TUTA/IOE/PCU

Journal of the Institute of Engineering, 2018, ***14(1):*** *82-95*

Printed in Nepal

Optimization for Upgradation of Small Hydropower Plant in Nepal: A Case Study of Sundarijal Hydropower Plant

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Received: *Jan 2, 2018* ***Revised:*** *Jan 29, 2018* ***Accepted:*** *Feb 3, 2018*

Abstract: Efficiencies of electro-mechanical components of the Sundarijal Hydropower Plant in Nepal has been decreased and the plant has been generating less energy than design generation. The study shows that the plant can be upgraded to 1.1 MW capacity at Q_{60} design with rehabilitation. Main objective of the plant rehabilitation is to improve operational stability and reliability of power supply by increasing capacity, efficiency, and safety of the plant. The research is based on the Residual Life Assessment of hydro-mechanical components. Minimum thickness of existing penstock obtained from measurement is six mm which is sufficient for upgradation at Q_{60} design. Mechanical and chemical properties of penstock is found to be acceptable for upgradation. Machine foundations are tested to be safe for upgradation. Upgradation can be carried out for two scenarios: i) using two generating units system ii) using three generating units system. Energy generation per annum from two generating units system is 65.92 MWh lower than three generating units system. The difference in annual revenue between two systems is 3.93 thousand USD. Capital cost estimation shows that cost for three generating three generating units system is higher than two generating units system by 152 thousands USD. Cash flow analysis shows that IRR ratio for two generating units system is higher than three generating units system by three percentage. Upgradation with two generating units system is more suitable and beneficial than three generating units system. Optimization of turbine units is also carried out using nonlinear gradient reduction method in excel solver.

Keywords: Rehabilitation, efficiency, turbine, residual life assessment (RLA)

1. Introduction

Energy is one of the basic and essential requirements for the development of economic growth and social comfort. Different sectors of energy consumption are domestic, agriculture, industry, transportation, etc. Energy can be obtained from various resources like fossil fuel, biomass, geothermal, solar, wind, water (hydro), nuclear, etc. In 2010, 3400 TWh (equivalent to 780 million tons of oil) were produced [4] from hydropower energy, globally. Hence there is a strong need to scale up on energy from hydropower, at the same time it is necessary to optimize the current generation capacity of hydropower in Nepal. Recently in Nepal, World Bank has established a framework for hydropower investment projects which covers three types of hydropower projects: a) new storage hydropower projects, b) new small and peaking/ run-of-river hydropower projects and c) rehabilitation of existing facilities in hydropower projects. New hydropower projects are high risk investments with geographical terrain playing major role in their successful completion. However, these risks are less associated with the Renovation Modernization and Upgradation (RMU) of existing hydropower projects. The return on investment would be far earlier as compared to any new hydropower projects.

Rehabilitation of existing facilities in hydropower projects is performed in Sundarijal Hydropower Plant (SHPP). It is located at Sundarijal, 15 km north-east of Kathmandu with installed capacity of 640 kW and annual design generation of 5.338 GWh was commissioned in 1934 AD in a grant from British government. It consists two Pelton turbine units, each with 320 kW, are in normal operation and have the capacity to operate in full load when required. The SHPP tail race exist water is used as water supply system to Kathmandu Valley. The Bagmati and Nagmati Rivers are the principal water sources for this plant. In this research SHPP was upgraded to higher capacity with rehabilitation.

The primary objective of rehabilitation is to provide "life extension" to the existing facilities and restore their initial performances. It can often be justified to include an "upgrade" of the equipment (efficiency, output) which yields greater output but at increased costs which is justified by the additional revenue over the service life of the equipment. Hydropower plant rehabilitation covers a broad set of activities, including repairing/replacing components, upgrading generation capability/availability etc. In the current research, rehabilitation is focused on the major electrical and mechanical equipment associated with power generation, namely the turbine and generator, excluding civil works.

2. Methodology

This study is based on both qualitative and quantitative methods. The data is based on both primary and secondary data field. Primary data were taken from Sundarijal Hydro Power Plant. Secondary data were collected from other various sources.

2.1 Data Collection

Primary data were collected from Sundarijal Hydropower Plant. The primary data were measured using various equipment located in the power plant. Devices such as flow meter, level sensors, energy meters etc. were used to measure different outputs. Data was collected from various displays located at different panels in SHPP control room. Data stored on control room and hourly analogue data maintained by Shift In-charge on daily log sheets were taken and converted into digital data. Secondary data were collected from different sections of Nepal Electricity Authority (NEA) viz. Load Dispatch Centre (LDC) and Generation Directorate. Various related publications, reports, literatures, studies, etc. were referred along with related web sites. All the quantitative data obtained were encoded in Microsoft Excel Program and driving variables were analyzed. For the performance optimization of Hydropower plant, it is necessary to analyze existing parameters of Hydropower plant viz. active power with respect to variable discharge, head and efficiency. Different performance indices, such as overall plant efficiency, individual unit efficiencies, availability of units, availability of plant, plant capacity, capacity factor, etc., were calculated.

2.2 Residual Life Assessment (RLA) of Hydro Mechanical Equipment and Civil Structure

RLA study of an existing power plant is a difficult, complex and challenging task. It involves retrofitting of a new uprated machine in the existing space / water passage. It also involves complicated design assessment to retain original healthy parts. A systematic approach to check each and every part is necessary. The efficient way of checking the conditions of every component of the existing Hydropower Plant is done by Residual Life Assessment and Life Extension (RLA and LE) studies. RLA studies are helpful in determining which component of the plant is to retain and which one to discard and replace.

2.3 Civil Structure Testing

Civil structure testing work is carried out to check the safety of the structures. The wall brick testing show the compressive strength of brick is 10.52 N/mm^2, which is in good condition (minimum compressive strength being 3.5 N/mm^2 for normal brick and 10 N/mm^2 for A-graded brick). Similarly, water absorption capacity is 12.36% (should be less than 20% for normal brick) which is better for acceptance. (www.theconstructioncivil.org/test-for-bricks/, 2017). The report of concrete cube and rebound hammer test of machine foundations shows that the foundation is good. The ultra-sonic pulse velocity testing of turbines foundation shows that the quality of concrete is good. These suggests that civil structures are safe in SHPP.

Table 1: Testing of civil structures

Tested Material	Test Parameter	Value Observed	Standard Value*	Remarks
Brick	Compressive strength	10.52 N/mm^2	10 N/mm^2	Quality is Good
	Water absorption	12.36%	less than 20%	Quality is Good
Concrete cube	Compressive strength	42.10 N/mm^2	Above M35 (35 N/mm^2)	Quality is Good

2.4 Hydro Mechanical Equipment (Penstock) Testing

The water passage is designed for maximum head conditions for certain pressure rise upon full load tripping. In uprating conditions, the head may not vary but pressure rise, velocity increase, water hammer etc. would occurs. Visual examination is conducted for detecting those gross defects like cracks, breakages, dents, pitting, erosion, deformation, color changes, due to overheating, bulging, looseness, deposits etc. Die-penetration method is used, which brings out surface. Ultrasonic tests are carried out to detect and quantify surface and internal defects like cracks, dis-bonds, voids etc. in various components of penstock pipe. Thickness measurements using Ultra-Sonic technique were performed to observe the thickness of different segments of the penstock pipes. Hardness measurement provides a useful indication of the extent of the microstructural degradation due service conditions. Destructive tests are carried out for ascertaining mechanical characteristics of the materials for construction of critical components. Samples are examined for mechanical properties like strength and chemical composition, microstructure etc.

Table 2: Mechanical testing of Penstock Pipe

Test parameters	Value Observed	Standard Value of grade S235 as per EN 10025*
Ultimate Tensile Strength (MPa)	382.48	360
Yield Stress (MPa)	277.44	235
(%) Elongation	26.74	22
Ultrasonic Testing	No abnormality could be observed in the results on weld joints.	

3. Results and Discussion

3.1 Energy Generated by Existing SHPP

Sundarijal Hydropower Plant is installed with current capacity 640 kW and design energy generation of 5.338 GWh per annum. The energy generating capacity is decreasing due to ageing and losses. Fig. 1 shows design generation and actual generation by 640 kW SHPP [10]. From the graph, it is clear that the existing plant is generating less energy than design capacity. SHPP has been running for more than 80 years. Mainly, hydro-mechanical and electro-mechanical components are in degrading stage. Their efficiency has been reduced. It is riskier to operate such old and depreciated components. They should be replaced with new and highly efficient components. Therefore, the plant should be rehabilitated and upgraded to increase energy generation at design capacity.

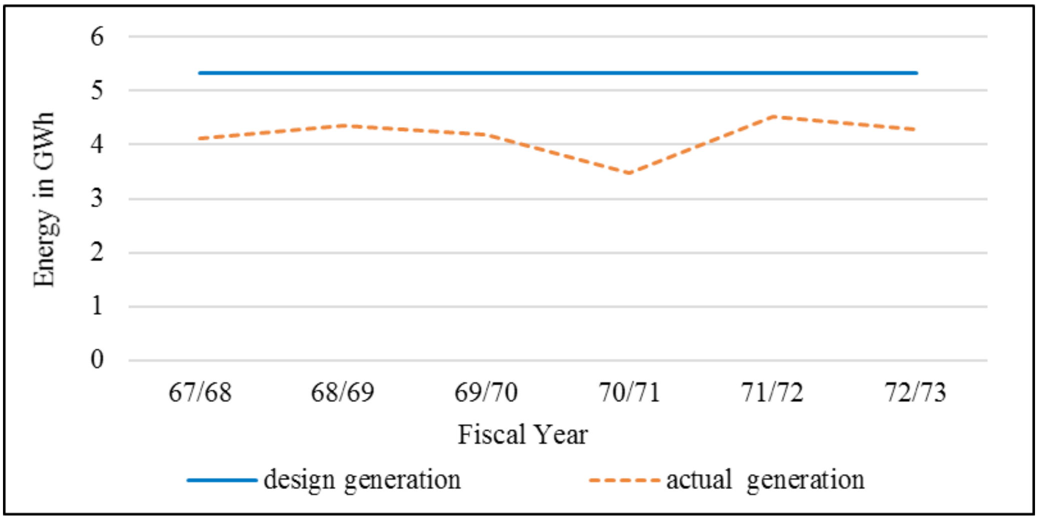


Fig. 1: Design generation and actual energy generation of 640 kW SHPP

3.2 Hydrology and Design Discharge

The flow discharge required for SHPP consists of water flow from Bagmati and Nagmati revers. The combined monthly flow rate [13] of Bagmati and Nagmati river are plotted against percentage exceedance as given in flow duration curve in Fig. 2. The discharge rate required for the upgraded plant will be calculated using this curve.

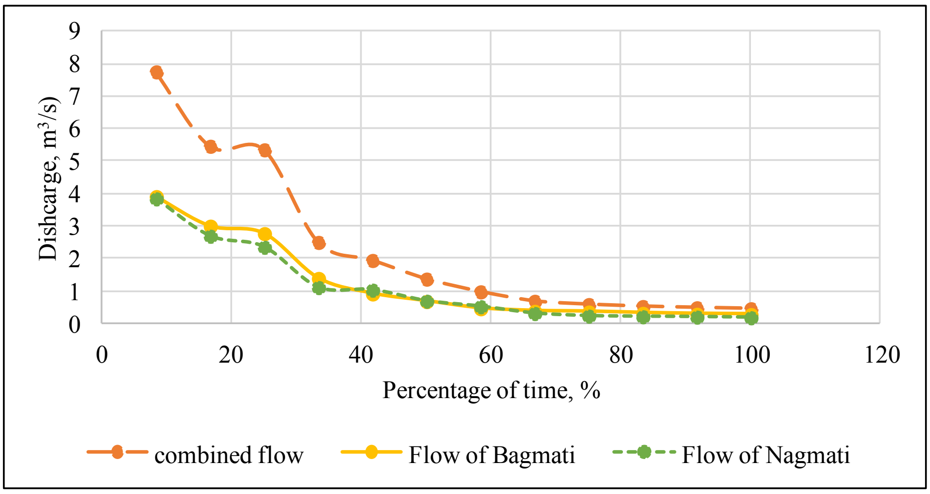


Fig. 2: Combined flow duration curve of Bagmati and Nagmati River

The monthly discharge available for SHPP is given in Fig. 3 below. From data it is clear that power generation capacity of Sundarijal Hydropower Project can be increased. The existing discharge utilized is 0.37 m^3/s and the plant is designed for approx. 95% exceedance flow. The plant generation capacity of Sundarijal Hydropower Project can be upgraded at new design discharge of 0.79 m^3/s with 60% exceedance flow.

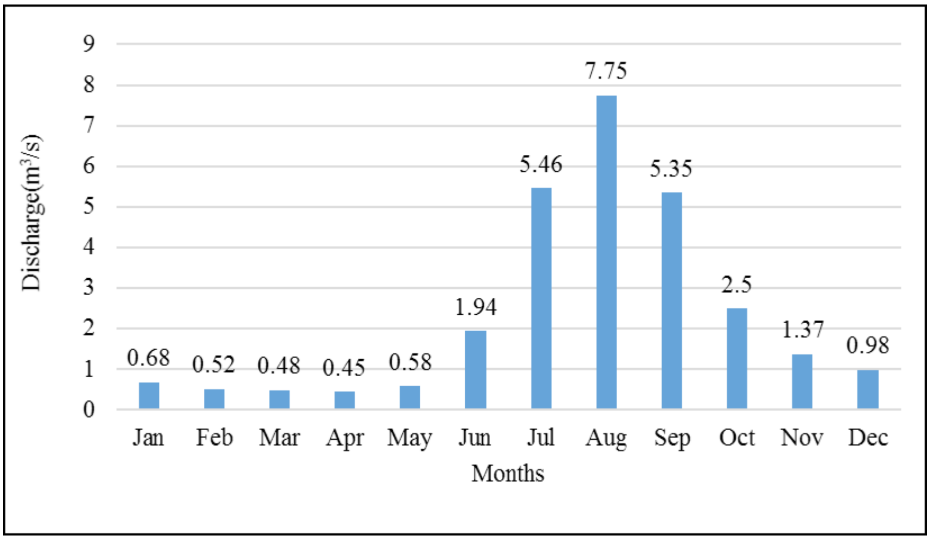


Fig. 3: Monthly river flow rate available for Sundarijal Hydropower Plant

3.3. Determination of Penstock Dimensions

3.3.1 Economic diameter

Design flow, $Q_{60} = 0.79 m^3/s$
Main Penstock length, l = 1146.07m
Penstock diameter, d = 0.45m

Gross Head, h =216.908m
Velocity in Penstock, $v = \frac{Q}{\Pi \times \frac{d^2}{4}} \frac{Q}{\Pi \times \frac{d^2}{4}}$ = 4.97m/s

Table 3: The economical diameter of penstock pipe is determined by using following formulas[1]

Formula	Economic diameter	Defining Parameters
Using Sarkaria formula	0.27 m	Power and Head
Using USBR formula	0.35 m	Flow and Velocity
Using Fahlbusch formula	0.416 m	Flow and Head

3.3.2 Penstock Thickness

The penstock thickness for upgraded plant is determined by considering following technical parameters:
For steel pipe at SHPP
Ultimate Tensile Stress, σ =382.48 MPa
Diameter, d=0.45m
ε = corrosion allowance = 1.5 mm
Internal pressure in the pipe, p=2.44 MPa
Welding joint efficiency η_W= 0.9
Taking factor of safety, FOS = 2.5,

The pipe shell thickness is given by the relation:

$$t = \frac{P \times d \times FOS}{2\sigma\eta} + \varepsilon t = \frac{P \times d \times FOS}{2\sigma\eta} + \varepsilon \;\; t = \frac{2.44 \times 450 \times 2.5}{2 \times 382.48 \times 0.9} \frac{2.44 \times 450 \times 2.5}{2 \times 382.48 \times 0.9} + 0.15 = 5.48 \text{ mm} \qquad [1]$$

Required thickness of penstock pipe = 5.48 mm

The required thickness of the penstock is found to be 5.48 mm but from the data available, the original thickness of the existing penstock pipe is about 6 mm. The calculation earlier, suggests that the existing penstock pipe can be used for the modified discharge of 0.79m^3/s. From the RLA study of the penstock pipe, thickness of different blocks varies from 6.0mm-10.5mm, reduced from 13 mm original thickness. The average thickness of the pipe is found to be about 8.85mm. The graph is plotted for required thickness (5.48 mm), original thickness (13 mm) and existing thickness. Fig. 4 shows reduction in the thickness of penstock pipe across the pipe length. But the thickness is not reduced below required thickness 5.48 mm. This shows that the existing penstock pipe can be used for upgradation.

The thickness of penstock has reduced from 13mm to 8.85 mm (average thickness) after 82 years. The reduced thickness is about 4 mm. The required thickness of the penstock is 5.48mm for upgradation. This shows that existing penstock shall be safe to use for about 30 years.

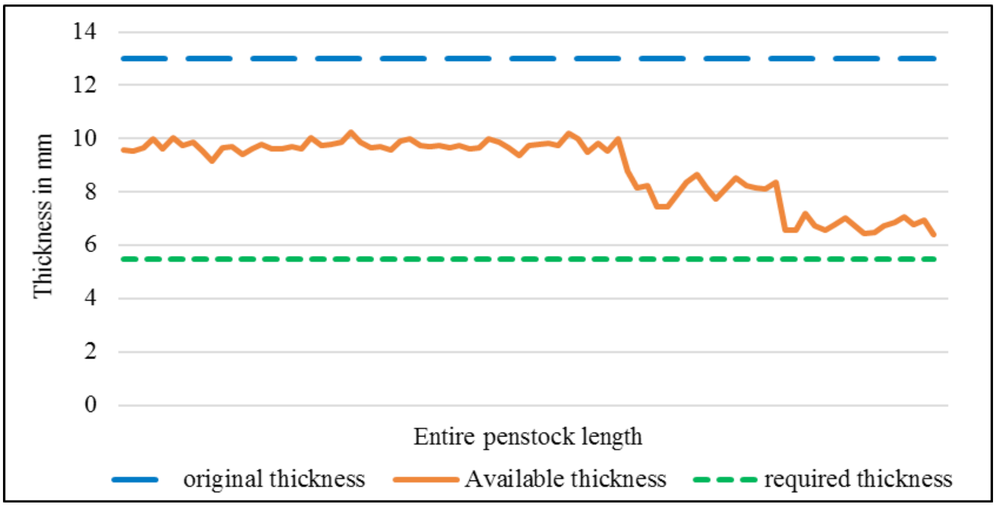


Fig. 4: Graph showing variation of thickness across the length of existing penstock

3.4. Head Loss

Head loss is calculated considering two scenarios: *i)* penstock single bifurcation for two generating unit system and *ii)* penstock double bifurcation for three generating unit system. The pressure pipe runs from head race to turbine unit. It is considered that the pipe has 610 mm diameter up to length 339 m. Then the pipe with diameter 450 mm is 1146.07 m long up to furcation point. The branches have diameter 300 mm. Head loss is calculated separately for different pipe dimensions and then total head loss is calculated. In Fig. 5, shows the comparison of head loss due to single bifurcated and double bifurcated penstock. The head loss due to single bifurcated penstock is found to be slightly more than double bifurcated pipe, due to higher flow rate and velocity. The head loss for both system is nearly equal from January to April. The difference in head loss increases from May and is constant up to December. The difference in head loss between single bifurcated and double bifurcated system is 0.76 m at rated discharge.

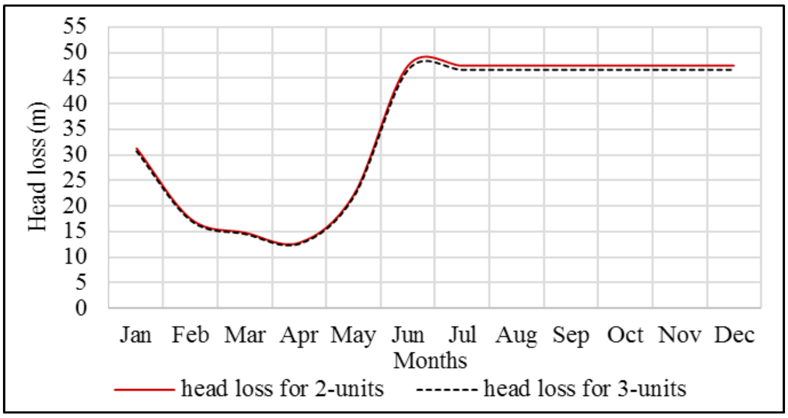
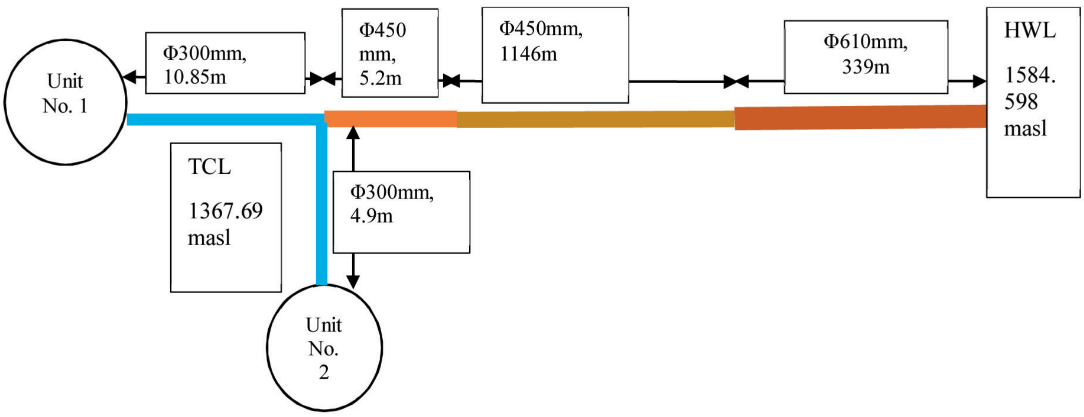


Fig. 5: Comparison between head loss due to single bifurcation and double bifurcation of penstock

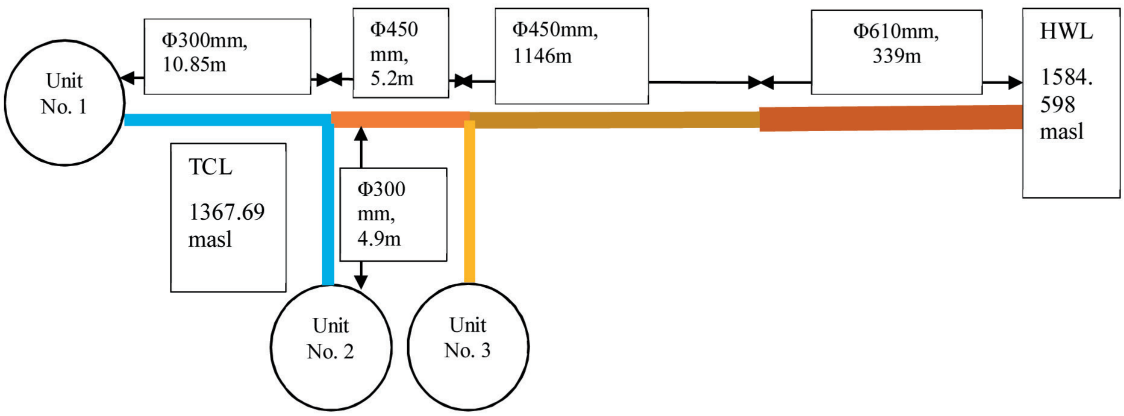
3.5. Design of Hydro-mechanical Component

Following are the summary of the design parameters, calculated for two units generating system and three generating unit system as shown schematic diagram in Fig. 6 and Fig. 7.



TLC: Turbine central level HWL: Height of water level Φ: Penstock internal diameter

Fig. 6: Schematic layout of penstock for two units generating system



TLC: Turbine central level HWL: Height of water level Φ: Penstock internal diameter

Fig. 7: Schematic layout of penstock for three units generating system

Table 4: Summary of Pelton turbine design

Number of units	2- units generating system	3- units generating system
Rated capacity of a unit	600 kW	400 kW
Rated Design Head, h	169.40 m	170.16 m
Rated speed, N	750 rpm	750 rpm
Discharge per unit	0.395 m^3/sec	0.263 m^3/sec
Calculation of Pelton Design Parameters		
Velocity of the jet at inlet , C_1	56.49 m/sec	56.62 m/sec
Velocity of the turbine wheel, U_1	25.94 m/sec	26 m/sec

Number of nozzle, z	2	2
Mean diameter or the pitch diameter 'D'	0.66 m	0.67 m
Diameter of nozzle, d	0.0667 m	0.054 m
Number of bucket on a runner, N_b	20	22
Bucket Depth, T	0.06 m	0.049 m
Specific speed, N_s	25.96 rpm	21.10 rpm
Runaway speed	1425 rpm	1425 rpm
U1/C1(speed ratio)	0.46	0.46
Hydraulic efficiency of the Pelton turbine, η_h	92.80%	92.80%

The turbine efficiencies of units are determined from model test of a horizontal two jet Pelton turbine model [10]. The generator efficiency is taken constant at different load operations during optimization. The unit efficiency curve for two and three units generating systems at various unit discharge conditions is given in Fig. 8.

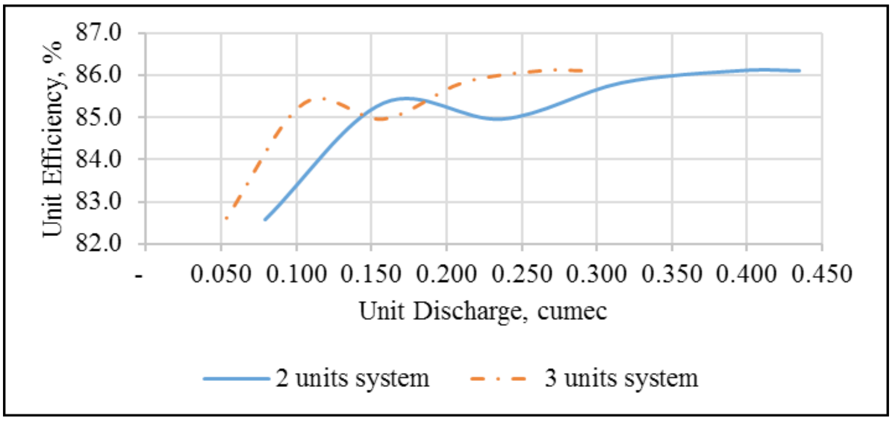


Fig. 8: Efficiency curve of two and three units generating system

3.6. Optimization

Even though all generating units are of same capacity, they are located in branches with slightly different values of head losses. This results unequal power output from each generating units even under same value of gross head and unit discharge. So it is not optimal to distribute discharge equally. Rather it would be wise to be biased towards generating unit with lower value of head loss. From the combined efficiency value and head loss in water conduit, unit power output can be calculated for all values of total discharge. Excel add-in program solver has been used to determine the optimal discharge distribution in case of both two units generating system and three units generating system to obtain highest possible value of total power output. Figure can be used by a plant operator to operate two units generating system in optimal manner with optimal discharge distribution. Figure shows that initially only unit number two is operated up to the point (0.45cumec) where maximum operating point of unit number two is reached. After that point, unit number one is operated along with unit number two. Unit number two is always provided with maximum possible discharge and unit number one receives whatever discharge that is left.

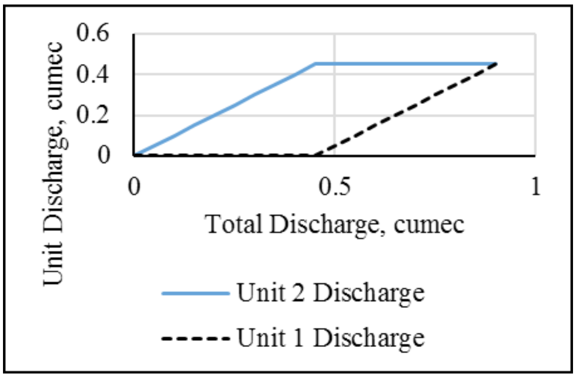


Fig. 9: Optimal Discharge Distribution of two units generating system

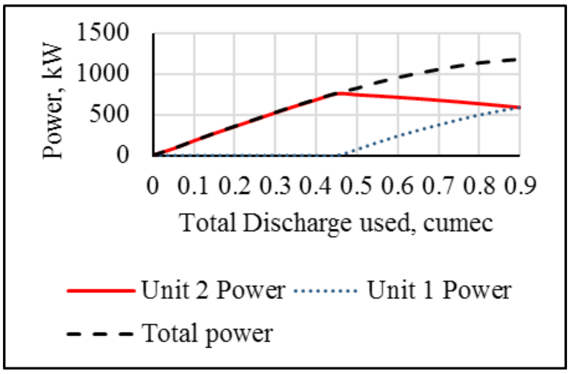


Fig. 10: Optimum power output of two units generating system

Optimum power output from two units generating system obtained after optimization process is shown in **Error! Reference source not found.**. It is seen that unit number two power is the total power since discharge is allocated to unit number two alone up to 0.45cumec, after which unit number two is also operated along with unit number one. Unit number two power decreases when total discharge increases above 0.45cumec even when unit 2 is provided with same discharge of 0.45cumec because head loss before the bifurcation increases along with total discharge which decreases net head for unit number two.

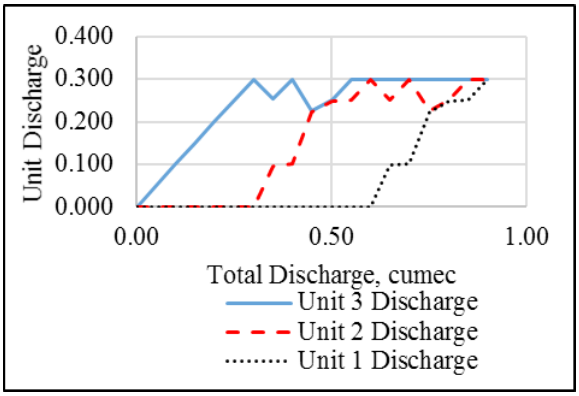


Fig. 11: Optimal discharge distribution of three units generating system

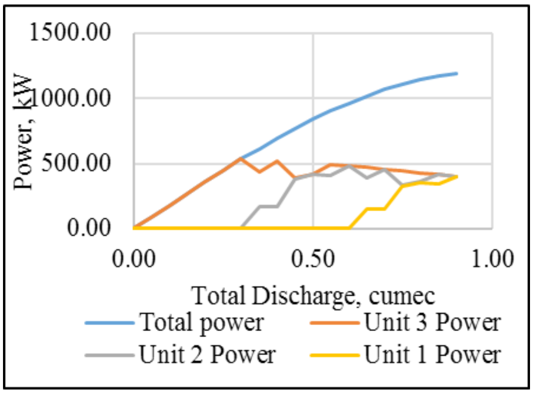


Fig. 12: Optimum power output of three units generating system

Fig. 11 above shows discharge distribution for three units generating system. Initially, only unit number three is operated, then unit number two is operated and after then unit number one is operated. Since unit number three has the shortest hydraulic path whereas unit number one has the longest hydraulic path. When total discharge exceeds the maximum operating condition of unit number three *i.e.* 0.3cumec, both unit number three and unit number two are operated with provided total discharge up to 0.6cumec. Similarly, when total discharge exceeds 0.6cumec, all three units are operated with provided total discharge up to 0.9cumec. Optimum unit power output and total power output from three units generating system obtained after optimization process is shown in **Error! Reference source not found** above.

3.7. Energy

The power generation at various flows for the upgraded SHPP has been estimated. The optimum energy generated from two unit generating system is about 8.78 GWh per annum whereas optimum energy generated from three unit generating system is about 8.84 GWh per annum.

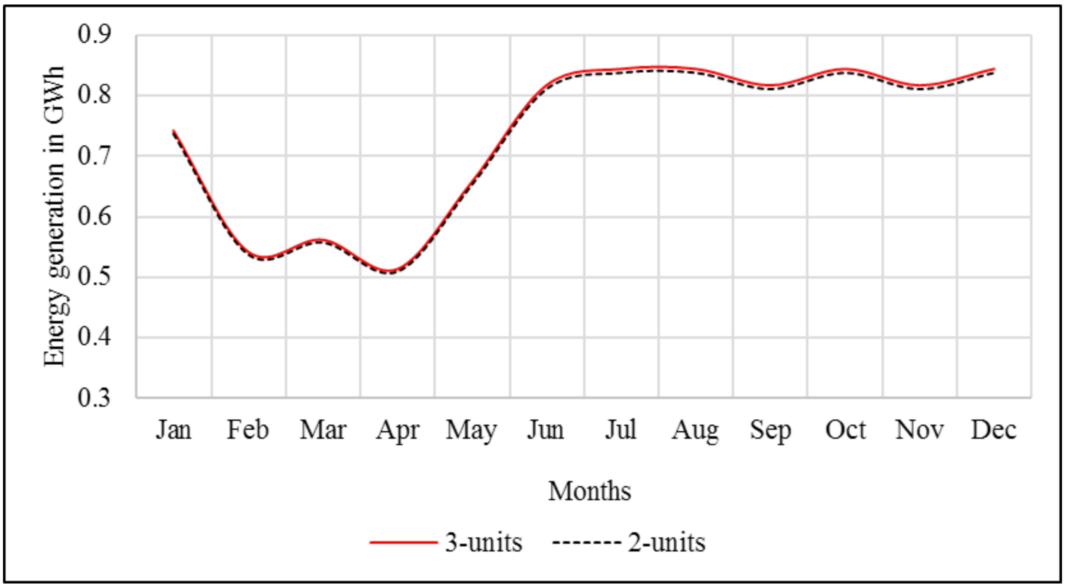


Fig. 13: Comparison of optimum energy between 2 units generating system and 3 units generating system

The energy generated from two units generating system and three units generating system is compared in Fig. 13 . The difference in energy generated two generating system and three unit generating system is only 65.92 MWh per annum. The graph shows that nearly same energy is generated by both the systems.

3.8. Financial Analysis

3.8.1 Revenue Generation

The total revenue collected from generated energy is calculated for two unit generating system and three unit generating system. The selling rate is NRs. 4.8 during wet season and NRs 8.4 during dry season as per PPA standard of NEA. [1]. The revenue collected from two generating system is NRs. 52.94 million whereas revenue generated from three unit generating system is NRs 53.34 million. The revenue generated from two generating system and three unit generating system is compared in Fig. 14. The revenue generated from both systems have difference of 0.393 million rupees. Assuming 1 USD = 100 rupees, the revenue difference will be 3.93 thousand USD per annum. The revenue generated by 2- units and 3-units is shown in Fig. 14.

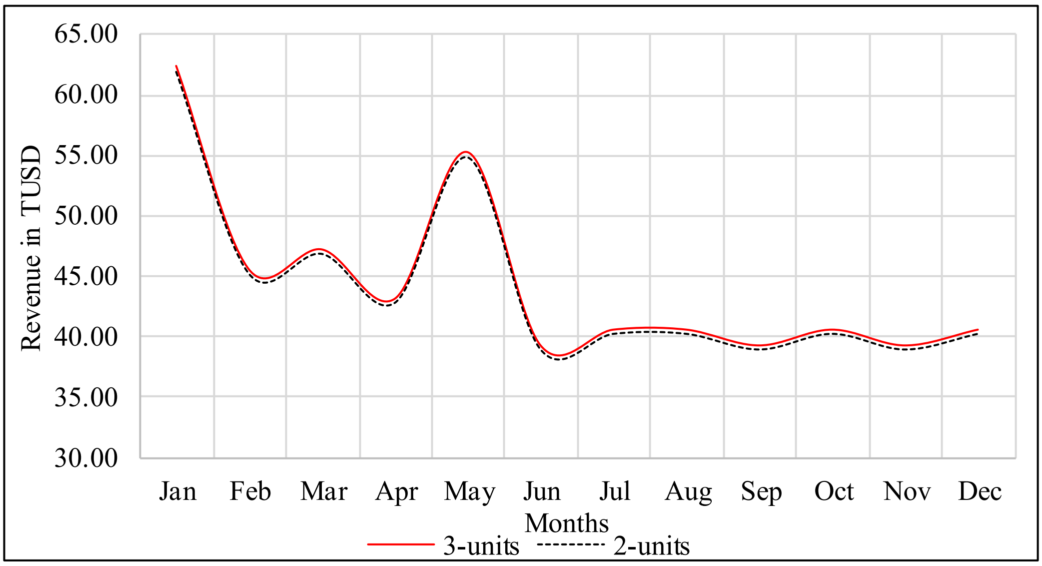


Fig. 14: Comparison of revenue generated from 2 units generating system and 3 units generating system

3.8.2 Cost Estimation

The financial evaluation for rehabilitation of Sundarijal Hydropower Plant is carried out to determine the feasibility of the project work. The preliminary estimate for upgradation to 1.1 MW capacity includes electro-mechanical cost only. The economic evaluation is performed for two different scenarios: two units generating system and three units generating system. The major cost consists of cost of electro-mechanical equipment since upgradation with carried out with replacement of electro-mechanical components. The cost of electromechanical equipment is calculated by using Gordon formula [14] as given below:

$C_{EM} = 20570 \times kW^{0.7} \times H^{-0.35}$ (2000, £)

The cost C_{EM} is in 2000 A.D. British Pound

Total capital cost for 2-units = 1,187,534.904 USD

Total capital cost for 3-units = 1,339,360.008 USD

3.8.3 Financial Evaluation

Financial analysis has been carried out by the normal discounted cash flow technique. Three tools such as Internal Rate of Return (IRR), Net Present Value (NPV) and Benefit Cost Ratio (BC ratio) have been applied. The analysis is carried out in US Dollar (USD). The following techno-economic parameters have been considered for the evaluation of this project.

Table 5: Techno-economic parameters for the evaluation of this project

Parameters	2- units generating system	3- units generating system
Installed capacity	1140 kW	1140 kW
Cost for rehabilitation works	1.187 million USD	1.339 million USD
Total annual energy production	8.78 GWh	8.84 GWh
Annual revenue	5.29 million USD	5.33 million USD
Rehabilitation duration	1.5 years	1.5 years
Discount rate	10%	10%
Evaluation period	25 years	25 years
Operation and maintenance cost	3% of the total cost	3% of the total cost

The energy generation calculation shows that only 65.92MWh more energy is generated by three units generating system than two units generating system per year. Since revenue generation depends upon energy generation, three units generating system generates NRs. 0.393 million more revenues than two units generating system per year. Financial analysis was performed to find out which system will be more beneficial as nearly equal energy is generated by both the systems.

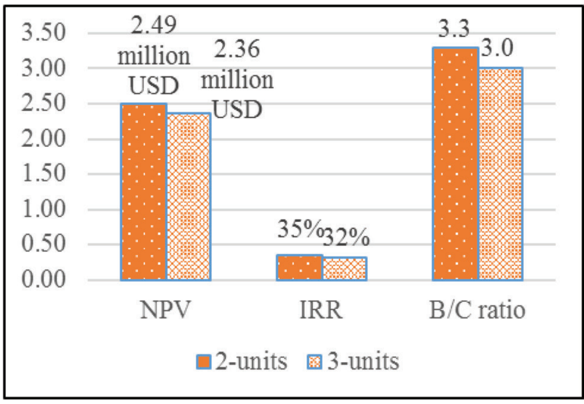


Fig. 15: Comparison of financial analysis between two units and three units system

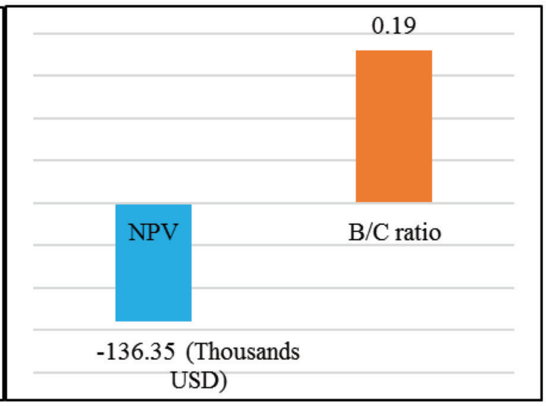


Fig. 16: Financial analysis of additional (differential) unit

The results of financial analysis show that net present worth is slightly more for upgrading with two units generating system than that with three units generating system and B/C (benefit/cost) ratio is also higher for two units generating system. Moreover, the IRR is also higher for two units generating system than three units generating system by 3%. The capital cost for upgrading the plant with three units generating system is more than upgrading with two units generating system by the margin of 0.152 million USD. The maintenance and repair cost will also be higher for three units generating system. This shows that upgradation with two units generating system is beneficial than that with three units generating system. The comparison of financial analysis between two unit and three unit system is given in figure. The cash flow analysis for additional installed unit is performed using excel program. The net present worth for the additional (differential) unit is obtained -136.34 thousands USD and B/C ratio 0.19 (which is less than one). This shows that two units generating system is beneficial over three units generating system as given in Fig.15 and 16 .

4. Conclusion

Sundarijal Hydropower Plan is the oldest hydro power plant of Nepal after Pharping Hydropower Plant, operating for more than 80 years. It has been installed with capacity of 640 kW and design generation of 5.338 GWh but it is generating less energy during recent years. The hydro and electro mechanical equipment are very old and their performance has been decreasing. It also requires frequent repair and maintenance. The study of the SHPP shows that its installed capacity can be upgraded above 1.1 MW with the available discharge at Q_{60} design. The existing civil structures, gates and penstock can be utilized for the upgradation work. The study shows that upgradation of SHPP can be carried out using the existing penstock pipe. The RLA study report and analysis shows that the civil structures are safe and can be used for upgradation with minor maintenance and repair. Analysis is carried out between two and three generating units for upgradation at optimum capacity. The optimization of the generating units is carried out to determine optimum plant capacity and energy generation capacity. The capital cost of three units generating system is higher than two units generating system by 0.152 million USD. However, difference in energy generated from three units and two units generating system is found to be 65.92MWh per year and revenue generation also differ by only 3.93 thousand USD per year. The financial analysis shows that two units generating system is more beneficial than three units generating system for upgradation at 1.1 MW installed capacity. This project shows that old and low installed capacity hydropower plants can be rehabilitated and upgraded to higher capacity using modern technology at economical capital cost. The upgraded plant can generate more energy and revenue which makes the system voltage reliable by generation of reactive power near huge load center and also boosts the economy of the nation.

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