86.9	406	11	2,711	21%	1.7
KMG PSPPC	1,117,397,665	116,179,268	230,896,048	2,383,233,673	KM / 250 / KG 500	KM / 80.2 / KG 98.25	KM / 366.7 / KG 598.7	KM / 11.6 / KG 9.0	3,178	18%	1.5
KG PSPP	904,786,946	58,418,642	154,363,088	1,826,567,624	500	98.25	598.7	9	3,653	15.35%	1.35

Calculation of Construction Cost (Civil Cost)-Maha PSPP Complex

Item	Unit	Unit Price	Quantity	Cost	Remark
(1) Upper dam					
1. Care of river	L.S.	—	1	28,269,870	1. = 2. × 0.20
2. Concrete dam					2. = ① + ② + ③
①Excavation	m ³	22	215,400	4,727,942	①
②Concrete	m ³	262	432,255	113,063,183	②
③Others	L.S.	—	1	23,558,225	③ = (① + ②) × 0.2
Sub Total				169,619,220	
(2) Lower dam					
1. Care of river	L.S.	—	1	12,472,633	1. = 2. × 0.2
2. Concrete dam					2. = ① + ② + ③
①Excavation	m ³	22	199,500	4,378,944	①
②Concrete	m ³	262	181,944	47,590,360	②
③Others	L.S.	—	1	10,393,861	③ = (① + ②) × 0.2
Sub Total				74,835,797	
(3) Intake					
①Excavation	m ³	22	51,583	1,132,234	①
②Concrete	m ³	273	18,978	5,172,258	②
③Reinforcement bar	ton	2,625	759	1,992,534	③
④Others	L.S.	—	1	2,074,256	④ = (① + ② + ③) × 0.25
Sub Total				10,371,282	
(4) Headrace					
①Excavation	m ³	134	136,115	18,175,012	①
②Concrete	m ³	267	42,813	11,433,315	②
③Reinforcement bar	ton	2,625	1,713	4,495,016	③
④Others	L.S.	—	1	5,115,501	④ = (① + ② + ③) × 0.15
Sub Total				39,218,844	
(5) Surge tank (Headrace)					
①Excavation	m ³	172	70,093	12,051,612	①
②Concrete	m ³	216	20,290	4,379,337	②
③Reinforcement bar	ton	2,625	1,014	2,662,860	③
④Others	L.S.	—	1	3,818,762	④ = (① + ② + ③) × 0.2
Sub Total				22,912,570	

(4) Penstock					
①Excavation	m ³	199	86,034	17,153,029	①
②Concrete	m ³	190	33,799	6,429,569	②
③Others	L.S.	—	1	3,537,390	③ = (① + ②) × 0.15
Sub Total				27,119,988	
(5) Powerhouse					
①Excavation	m ³	209	278,598	58,093,626	①
②Concrete	m ³	424	52,898	22,447,903	②
③Reinforcement bar	ton	2,625	2,116	5,553,921	③
④Others	L.S.	—	1	43,047,725	④ = (① + ② + ③) × 0.5
Sub Total				129,143,175	
(6) Tailrace					
①Excavation	m ³	134	20,199	2,697,057	①
②Concrete	m ³	267	6,318	1,687,252	②
③Reinforcement bar	ton	2,625	253	663,344	③
④Others	L.S.	—	1	757,148	④ = (① + ② + ③) × 0.15
Sub Total				5,804,802	
(7) Surge tank (Tailrace)					
①Excavation	m ³	172	43,895	7,547,290	①
②Concrete	m ³	216	12,707	2,742,548	②
③Reinforcement bar	ton	2,625	635	1,667,609	③
④Others	L.S.	—	1	2,391,489	④ = (① + ② + ③) × 0.2
Sub Total				14,348,936	
(8) Outlet					
①Excavation	m ³	22	59,749	1,311,476	①
②Concrete	m ³	273	21,879	5,962,897	②
③Reinforcement bar	ton	2,625	875	2,297,116	③
④Others	L.S.	—	1	2,392,872	④ = (① + ② + ③) × 0.25
Sub Total				11,964,361	
(9) Access tunnel to					
①Excavation	m ³	134	3,600	480,696	①
②Concrete	m ³	267	800	213,643	②
③Reinforcement bar	ton	2,625	24	62,995	③
④Others	L.S.	—	1	113,600	④ = (① + ② + ③) × 0.15
Sub Total				870,934	
(10) Miscellaneous	L.S.	—		50,620,991	(10) = Σ{(1~9)} × 0.1
Total				556,830,901	

Calculation of Construction Cost (Hydro Mechanical Equipment Cost) - Maha PSPP Complex

Item	Unit	Unit	Quantity	Cost	Remark
1. Upper Dam and spillway					
Gate	ton	12,842	34	433,169	
2. Lower Dam and spillway					
Gate	ton	12,842	157	2,013,642	
3. Intake					
Gate	ton	10,767	430	4,634,876	
Screen	ton	5,578	239	1,334,001	
4. Penstock (steel pipe)	ton	6,097	21,141	128,892,381	
5. Tailrace outlet					
Gate	ton	10,767	437	4,707,810	
Screen	ton	5,578	243	1,354,992	
6. Others	L.S.	—	1	28,674,174	$(1 + 2 + 3 + 4) \times 0.2$
Total				172,045,045	

Construction Cost Summery - Maha PSPP Complex

Item	Cost (USD)	Note
1. Preparation and Land acquisition		
(1) Access road	27,841,545	$(3 \text{ Civil work}) \times 0.05$
(2) Compensation & Resettlement		
(3) Camp & Facilities	11,136,618	$(3 \text{ Civil work}) \times 0.02$
2. Environmental mitigation cost	16,704,927	$(3 \text{ Civil work}) \times 0.03$
3. Civil Work		556,830,901
(1) Upper Dams	169,619,220	
(2) Lower Dam	74,835,797	
(3) Intakes	10,371,282	
(4) Headrace	39,218,844	
(5) Surge tank (Headrace)	22,912,570	
(6) Penstocks	27,119,988	
(7) Powerhouses	129,143,175	
(8) Tailraces	5,804,802	
(9) Surge tanks (tailrace)	14,348,936	
(10) Outlets	11,964,361	
(11) Access tunnels to powerhouses	870,934	
(12) Miscellaneous	50,620,991	$((1) \sim (9)) \times 0.1$
4. Hydraulic equipment	172,045,045	Gate, Screen, Steel Penstock, etc
5. Electro-mechanical equipment	273,702,618	Turbine and Generator, Transformer, Switchyard, etc
6. Transmission line		
Direct cost	1,058,261,654	$1 + 2 + 3 + 4 + 5 + 6$
7. Administration and Engineering service	158,739,248	$(\text{Direct cost}) \times 0.15$
8. Contingency	211,652,331	$(\text{Direct cost}) \times 0.2$
9. Interest during construction	171,438,388	$(1+2+3+4+5+6+7+8) \times 0.4 \times 6\% \times 5\text{year}$
Indirect Cost	541,829,967	$7 + 8 + 9$
Total cost	1,600,091,621	$1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9$

Install Capacity	1,000,000	(kW)
Project Cost per kW	1,600	(USD/kW)

Calculation of Economic Evaluation Indices (Base Case) - Maha PSPP Complex

Year in order		Year	Cost				Benefit(Unit: US\$ 1,000,000)				
			Construction & Replacement	O & M	Pumping	Total	Construction & Replacement	O & M	Fuel Cost	Total	Balance
1		2015	100.26			100.26				0.00	(100.26)
2		2016	200.52			200.52				0.00	(200.52)
3		2017	300.77			300.77				0.00	(300.77)
4		2018	300.77			300.77	260.48			260.48	(40.30)
5		2019	100.26			100.26	362.40			362.40	262.14
6	1	2020		30.08	92.05	122.13		8.07	499.83	507.91	385.78
7	2	2021		30.08	92.05	122.13		8.07	499.83	507.91	385.78
8	3	2022		30.08	92.05	122.13		8.07	499.83	507.91	385.78
9	4	2023		30.08	92.05	122.13		8.07	499.83	507.91	385.78
10	5	2024		30.08	92.05	122.13		8.07	499.83	507.91	385.78
11	6	2025		30.08	92.05	122.13		8.07	499.83	507.91	385.78
12	7	2026		30.08	92.05	122.13		8.07	499.83	507.91	385.78
13	8	2027		30.08	92.05	122.13		8.07	499.83	507.91	385.78
14	9	2028		30.08	92.05	122.13		8.07	499.83	507.91	385.78
15	10	2029		30.08	92.05	122.13		8.07	499.83	507.91	385.78
16	11	2030		30.08	92.05	122.13		8.07	499.83	507.91	385.78
17	12	2031		30.08	92.05	122.13		8.07	499.83	507.91	385.78
18	13	2032		30.08	92.05	122.13		8.07	499.83	507.91	385.78
19	14	2033		30.08	92.05	122.13		8.07	499.83	507.91	385.78
20	15	2034		30.08	92.05	122.13		8.07	499.83	507.91	385.78
21	16	2035		30.08	92.05	122.13		8.07	499.83	507.91	385.78
22	17	2036		30.08	92.05	122.13		8.07	499.83	507.91	385.78
23	18	2037		30.08	92.05	122.13		8.07	499.83	507.91	385.78
24	19	2038		30.08	92.05	122.13	260.48	8.07	499.83	768.38	646.25
25	20	2039		30.08	92.05	122.13	362.40	8.07	499.83	870.31	748.18
26	21	2040		30.08	92.05	122.13		8.07	499.83	507.91	385.78
27	22	2041		30.08	92.05	122.13		8.07	499.83	507.91	385.78
28	23	2042		30.08	92.05	122.13		8.07	499.83	507.91	385.78
29	24	2043		30.08	92.05	122.13		8.07	499.83	507.91	385.78
30	25	2044		30.08	92.05	122.13		8.07	499.83	507.91	385.78
31	26	2045		30.08	92.05	122.13		8.07	499.83	507.91	385.78
32	27	2046		30.08	92.05	122.13		8.07	499.83	507.91	385.78
33	28	2047		30.08	92.05	122.13		8.07	499.83	507.91	385.78
34	29	2048		30.08	92.05	122.13		8.07	499.83	507.91	385.78
35	30	2049		30.08	92.05	122.13		8.07	499.83	507.91	385.78
36	31	2050	61.78	30.08	92.05	183.91		8.07	499.83	507.91	324.00
37	32	2051	44.57	30.08	92.05	166.70		8.07	499.83	507.91	341.20
38	33	2052	179.86	30.08	92.05	301.99		8.07	499.83	507.91	205.92
39	34	2053	114.96	30.08	92.05	237.09		8.07	499.83	507.91	270.82
40	35	2054	44.57	30.08	92.05	166.70		8.07	499.83	507.91	341.20
41	36	2055		30.08	92.05	122.13		8.07	499.83	507.91	385.78
42	37	2056		30.08	92.05	122.13		8.07	499.83	507.91	385.78
43	38	2057		30.08	92.05	122.13		8.07	499.83	507.91	385.78
44	39	2058		30.08	92.05	122.13	260.48	8.07	499.83	768.38	646.25
45	40	2059		30.08	92.05	122.13	362.40	8.07	499.83	870.31	748.18
46	41	2060		30.08	92.05	122.13		8.07	499.83	507.91	385.78
47	42	2061		30.08	92.05	122.13		8.07	499.83	507.91	385.78
48	43	2062		30.08	92.05	122.13		8.07	499.83	507.91	385.78
49	44	2063		30.08	92.05	122.13		8.07	499.83	507.91	385.78
50	45	2064		30.08	92.05	122.13		8.07	499.83	507.91	385.78
51	46	2065		30.08	92.05	122.13		8.07	499.83	507.91	385.78
52	47	2066		30.08	92.05	122.13		8.07	499.83	507.91	385.78
53	48	2067		30.08	92.05	122.13		8.07	499.83	507.91	385.78
54	49	2068		30.08	92.05	122.13		8.07	499.83	507.91	385.78
55	50	2069		30.08	92.05	122.13		8.07	499.83	507.91	385.78
56	51	2070		30.08	92.05	122.13		8.07	499.83	507.91	385.78
Total			1,448.33	1,533.95	4,694.64	7,676.91	1,868.63	411.79	25,491.47	27,771.89	20,094.98
In the condition of a discount rate of 10 %:											
Present value:						1,515				3,601	2,086.14
Economic Internal rate of return (EIRR):											33.98%
B/C											2.38