Expansion Planning of Electricity Generating System Using the VALORAGUA and WASP-IV Models in Nepal

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Abstract: This paper presents a framework for a possible expansion plan of Nepal's electricity generation system using VALORAGUA and Wien Automatic System Planning (WASP-IV) models as examples. Given that Nepal seeks to add several hydropower plants to the Integrated National Power System (INPS) in the next few years, this type of planning is crucial. To explore potential expansion plans, the 48 hydropower plants (20 of which are currently operating) within 18 hydro networks and two diesel plants are included, and different options such as the possibility of export, seasonal variations in hydrology, and projected growth rates in gross domestic product are considered. The results illustrate the long run marginal cost (LRMC) and loss of load probability (LoLP) through 2030 in Nepal. It is found that LRMC is 3.50 Nepali Rupees per kilowatt hour at 4.1% of average LoLP. While scrutinizing the results, it is found that LoLP is higher in early stage of projections due to generation capacity limitations from 2014 to 2016. However, by the end of 2017, the LRMC and LoLP begin to decrease significantly. On this premise, the model suggests to introduce large storage plants for hydropower generation and export of that excess energy. Furthermore, a proper implementation of proposed peaking and storage plants to meet rising demand can offset the need to obtain electricity through more expensive and less environmentally-friendly means such as thermal/diesel plants.

Keywords: VALORAGUA, WASP-IV, Generation Expansion Plan, Loss of Load Probability, Long Run Marginal Cost, Hydropower, Nepal

Introduction

The perennial nature of rivers and steep gradient topography of the country provide an ideal condition for the development of hydroelectricity in Nepal. Hence, water is one of the principal physical resources that can play a vital role in enhancing the pace of overall development in Nepal. Nevertheless, despite some efforts by concerned agencies, development of hydropower projects has not risen to satisfactory levels, mainly due to insufficient funds and poor infrastructure facilities. As a result, Nepal is suffering from an acute shortage of electricity which is badly affecting people's daily lives and the nation's economic development. The Nepal Electricity Authority's (NEA) latest peak load forecast for the country's Integrated National Power System (INPS) from 2013 to 2034 shows that peak load demand in the system could grow by an average of 8.1% every year. To fulfill this future demand, hydropower projects must be developed rapidly. However, simply adding projects into Nepal's energy portfolio is not enough. There must be a vision to plan that expansion in step with Nepal's growing needs. For example, if Nepal could, hypothetically, add 3,500MW to the grid next year by way of hydroelectricity, much of that generation would go unused, not even usable for export at least in the short term. Therefore, expansion plans must account for a host of factors that will impact how and at what rate Nepal should increase its hydropower development.

Thus, the main objective of this study is to develop a generation expansion plan model with the help of numerical models namely, VALORAGUA and WASP-IV. These models evaluate the cost of electricity generation, the types and sizes of hydroplants needed, and the potential commencement dates of hydroplants in coordination with national energy demand forecasts. Hence, it is attempted to determine the optimal pattern of system expansion to meet the growing electricity demand of the country.

Materials and Methods

Data Collection and Processing

Running these calculations and projections, required a wide range of data from a variety of sources:

- Hydrological data
- Hydropower plant data
- Load data
- Thermal plants and power import data
- Costs/tariffs
- Plant characteristics
- Reservoir/pond characteristics

All hydro-meteorological data were collected from the Department of Hydrology and Meteorology (DHM, 2012) and checked for consistency. Flow data were collected over a range of 30 years. In the case of ungauged locations, data at intake sites were generated simply by catchment area ratio method (Shrestha et al, 2014).

To forecast load demand and load duration curves (LDC), the data were used from NEA annual reports. The time duration of each load step of LDC and the fraction of peak power was optimized using the auxiliary tool DIAGOPTM available within VALORAGUA model.

These data were assembled in MS-EXCEL files and MATLAB codes were written to generate data files in ASCII format for input to the VALORAGUA and WASP.

Optimization Model Using Valoragua and Wasp-IV

The flow chart in figure 1 illustrates the modelling process using VALORAGUA and WASP-IV. Using this combined software with the provided data, VALORAGUA first optimizes an operation policy for a given configuration of the power system. The end data from this step shows the individual hydroplants' capabilities and energy generation potentials, which are entered in the WASP-IV model. From here, WASP-IV calculates an optimum generation expansion plan, which includes minimum total cost and reliability factors (e.g., loss of load probability, LoLP) of the system. The long-run marginal cost (LRMC) is the basis for the calculation of the avoided cost. LRMC is the cost of providing an additional kWh of energy and the corresponding kW of capacity from the generating system in the long-run.

VALORAGUA and WASP-IV will be used repeatedly to generate LRMC under constraints inclusively or exclusively imposed. The LoLP index indicates the probability that some part of load will not be satisfied by the available generating capacity. Moreover, LoLP is defined as the ratio of days/hours per year when sufficient generating capacity is not available to serve all the daily/hourly loads. This reliability criterion is essential to fix target reliability levels (i.e., LoLP) values and to consistently analyze and compare the future reliability levels with optimum alternative expansion plans (Abdullah, 2011).

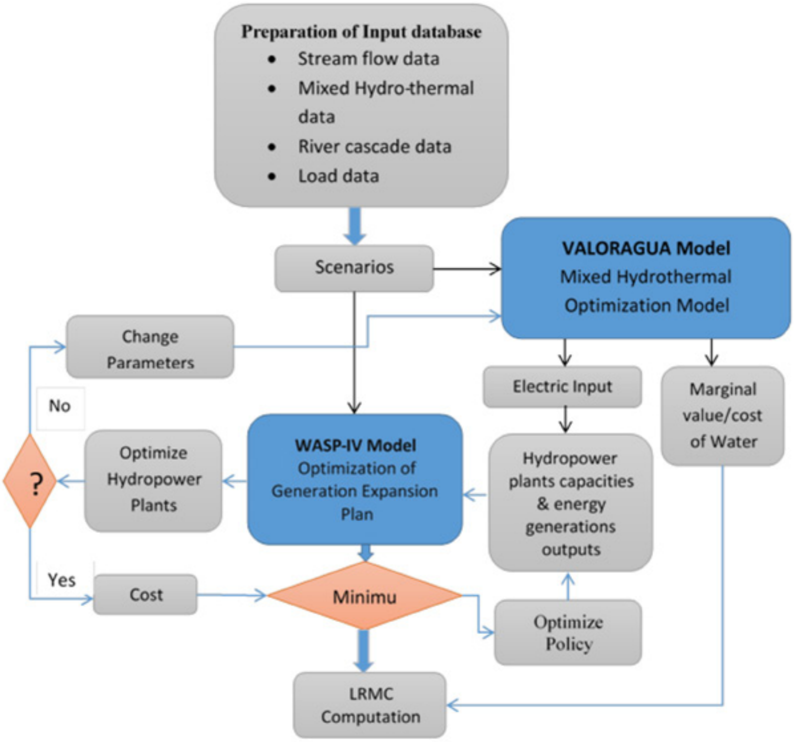

Figure 1: Flow Chart for Power Generation Expansion Plan using VALORAGUA-WASP-IV Model

VALORAGUA Model

The objective of VALORAGUA model is to determine an optimal operating strategy for the given configuration of mixed hydro-thermal electric power systems (IAEA, 1984). This computer tool essentially provides the information needed to support and to assist the decision making processes in the electricity sector. Like many optimization models, this tool has incorporated state-of-the-art mathematical techniques, to better cover the constraints and conditions in the operation of the Electric Power System. The model enables a detailed management of the electric power system, which in turn is an interconnected collection of main subsystems: production subsystem, transmission subsystem and consumption subsystem. In VALORAGUA, each component of every subsystem is completely individualized, with its identification and topological connection to the electric and/or the hydraulic network, and performs an economic or physical activity. This model takes into account the most important constraints and uncertainties that characterize the operation of mixed hydrothermal systems such as hydrological inflow fluctuations, forced outages of thermal plants, and hydro reservoir operation dynamics. The model simulates system operation over a time period for one year, for up to 30 different hydrological conditions (hydrological years).

WASP-IV Model

WASP-IV is designed to find the economically optimal generation expansion policy for an electric utility system within user-specified constraints. It utilizes probabilistic estimation of system-production costs, unserved energy cost and reliability, linear programming techniques for determining optimal dispatch policy satisfying exogenous constraints on environmental emissions, fuel availability and electricity generation by some plants, and the dynamic method of optimization for comparing the costs of alternative system expansion policies (IAEA, 2006). The WASP-IV model is aimed at finding an optimal expansion plan for a power generating system over a period of up to 30 years against the constraints imposed by the planners. The optimum option is evaluated in terms of minimum discounted total costs. The cost function to be optimized in WASP-IV is given by (1), the basic minimized cost function is represented depending on certain constraints as described below:

$$B_j = \Sigma_{t=1} (I_{j,t} - S_{j,t} + F_{j,t} + L_{j,t} + M_{j,t} + O_{j,t}) \ldots\ldots \quad (1)$$

Where,

B_j = is objective function of the expansion plan j,

t = is time in years. The values will be summed for the study period (T years)

The rest members of the equations are the discounted values to a reference date.

$I_{j,t}$ = capital investment costs

$S_{j,t}$ = salvage value of investment cost

$F_{j,t}$ = fuel costs

$L_{j,t}$ = fuel inventory costs

$M_{j,t}$ = non-fuel O&M costs and

$O_{j,t}$ = cost of the energy not served.

The optimal expansion plan is defined by Minimum

Bj among all j (IAEA, 2006).

Design of Hydraulic Network

A power system is modeled in VALORAGUA as an electricity network comprised of nodes connected by transmission lines, with each node encompassing all the thermal and hydroelectric power plants in the region. The hydroelectric plants are represented as a hydraulic network, where each plant is represented as a reservoir, with or without storage (run-of-river), connected to other plants in a cascade by waterways. Each reservoir gets natural inflow from river, if first in the cascade or incremental or intermediate inflows for downstream reservoirs. Water from one reservoir to another in the downstream flows either through turbines—thereby generating power or through spills, in excess of design flow—or when the turbine is shut off. The last reservoir in the cascade discharges into sink. All hydraulic nodes having influence from upstream inflows are kept in the same cascade.

Input Data for Model Simulation

Hourly values of daily loads and peak demands from August 2012 to July 2013 were collected to prepare the monthly load duration curve or LDC. Using VALORAGUA, these steps were followed:

1. The coefficients of the fifth order polynomial equation representing the LDC;
2. The time duration of each load step and the fraction of peak power were optimized using the auxiliary tool WASPLDC and DIAGOPTM

This is how one arrives at a peak load forecast. NEA's peak load forecast for 2011-2027 and interpolated up to 2030 is shown in figure 2.

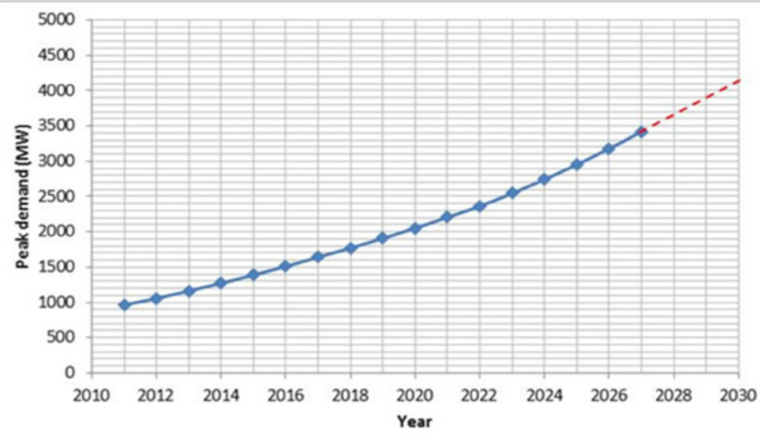

Figure 2: Peak Load Forecasted by NEA, 2010

The basic data and parameters, employed for simulation in VALORAGUA and WASP-IV are as follows:

- Simulation period = 2011 to 2030
- Periods per year = 12
- Starting year of inflow data = 1980, ending year of inflow data = 2009
- Equal probability of all hydroconditions
- Peak Load Demand = 4155 MW
- Number of load steps = 5
- Number of electric node = 1 (Nepal as a single node)
- Annual energy peak demand = 18000 GWh
- Monthly breakdown of energy demand (%): obtained from auxiliary tool DIAGOPTM 8.4 8.4 8.5 8.5 8.7 8.6 8.6 8.2 8.1 8.2 7.8 8.0
- Average energy selling price = 9 NRs/kWh, Maximum variation = 1%, maximum power supply in each month = 105 MW (About 2.5% of peak demand 4155MW for year 2030)
- Two existing thermal power plant, Hetauda and Duhabi, Nepal
- Numbers of hydro networks (hydro cascades in VALORAGUA) = 18
- Import system: Possibility of 300MW until 2015 and up to 1000MW after the construction of 400kv transmission system, considered 1000 MW in total
- No thermal addition in expansion plan
- Operation and maintenance (O & M) cost of thermal/diesel plants = 40NRs/kWh (considering current market diesel price)
- Cost of Energy not Served (ENS) = 55 NRs/kWh (referring NEA reports)
- Internal consumption fraction = 1%
- Forced outage rate = 5%
- Nominal head, nominal flow and minimum tail water level: taken from the database of hydroplants
- For Peaking Run-of-River (PRoR) and storage plants, maximum discharge of each month was taken as design discharge. For Run-of-River (RoR) projects, if the mean flow of any particular month was less than design discharge, then the mean monthly flow of that month was taken as maximum flow.
- Discount rate for domestic and foreign cost is 10%
- Plant life of thermal is considered to be 25 year
- Plant life of hydro is considered to be 50 year
- Interest during construction is taken as 10%
- Depreciation on capital cost for hydro plant is 3% per annum (25% domestic and 75% foreign)

The critical value of LoLP was taken as 25% as an initial value so that the model runs smoothly even in poor situations. The final value for each year was optimized by model.

Formation of Scenarios

Reference least cost expansion scenarios with annual breakdown of LRMC will be determined. LMRC will be calculated under each scenario with an annual breakdown of the LMRC. The four different scenarios were formulated in this study.

Reference Case

In the reference case, the existing major 23 hydroplants with thermal power plants were selected for study. The under-construction and under study hydropower projects were considered only as candidate projects. The selected existing hydropower projects and the candidate plants are shown in Table 1.

Project Name	Design discharge (m^3/s)	Installed capacity (MW)	Under construction/Candidate plants	Design discharge (m3/s)	Installed capacity (MW)
Puwa Khola	2.5	6.2	Khani Khola	5.1	30
Mai Khola	16	15.6	Baramchi Khola	0.9	4.2
Piluwa Khola	3.5	3.0	Kulekhani 3	16	14
Sipring Khola	7.5	9.6	Lower Modi 1	29	20
Khimti Khola	10.8	60	Chameliya	36	30
Middle Bhotekoshi Khola	36.8	45	Hewa Khola	8.1	15
Chakukhola	2.7	3	Phawa Khola	2.1	5
Sunkoshi Khola	2.7	2.5	Balefi Khola	25	10.6
Sunkoshi	40	10	Upper Sanjen	11.1	14.6
Indrawati III	15	7.5	Ikhuwa Khola	6	30
Chilime	8.3	22	Kabeli A	37.7	38
Trishuli	45.3	24	Lower Chepe Khola	7.5	8.3
Devighat	45.3	15	Maiwa Khola	8.1	13.5
Kulekhani 1	12.1	60	Lower Sanjen	11.6	42.5
Kulekhani 2	13.5	32	Balephi B	30	18.5
Middle Marsyangdi	80	70	Trishuli 3B	51	37
Khudi Khola	4.6	4	Upper Marsyangdi	48.7	45
Marsyangdi	91.5	69	Upper Tamakoshi	66	456
Bijaypur Khola	8.3	4.5	Rasuwagadhi	80	111
Modi Khola	27.5	15	Upper Tamor	10.5	415
Kali Gandaki 'A'	134	144	Middle Tamor	105	75
Andhikhola	4.9	9.4	Trishuli 3A	51	60
Jhimrukkhola	36	12	Budhi Gandaki	430	600
Total		**643.30**	**Total**		**2093.2**

Table 1: Selected existing and candidate hydropower plants

The existing Hetauda Diesel plant (10 MW) and Duhabi Thermal Plant (39.5 MW) have been included as the thermal power plants. According to this scenario, the total installed capacity for Nepal will be 2,786MW by the end of 2030 but the forecasted load for 2030 is 4,155 MW. Hence, this expansion plan will be insufficient to meet the energy demands for a 20 year time horizon. In order to overcome this power deficit, hydropower plants under construction and under study have to be considered in the expansion plan. So, the expansion plan was revised by including the 20 existing hydroplants and 28 candidate plants, which will include several storage projects. The expansion plan required to meet the forecasted demand in 2030 is presented in Table 2.

According to this expansion plan, by 2030 it will be possible to generate 4,388MW of energy to meet the need for 4,155MW domestically. Hence, above table shows the selected existing and candidate hydroplants for the Reference Case. No additional thermal/diesel plants were considered for this expansion plan however existing Hetauda and Duhabi Diesel plants have included for simulation.

Power Export Case

In this case, it was assumed that there will be possibility of exporting up to 700 MW electricity in addition to the Reference Case scenario. So that the load demand was higher in this case than in the Reference Case and remaining all other conditions same as in the Reference Case.

Seasonal Variation Case

In this case, the seasonal variation of hydrology has been considered remaining all other conditions same as in the Reference Case scenario. The seasonal variation of hydrology assesses the hydrological risk and thus the probability values of hydro conditions will be different than in the Reference case. For this case, 30 year hydrological data were analyzed and according to their flow patterns, these inflow data were divided into dry, wet and mean hydrological years. Specifically, the year in which flow is higher than that of mean year is considered as a wet hydrological year and in which lower flow was considered as a dry hydrological year. The 1980, 1983, 1988, 1997 and 2007 were considered as dry years, 1986, 1995, 1998, 2000 and 2007 were considered as wet years and remaining years were considered as mean years.

Growth in Gross Domestic Product (GDP) Case

In this case, the power demand of the Reference Case scenario has increased considering 5% and 7.5% of GDP growth. Hence, the load demand will be increased according to increase in the GDP growth rates.

Results

Input data for both VALORAGUA and WASP-IV models have been prepared for all considered scenarios as explained above. The LRMC was computed for each of the different scenarios by perturbation approach. After determining the reference optimized expansion plan and reference LRMC, monetary values for different sets of candidate hydropower plants were determined.

Existing Plants	Installed capacity (MW)	Candidate Projects	Installed capacity (MW)
Kali Gandaki	144	Upper Tamakoshi	456
Middle Marsyangdi	70	Rasuwagadhi	111
Marsyangdi	69	Middle Bhotekoshi	102
Kulekhani-1	60	Trishuli3A	60
Kulekhani-2	32	Tanahu Storage (SETI)	128
khimti-1	60	Budhi Gandaki Storage	600
upper Bhotekoshi	45	Dudh Koshi Storage	300
Puwa Khola	6.2	Nalsing Gad Storage	400
Mai Khola	15.6	West Seti Storage	750
Piluwa Khola	3.0	Middle Tamor	75
Siprin Khola	9.6	Upper Tamor	415
Chakukhola	3	Baramchi	4
Sunkoshi small	2.5	Kulekhani-3	14
Sunkoshi	10	Lower Modi	20
Chilime	22	Chameliya	30
Trishuli	24	Hewa Khola	15
Devighat	15	Rahughat	32
Khudi	4	Phawa Khola	5
Modi	15	Balephi-A	11
Jhimruk	12	Upper Sanjen	15
Total	**622**	Ikhuwa Khola	19
		Kabeli-A	38
		Lower Chepe	8
		Maiwa Khola	14
		Lower Sanjen	43
		Balephi-B	19
		Trishuli 3B	37
		Upper Marsyangdi	45
		Total	**3766**

Table 2: Selected existing and candidate hydropower plants for the Reference Case

Figure 3 shows the variation of LRMC and critical value of LoLP for the simulation period from 2011 to 2030 for the reference case scenario. The figure illustrates that the LRMC in this scenario decreases with a decrease in LoLP through the time period of model simulation. The values of LRMC and LoLP are maximum in 2014 and are 13.10 NRs/kWh and 18.71% respectively. Similarly, the minimum values of LRMC and LoLP are 0.70 NRs/kWh and 0.016%, respectively, in 2029. Hence, it can be concluded that the LRMC and LoLP decrease as time passes for this expansion plan. This is due to large storage hydropower projects that will be introduced to the expansion plan and start to generate energy by 2017.

The results of model simulation for different scenarios are presented here in Table 3:

From the Table 3, it is found that the LRMC for the power export case scenario is slightly less than the Reference case. In the power export case, the excess energy will be exported to neighboring countries. However, the LoLP has been increased to 4.20%, and this may be due to increases in load demand.

Moreover, the LRMC for the dry season is higher than the wet season due to a decrease in generation of power during dry years (figure 5). While analyzing figure 5, it can be seen that the given expansion plan cannot fulfill the load from 2025 because it has higher LoLP values. So, this result suggests that to fulfill demand at dry period, it needs more storage and peaking hydroplants or other means of energy sources.

Furthermore, in case of a 5.5% projected GDP growth rate, the result is quite similar with the Reference Case and, LRMC and LOLP are comparatively very lower than in case of a 7.5% projected GDP growth rate (figure 6). Similarly, in case of a 7.5% projected GDP growth rate, the result (figure 6) shows a similarity to the dry/wet season comparison. Moreover, the LRMC increases with the increase in GDP growth rates due to increment of load in this case. Again, the LoLP results also coordinate with LRMC results for this case. In this way, it can be concluded that run-of-river, peaking run-of-river, and some storage plants will be the best option for Nepal to optimally meet its future energy demands.

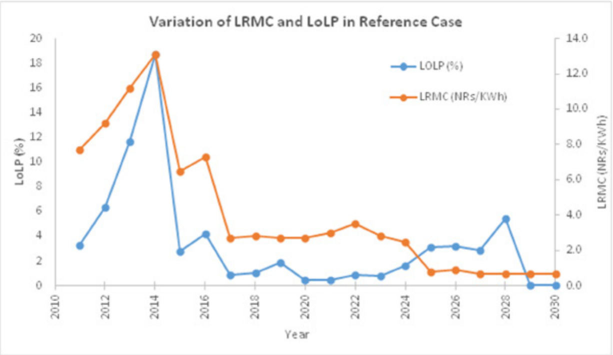

Figure 3: Variation of LRMC and LoLP in Reference Case

Scenario	Case	LRMC (NRs/kWh)	LoLP(%)
1.	Reference	3.5	4.10
2.	Power Export	3.2	4.20
3.	Dry season	12.0	32.35
	Wet season	5.0	4.53
4.	5.5% growth of GDP	4.2	6.70
	7.5% growth of GDP	6.6	18.00

Table 3: LRMC and LoLP comparison for different scenarios

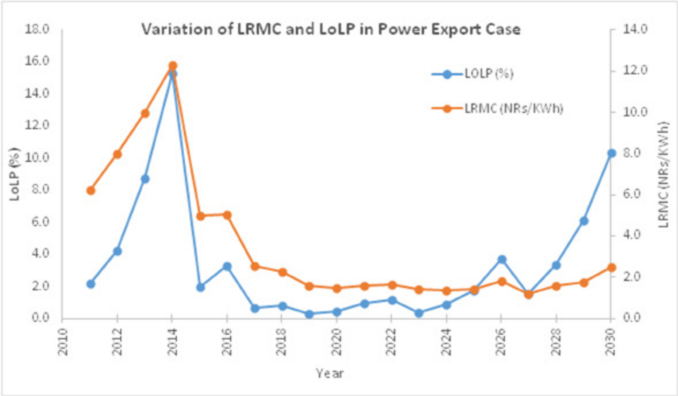

Figure 4: Variation of LRMC and LoLP in Power Export Case

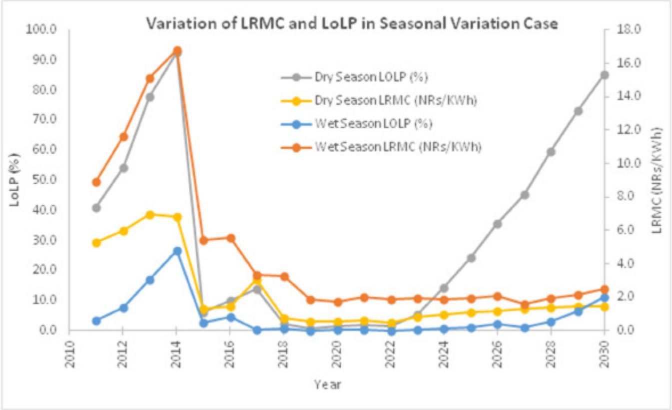

Figure 5: Variation of LRMC and LoLP in Seasonal Variation Case

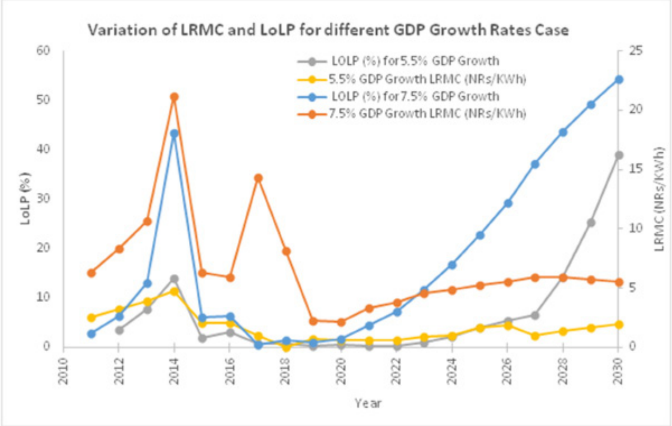

Figure 6: Variation of LRMC and LoLP for different GDP Growth Rates Case

Conclusion

Nepal is suffering acute shortages of electricity, which is affecting daily life and national development. Hence, hydropower development is a key to improving economic development of Nepal.

In this paper, the simulations of expansion planning were run using VALORAGUA and WASP-IV models for the present day through 2030, paying attention to LRMC and LoLP values. Specifically, it was found that the optimal expansion plan has high LoLP values in the early stage of simulation period because of limited generation capacity. However, by the end of 2017, LRMC and LoLP decrease significantly as storage plants come online. Therefore, timely implementation of proposed peaking and storage plants in Nepal is a key to meet the sharply increasing demands for electricity.

The VALORAGUA model is specifically useful for short term optimization. If there is a need to optimize the expansion plan up to 30 years, the WASP-IV model is useful. Hence, this model significantly aid to the energy system planners and decision makers to solve the energy issues in generation expansion planning. Moreover, this study can be used as a reference generation expansion plan to find an optimal investment plans in context of Nepalese hydropower. However, the uncertainties in future load demand, time required for the construction of large storage hydro plants and cross-border power grid can affect the system reliability levels as well as LRMC of the expansion plan.

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