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# Benchmarking Results of Electricity Generating Plants in Nepal Using Modified DEA Models

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This paper analyzes performance of the hydropower plants owned by Nepal Electricity Authority (NEA), through investigation of operational relative efficiency of the respective plants. NEA is sole owner and operator of the Integrated Nepal Power Systems (INPS) which, covers over 95% of the total electrified area of the country. Modified DEA model, based on expert's opinion as well as available economic parameters, has been formulated to analyze operational performance of the hydropower plants. The model incorporates a wide range of inputs and outputs capturing essence of electricity production process by the hydropower plants. The results obtained are compared against those from conventional DEA model. Sensitivity analysis is carried out in order to investigate the robustness of the results and to identify the improvement directions for each hydropower plant. Based on the results of the sensitivity analysis, strengths and weaknesses of individual plants are identified.

**Keywords**: Data Envelopment Analysis (DEA), Hydropower plants, Performance evaluation, Sensitivity analysis

## 1. Introduction

Efficiency measurements have been carried out in the power and energy sector for many years. In this era of restructuring and privatization of vertically integrated electric utilities around the world, productivity assessment has become a serious matter of concern. Various reports generated due to the research studies on organizational performances have pressurized the decision makers to be more concerned about finding ways to improve productivity.

Among many possible productivity-efficiency measurement approaches, Data Envelopment Analysis (DEA) is probably the most widely used mathematical approach for benchmarking of organizational units. It was first proposed by Charnes et al. to evaluate the efficiency of organizations involving multiple inputs and outputs [1,7]. It is a linear programming based relative efficiency measurement tool, which uses optimization technique to automatically calculate the weights assigned to the inputs and outputs of the production units being accessed. The actual input and output variables are then multiplied with the weights to determine the efficiency of the Decision Making Units (DMUs). Since its introduction, DEA has undergone several modifications and developments. Application of DEA in power system is not a recent phenomenon. DEA has been used to assess the performance of several electricity generation and distribution systems in the recent past [3-5, 12-17, 19-24].

Hydropower plants are one of the major sources of electrical energy as they continue to produce around 24% of the world's total electricity needs [6]. Electric Supply Industry (ESI) in countries like Nepal is hydro-dominated since more than 90% of the electricity demand is met by the hydropower plants [10]. There is huge investment in this sector; therefore, even a small operational improvement can result in saving of significant amount of money. Determining the performance of each hydropower plant and comparing one another can help identify the poor performers. Afterwards, those inefficient plants can be studied and improvement directions can be suggested on to enhance their performance. Therefore it is important to investigate the operational efficiency of the hydropower plants.

During the recent study on measuring efficiency of Nepalese hydropower plants using classical DEA models [3,4], the authors found that some of the hydropower plants were highly efficient mainly due to a single variable or some specific set of variables. The results of sensitivity analysis revealed that the variation in efficiency scores was very high for some of the power plants, and possibly, the true efficiency might have been masked. As a matter of fact, the original DEA model has one serious drawback that it allows total flexibility in allocating weights to the input and output data of the DMU under consideration. This can lead to artificially high efficiency scores, and might suggest an operating target which is not feasible. The model sometimes assigns excessively high weight to a less significant variable to make the DMU efficient. Although, some degree of weight flexibility is desired since it allows the DMUs to reflect their particular state, however, complete flexibility, at times, becomes unacceptable as most of the DMUs employ similar technologies, pay similar prices for inputs, produce the same kind of outputs, and have the same overall objectives [2].

In the previous studies [3,4], some important parameters related to reliability and storage capacity of the hydropower plants were left out while assessing their performance. In addition to this, prior views or available information were not incorporated in the model used in those studies. For example, Kulekhani-I, which is a storage type plant, was analyzed with the run-off-the river (ROR) type hydropower plants on the same ground. There were some critical views presented by the concerned experts over the issue arguing that the analysis should be made comprehensive by incorporating available information about the DMUs.

The previous study has analyzed the hydropower plants owned by Nepal Electricity Authority (NEA) by considering multi-period data of the same power plant as

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separate DMUs. DEA, in its conventional form, allows almost total flexibility in the selection of weights, especially if fewer DMUs are included in the analysis. With a conventional DEA model, selection of inputs and outputs affects the discriminatory power of DEA as the number of variables selected needs to be ‘sufficiently small’ compared to the total number of DMUs for effective discrimination [2,5]. The reason for this is obvious: if the number of DMUs is close to the number of inputs and outputs, it is quite likely that almost all the DMUs will be deemed efficient.

The most widespread method of introducing the decision maker’s judgment into the classical DEA technique is, probably, the inclusion of restriction on weights. These DEA models are known as weight restriction DEA models. However, the efficiency scores calculated by the weight restriction DEA models are sensitive to the weight bounds; it becomes, sometimes, unacceptable for the organizations to take suggested action based on the DEA results, if the decision maker’s opinion regarding the DMUs is not judiciously incorporated during the analysis [2].

This study aims to benchmark the hydropower plants owned by NEA using weight restricted DEA model. A model is formulated including Assurance Region (AR) type constraints and ordering of weights. The upper and lower bounds for the weights are set up based on the market price information as well as expert’s views. Sufficient number of variables reflecting the electricity production process is incorporated in this analysis for a more comprehensive comparison of the hydropower plants. Since the decision maker’s prior experience and expert’s opinion regarding the operation of the plants has been judiciously included, we assume that utility can benefit from this analysis.

The rest of the paper is organized as follows: section 2 discusses the conventional CCR DEA model, followed by the proposed model of this study. The variables (inputs and outputs) selected for carrying out the analysis are also explained. Section 3summarizes the data set used in the study, where as, section 4 includes the results and discussions. Sensitivity analysis has been done in section 5, and finally, in section 6, we present the concluding remarks.

## 2. Methodology

[Notations]

$\theta_0$ .......... *Efficiency score of the current DMU $j_0$*
$y_{rj}$ .......... *Amount of output r from DMU j*
$x_{ij}$ .......... *Amount of input i to DMU j*
*n* .......... *Number of units (DMUs)*
*t* .......... *Number of outputs*
*m* .......... *Number of inputs*
*ε* .......... *A small positive number*
*Following are the weights assigned to:*
$u_r$ .......... *output r*
$v_i$ .......... *input i*
$v_{O\&M\ cost}$ .......... *annual O&M cost*
$v_{inst\text{-}cap}$ .......... *installed capacity*
$v_{staff\text{-}perm}$ .......... *number of permanent staff*
$v_{staff\text{-}temp}$ .......... *number of temporary staff*
$v_{trip\text{-}full}$ .......... *plant tripping*
$v_{trip\text{-}partial}$ .......... *unit tripping*
$u_{energy\text{-}dmonth}$ .......... *energy generation in the driest month*
$u_{annual\text{-}energy}$ .......... *annual energy generation*
$u_{winter\text{-}peak}$ .......... *winter season peaking capacity*
$u_{summer\text{-}peak}$ .......... *summer season peaking capacity*

The DEA model developed originally by Charnes, Cooper and Rhodes (known as CCR model) in linear form is given by [1]:

$$\begin{aligned}
&\textit{Maximize} \quad \theta_0 = \sum_r u_r y_{rj0} \\
&\textit{Subject to} \\
&\sum_i v_i x_{ij0} = 1 \qquad \textit{for } j = 1 \textit{ to } n \qquad (1) \\
&\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \le 0 \\
&u_r, v_i \ge \varepsilon \qquad \textit{for } r = 1 \textit{ to } t \textit{ and } i = 1 \textit{ to } m
\end{aligned}$$

Here, $y_{rj0}$ and $x_{ij0}$ denote the current DMU of which efficiency is being maximized whereas *n* is the number of DMUs under consideration. In each optimization run the efficiency of a specific DMU is maximized and it is then repeated for all the DMUs.

In conventional DEA models, weight flexibility allows different DMUs to assign vastly different weights to the same factor. The argument in favor of this is that different DMUs have different circumstances, and therefore, one factor may be more important to one DMU compared to another DMU. However, complete flexibility becomes unacceptable as most of the DMUs employ similar technologies, pay similar prices for inputs, produce the same kind of outputs, and have the same overall objectives [2].

In addition to eliminating the drawbacks of unbounded DEA models, weight restrictions also serve some additional purposes as listed below:

1. To ensure incorporation of all inputs and outputs in the assessment of performance
2. To incorporate prior views on the values of individual inputs and outputs
3. To relate values of certain inputs with values of certain outputs
4. To move from technical efficiency measurement to overall efficiency measurement
5. To enable discrimination among efficient units

In this study, we have formulated a model to evaluate the performance of the NEA hydropower plants based on the concepts of Assurance Region (AR) type I DEA model. The data set is modified in a way to incorporate the categorical inputs. The AR I type relations are introduced to accomplish either of the following two purposes:

1. Incorporate the relative ordering of inputs/outputs
2. Incorporate information on prices or values of inputs/outputs.

In these types of constraints, upper and lower bounds are imposed on the ratios of factor weights. Bounds are determined using market price information [6]. If price information is not available, then expert's opinion on the relative importance of the inputs/outputs is used to determine the bounds [7]. Thus, an AR model represents a move from measurement of technical efficiency to measurement of overall efficiency [2].

We found it difficult to identify the price based information for all the variables used in the present analysis. As a result, we used expert's opinion based information where no distinct price based information was available. Alternative preference structures over weights on some of the input-output variables were also applied. Before explaining the model used in the analysis, we present the details of inputs and outputs considered for this study to facilitate better understanding of the proposed model. We have incorporated a wide range of variables involved in the electricity production process in hydropower plants. The following is the list of inputs and outputs included in the analysis:

**Inputs:**

1. *Installed capacity of the plant*: This represents the gross capacity of the power plant in MW.
2. *Annual O&M cost:* It is the annual expenditure for both labor and non-labor inputs expressed in '000 of Rupees.
3. *Number of staff (Permanent):* The number of personnel working at respective NEA power stations having permanent status.
4. *Number of staff (Temporary/Contract):* The number of personnel working at respective NEA power stations having temporary status, or working under contract basis.
5. *Plant tripping:* This represents the number of times the plant (all units of the plant) tripped suddenly.
6. *Unit tripping:* This represents the number of times some units of the plant tripped suddenly.

**Outputs:**

1. *Annual energy generation:* This represents the gross energy generated annually by a plant in GWh.
2. *Energy generated in the driest month:* This is the energy generated by the plant during the driest month of the year (May-June). It is measured in GWh.
3. *Summer season peaking capacity:* It is the maximum power output by power plants measured in MW during the system peak in summer season.
4. *Winter season peaking capacity:* It is the maximum power output of the hydropower plants measured in MW during the system peak in winter season.

**Categorical inputs**:

1. *Storage type plant:* Plants having a big storage reservoir with an ability to generate electricity for more than 24 hours continuously at its rated capacity.
2. *Peaking storage type plant:* Plants having a small reservoir with an ability to take up increased demand during peak hours.

In this analysis, we have proposed a way to redefine the actual input/output data set to incorporate categorical inputs. The categorical inputs are not dealt with separately in the analysis, hence simplifying the DEA model. The proposed model formulated to analyze the performance of hydropower plants of NEA is given below:

$$\text{Maximize} \quad \theta_0 = \sum_r u_r y_{rj0}$$

$$\text{Subject to}$$

$$\sum_i v_i x_{ij0} = 1$$

$$\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \leq 0$$

$$v_{O\&M\,\cos t} \geq v_{inst-cap}$$

$$v_{O\&M\,\cos t} \geq v_{staff-perm}$$

$$LB_1 \leq \frac{v_{staff-perm}}{v_{staff-temp}} \leq UB_1 \qquad \text{.....................................} \; (2)$$

$$v_{trip-full} \geq K * v_{trip-partial}$$

$$u_{energy-dmonth} \geq u_{annual-energy}$$

$$u_{\mathrm{wint}\,er-peak} \geq u_{annual-energy}$$

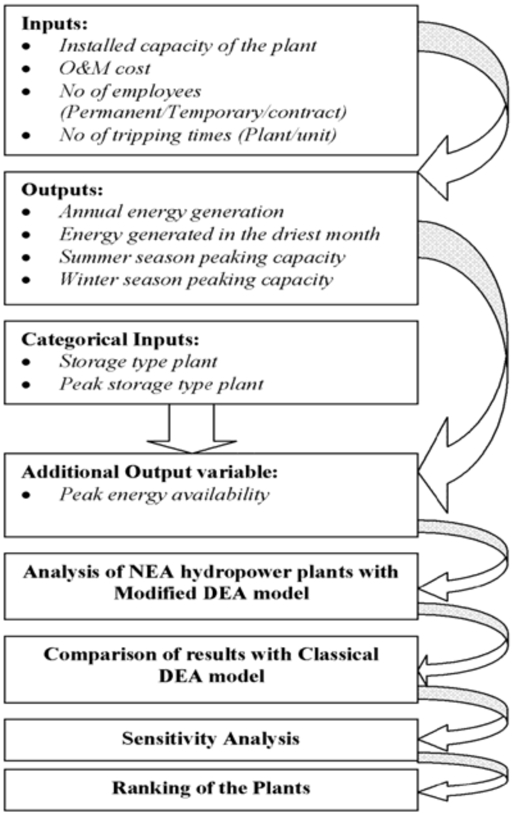
$$LB_2 \leq \frac{u_{\mathrm{wint}\,er-peak}}{u_{summer-peak}} \leq UB_2$$

$$u_r, v_i \geq \varepsilon \qquad \textit{for } r = 1 \textit{ to } t \textit{ and } i = 1 \textit{ to } m$$

Here, in the proposed DEA model, we have introduced a number of features. First, the input/output data set is redefined based on the categorical inputs, thus, eliminating a complex procedure of inclusion of categorical inputs separately in the analysis. Next, we have used the ordering of weights approach for some of the input/output weights for which no quantitative information was available. Also some additional constraints are added for some of the weights, based on expert's opinion on some of the weights. Finally, we have used the Assurance Region approach for some of the variables of where the weights are supposed to vary within a specified range. Programs written in General Algebraic Modeling Systems (GAMS) are executed to obtain the results.

With the modification of data set based on the categorical inputs, we identified a variable called *peak energy availability*, which is defined as the energy that a plant can potentially generate during a day in dry season at peak capacity. It is measured in MWh. By introducing this variable in the analysis, the peak energy generation capacity differing for individual plants according to its storage capacity can be incorporated. For example, Kaligandaki hydropower plant has a daily storage capacity of around 5 hours; therefore, the peak energy availability for Kaligandaki will be 144MW X 5hrs = 720MWh.

The following is a block diagram illustrating the sequence of events considered in this study:



## 3. Results and Discussion

operational data of NEA owned grid-connected hydropower plants for fiscal year 2004/05 are used to run the model (2). Programs written in General Algebraic Modeling Systems (GAMS) are executed to obtain the results presented in Table I. To facilitate comparison, efficiency scores of the hydropower plants with CCR model are also included.

Table I: Overall Efficiency of the Hydropower Plants

| Power plants | Efficiency with modified DEA model | Efficiency with CCR DEA model |
|---|---|---|
| Kaligandaki | 1 | 1 |
| Marsyangdi | 1 | 1 |
| Kulekhani I | 1 | 1 |
| Kulekhani II | 0.894 | 0.993 |
| Trishuli | 0.742 | 1 |
| Gandak | 0.200 | 0.533 |
| Modi Khola | 0.452 | 1 |
| Devighat | 0.664 | 1 |
| Sun Koshi | 0.256 | 0.995 |
| Puwa Khola | 0.277 | 1 |
| Chatara | 0.395 | 0.604 |
| Seti | 0.138 | 0.667 |
| Phewa | 0.325 | 1 |
| Panauti | 0.153 | 1 |
| Sundarijal | 0.214 | 1 |

It is clear that for smaller number of DMUs, if variables selected for the analysis are close to the number of DMUs, the classical DEA model looses its discriminatory power (2, 6). Ten out of total fifteen hydropower plants are found to be efficient with the classical (CCR) DEA model. With the modified DEA model proposed for this study, incorporating information based on economic value and expert's opinion, we found that the average overall efficiency of the NEA hydropower plants is 51.4%. Results show that only three hydropower plants (Kaligandaki, Marsyangdi, and Kulekhani I) are overall efficient. In the previous analysis [2-3], Kulekhani I was found to be inefficient in the FY 2004/05. But in this analysis, It is declared efficient thanks to the inclusion of the information that it has a big storage reservoir, which enables it to generate more power to meet peak demand in the system. Kulekhani I is also used during off-peak conditions in winter season when most of the run-off-the-river plants fail to produce designated amount of power owing to low discharge in the respective rivers. Kulekhani I was found to have better reliability figures as well. However, 60% of the hydropower plants showed poor efficiency scores. Seti and Panauti displayed the worst performance in the FY 2004/05.

We believe that the results obtained through the analysis are far comprehensive than the previous results [2-4], as wide range of operational data has been included. The modified DEA model consists of expert's opinion as well as information available regarding the operation of the plants based on economic parameters and it does not necessarily require multi-period data of the same plants to be considered as separate DMUs.

## 4. Sensitivity Analysis

Sensitivity analysis is a very important aspect of DEA to evaluate the robustness of the results. Since DEA is a data based analysis, any error in the data set can change the results. Sensitivity analysis has been carried out in a number of ways in the literatures. In this study, we assume that the data set is correct and precise, as it is taken from various sources of NEA. So, we have carried out the sensitivity analysis based on removal of variables one by one from the data set, and finding out the efficiency scores to check the robustness of the DEA results [5].

Table II summarizes the results of sensitivity analysis carried out to check the robustness of the results (efficiency scores) obtained for hydropower plants.

Table II: Performance Report of the Hydropower Plants

| Power Plants | Change in efficiency score | Strengths | Weaknesses |
|---|---|---|---|
| Kaligandaki | 0.969 to 1 | Plant tripping | |
| Marsyangdi | 0.97 to 1 | Annual energy generation | |
| Kulekhani I | No variation | | |
| Kulekhani II | 0.532 to 0.989 | Plant tripping | Annual O&M cost, No of permanent staff |

| | | | |
|---|---|---|---|
| Trishuli | 0.547 to 1 | Plant tripping, energy generation in the driest month | No of permanent staff, annual O&M cost |
| Gandak | 0.146 to 0.454 | Plant tripping, energy generation in the driest month | Annual O&M cost |
| Modi Khola | 0.423 to 0.75 | Annual energy generation, plant tripping | Annual O&M cost, winter season peaking capacity |
| Devighat | 0.491 to 1 | Plant tripping, energy generation in the driest month | Annual O&M cost, No of permanent staff |
| Sun Koshi | 0.207 to 0.813 | Annual energy generation, plant tripping | Annual O&M cost, No of permanent staff |
| Puwa Khola | 0.225 to 0.96 | Annual energy generation | Annual O&M cost, No of permanent staff, winter peaking capacity |
| Chatara | 0.395 to 0.475 | | Annual O&M cost, No of temporary staff |
| Seti | 0.119 to 0.563 | Summer season peaking capacity | Annual O&M cost, winter season peaking capacity |
| Phewa | 0.293 to 1 | Annual energy generation | No of permanent staff, annual O&M cost, energy generation in the driest month |
| Panauti | 0.153 to 1 | | Annual O&M cost, No of permanent staff |
| Sundarijal | 0.178 to 1 | Annual energy generation | Annual O&M cost, energy generation in the driest month |

The results show that Kulekhani I displayed 100% efficiency score throughout, whereas, Kaligandaki and Marsyangdi had a marginal variation in their efficiency scores. We have also identified the strengths and weaknesses of the plants, and summarized them in Table II. It is observed that most of the plants are deemed inefficient due to overuse of annual O&M cost. Based on the performance during the sensitivity analysis, we ranked the plants according to their average efficiency scores. Table III presents the ranking of NEA owned hydropower plants during the FY 2004/05:

TABLE III: RANKING OF NEA OWNED HYDROPOWER PLANTS

| Power plants | Average overall efficiency score | Rank |
|---|---|---|
| Kulekhani I | 1 | 1 |
| Marsyangdi | 0.998 | 2 |
| Kaligandaki | 0.997 | 3 |
| Kulekhani II | 0.853 | 4 |
| Trishuli | 0.764 | 5 |
| Devighat | 0.692 | 6 |
| Modi Khola | 0.482 | 7 |
| Phewa | 0.433 | 8 |
| Chatara | 0.402 | 9 |
| Puwa Khola | 0.356 | 10 |
| Sun Koshi | 0.297 | 11 |
| Panauti | 0.294 | 12 |
| Sundarijal | 0.274 | 13 |
| Gandak | 0.215 | 14 |
| Seti | 0.174 | 15 |

Interestingly, plants like Trishuli have displayed good efficiency index in contrast to the results shown in the previous analysis [3]. This is mainly due to its high reliability and its capability to generate good amount of energy even in the driest month. In the previous analysis, variables like *plant tripping* and *energy generation in the driest month* were not included. We are convinced that the ranking results match the real scenario. Kulekhani I, being the only power plant with big storage reservoir, understandingly, secures the best position in the hierarchy.

## 5. Improvement Directions

Improvement directions are identified for the utility (NEA in the present case) based on the DEA analysis. The utility should emphasize on the strengths and weaknesses of the DMUs, and take actions to improve their performance accordingly. For most of the hydropower plants owned by NEA, the number of employees and annual O&M expenditure are very high, resulting in the poor efficiency scores of the plants. Ideally, the resources used by a plant should be decreased proportionally to the lowest possible level, as suggested by its efficiency score, in order to make the plant efficient. For example, Kulekhani II, with efficiency score of just over 89%, should try to decrease its inputs by around 11%. Emphasis should be given to the results revealed by performance report of the plants. However, it might not be always possible to reduce all the inputs by the specified proportion.

## 6. Conclusion

The present study has many merits compared to the previous studies conducted for the same purpose [3,4]. This analysis does not necessarily require a large set of data (multi-period data) to have a proper discrimination in the results. The analysis has included a wide range of variables to make it a comprehensive one. The constraints of the proposed DEA model can be modified based on the possible changes in the operational features, or economic considerations during future analysis.

In this study, we have formulated a weight restriction type DEA model to evaluate the performance of hydropower plants owned by NEA based on operational data as well as the pre-known features regarding the operation of the plants. Decision-maker's preferences and expert's opinion are included in the DEA model. However, this analysis should not be sought as applicable for a specific set of hydropower plants; rather, the idea can be extended to analyze the performance of other system of hydropower plants involving different operational features.

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