# Economic Valuation of Storage in a Power System: A Case of Pumped Storage with Solar PV

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***Abstract*— The paper formulates a unit commitment problem with the objective to minimize the overall cost of system operation while fulfilling the system constraints for a power system characterizing, thermal, pumped hydro and PV generation plants along with demand. The model is applied with and without the presence of the pumping capability of the PHES unit for a 6-bus test system. Comparison of overall system cost for the demand to be met allows us to assess the economic impact of the storage characteristics in a PHES. The results indicate a reduction in overall cost of system operation by 26.5%. The paper also calculates the economic value of pump storage in the power system with VRE sources like solar PV.**

**Keywords- economic operation, large scale renewables, PHES, SCUC, Solar PV.**

## I. Introduction

Most of world's electrical energy requirements are currently fulfilled from conventional energy resources such as oil and coal. As of 2015, oil and coal together provided 62.14% of the world's total electricity followed by natural gas (23.85%), hydro (6.79%), nuclear (4.3%) and other renewable sources [1]. As of 2014, India's electricity consumption is 805 kWh per capita which is much lower compared to the global average of 3144 kWh per capita. Since 1990 the country has recorded significant growth in electricity generation. The gross utility electricity generation of the country is recorded to be 1,236 billion kWh during the year 2016-17. As of April 2017, coal accounts for 76.4%, gas- 3.9%, oil – 0.03%, nuclear – 3.04%, hydro 9.9% and renewable sources 6.6 % respectively of the total generation. In past few years, the power industry observed a significant annual growth in the share of renewable sources for electricity generation. The share of renewable energy resources in electricity generation capacity grew up to 6.47% in year 2015 and went as high as 14.58% in the year 2016. [2].

Driven by the concerns for energy security and environment, India adopted a road map to harness renewable energy sources in the country. Various legal and regulatory acts have been taken to promote greater role of renewable energy (RE) in electricity sector. The Electricity Act 2003 mentions and promotes co-generation and generation of electricity from renewable sources of energy. The Indian government also launched Jawaharlal Nehru National Solar Mission (JNNSM) in the year 2010 to promote solar power in the country with a target for the same has been scaled up to 100 GW installed solar capacity. Integration of large RE capacity poses certain challenges for the power system. RE sources, especially wind and solar, are intermittent and variable in nature. The energy output from these sources does not coincide with the daily load pattern. The variability and seasonality of such renewable energy sources makes it challenging to integrate larger proportion of renewable energy in the Indian power system. Challenge for integration of renewable energy with power grids can be mitigated by load forecast and including storage element within the system. This work develops a modeling framework to analyze the techno-economic impacts of grid level storage in the presence of variable renewable energy like solar energy in a power system.

Given the non-operational storage function in pumped hydro generation plants in the country, this research addresses a key concern. The next section, provides a literature survey as a background as a methodological approach to model unit commitment (UC) problem in a power system and the economic value of energy storage system (ESS) in the case of pumped hydro energy storage (PHES) in a power system. Section III introduces mixed integer non-linear problem (MINLP) approach as a formulation for UC model. The relevant data for the case study is given in section IV. Results, outputs and analysis are presented and discussed in section V.

## II. Background

### A. *Literature Review*

Cost effectiveness of energy storage system in a power system integrated with Variable renewable energy (VRE) source like PV needs to be studied in a modelling framework simulating short-term operation of the power system. Scheduling of power units in a power system in a cost way is known as Unit Commitment (UC). A security constrained unit commitment (SCUC) determines optimal order of operation of power generators with the objective of cost minimization while maintaining a certain system security and reliability constraints [3]. An optimal UC procedure must result in real life system schedule that can be executed while maintaining system. The identified constraints are:

a) Power balance
b) Generation capability limits of units
c) Ramp up and ramp down rate limits
d) Minimum up-time and down-time of units
e) Spinning reserves
f) Transmission flow

Various optimization techniques are used to solve the problem of Unit Commitment. These include exhaustive enumeration, priority list, dynamic programming, Lagrangian relaxation and branch and bound method. Cohen et al. [4] used the algorithm based on branch and bound (B & B) technique to solve the problem of UC. B & B algorithm involves portioning of the solution space into subsets. The subsets whose elements violate the constraints are discarded and an upper bound on the value of cost function is computed. This value keeps improving as we move down the branches of tree. The solution is obtained when no further improvement in the value can be obtained. The method differs from most of the traditional methods as does not involves assumptions, priority ordering and allows time dependent startup costs.

## B. *Economic Value of ESS*

Power systems consisting of wind farms and PV generating units are expected to play a larger role. The mismatch between the generation profile of these VRE sources and load profile is stimulating an increasing need of ESS. ESS derive their value by storing electrical energy during excess generation and supply demand during higher demand periods. Black and Strbac evaluated the technical and economic implications of increased wind generation, specifically the value of reserve in the U.K.'s system-energy storage [5]. They quantified the storage value by determining the annual fuel costs for the conventional and wind generation system. The economic dispatch model was developed with the aim to minimize fuel costs in a system with power, storage and open cycle gas turbine (OCGT). Takagi and Iwafume et al assessed the economic value of PV energy storage using battery [6]. Marginal value of battery and invertor was estimated using Optimal Generation Mix model (OPTIGEN) and secondly an annual lease fee for the battery and inverter system was set up and optimal installed capacity of these devices were calculated. The OPTIGEN model determined the most economical operation by minimizing the total annual cost of utility which comprised of the fixed capital costs and fuel costs of the system. The power system consisted of nuclear generating units, gas units, PHES unit and rooftop PV systems. The results indicated that the combination of PV plants and battery reduced the electricity cost, though it is highly dependent on the annual lease fees of the battery and invertor system. Schill and Kemfert developed a game theoretical model to analyze the economic value of pumped storage in an imperfect market setting [7]. They formulated an oligopolistic Cournot electricity storage model (ElStorM) with strategic and non-strategic players. This model was applied on German market and the available pumped storage technology. The objective of the model was to maximize players' revenue generated from selling electricity. The analysis indicated that interrelation of strategic and/or non-strategic electricity storage with strategic electricity generation in an imperfect electricity market is a complex issue which leads to counter-intuitive results. It was concluded that strategic players generally tend to underutilize the storage capabilities and are caught in prisoner's dilemma. Although the model did not consider the integration of VRE sources like wind or solar which allow better utilization of storage due to the variability associated with them.

Brown and Lopes et al carried an economic analysis of inclusion of pumped hydro storage unit in a system with wind generation [8]. The objective of the problem was to identify the optimal size of a hydro plant while meeting the dynamic reserve requirements of the system. Inclusion of pumped hydro storage unit in the system reduced the expected fuel costs by 0.6%, and improved both dynamic security and economic operation of the test system. The optimal capacity of ESS was determined by optimizing the difference between earnings before interests and taxes and the energy costs and hence maximizing the NPV value of ESS. It was observed that the capital cost of ESS and its capacity influenced the size of subsidies required. They also concluded that the operation of ESS without subsidies is not economically viable. Denholm and Jogerson et al. carried out an analysis to determine the value of storage for grid application [9]. The analysis used a commercial grid simulation tool to determine the value of storage devices providing both energy and ancillary services. The value was examined by comparing the difference in electricity production cost in the systems with and without storage. This analysis considered value in hourly, day-ahead simulations under a variety of sensitivities, such as fuel price and storage size. The value of storage devices was examined as the sum of its operational and capacity values. The results indicated that the value of energy storage is largely dependent on its capacity value. Moreover, it was found that if ESS buy and sell energy, it can reduce the system operation cost as the overall generation cost will fall down but this will affect its own consumption due to reduced marginal price of energy. Sisternis and Jenkins et al determined the value of energy storage in the context of $CO_2$ reduction goals [10]. The analytical framework develops an optimal system with minimum generation cost while complying with a given carbon emissions limit. The main aim of the work was to reduce the carbon footprint of electricity with storage and assess the economics of this operation. It was observed that energy storage reduced the total generation costs excluding the cost of energy storage by 7-11%.

# III. SCUC Problem Formulation and Economic Value of PHES

## A. *MIP Formulation*

As mentioned in the previous chapter, the objective of SCUC is to determine day ahead UC schedule for the generating units in a power system. With a focus on minimizing the overall cost of operation, SCUC also ensures the reliability of the system while meeting the prevailing constraints.

Accordingly, a model is set up characterizing a power system that allows comparing scenarios under various operating conditions of the selected power system with an embedded PV generator and a PHES unit. Two scenarios are considered:

i. Without pumping mode of pumped hydro unit

ii. With pumping mode of pumped hydro unit

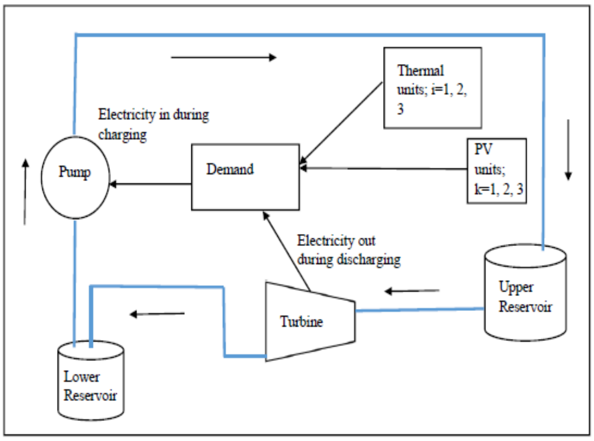



Figure. 1. Hybrid UC model

The hybrid UC model given in Fig. 1 is considered with the objective to minimize the total social cost which includes the cost of supplying the demand and the penalty cost for unmet demand. The cost of supplying the demand includes the fixed cost of generation, per unit and per square unit variable cost of generation from thermal units and the startup cost of thermal generators.

$$\min \sum_{i=1}^{I} \sum_{t=1}^{T} \begin{Bmatrix} a_i * u_{i,t} + b_i * G_{i,t} \\ + c_i * G_{i,t}{}^2 + SU_{i,t} \end{Bmatrix} + C_p \sum_{n=1}^{N} \sum_{t=1}^{T} E_{n,t} \qquad (1)$$

The objective function (1) combined with the above mentioned set of constraints constitutes a SCUC problem. The SCUC problem elaborated is for a hybrid system which contains both thermal units and solar PV unit(s). In order to ensure must run status of PV units, the PV generation profile is considered as a parameter. It is assumed that scheduled PV generation profile is forecasted reliably by the system operator (SO). In case the PV generation exceeds the demand in any time period, the surplus solar energy is spilled in absence of storage and is stored subjected to storage limits as per the case considered. Modeling of uncertainty of VRE is a potential extension of this work.

Since the aim of this work is to assess the performance of PHES system in a hybrid system, additional equations are added to the above stated model of SCUC. The demand balance equation is modified to consider generation or pumping from PHES units. Two reservoir units for hydrological equivalences are appropriately incorporated.

### B. *Solution Procedure*

Firstly the UC problem for the hybrid system with thermal and solar PV units in the absence of pumping mode of PHES unit as MINLP is solved. Next, the UC considering the pumping mode of PHES unit is simulated. The generation profiles of the thermal units and PHES units are compared to evaluate the economic value of storage function of PHES.

A 6-bus test system was modelled using General Algebraic Modelling System (GAMS). Since our SCUC For this MINLP problem solvers SBB and CONOPT have been used. SBB is a GAMS solver for MIP models. It is based on a combination of the standard B&B method known from mixed integer linear programming and some of the standard non-linear programming solvers. While CONOPT is used for solving nonlinear problems. The 6-bus test system used for analysis is described in following section.

## IV. Case Study and Results

The SCUC model described in the previous chapter is applied to a 6-bus test system. The two systems and the key technical and cost parameters used for the same are described below.

### A. *6-BUS system*

The 6-bus system used to apply the developed UC model is depicted in fig 2. The system has 2 thermal units, 1 PV unit and 1 PHES unit. It has 7 transmission lines. Generator 1 on bus 1 is coal fired and Generator 2 on bus 6 is gas fired. The PV generator is at bus 2. A PHES unit is connected at bus 6.

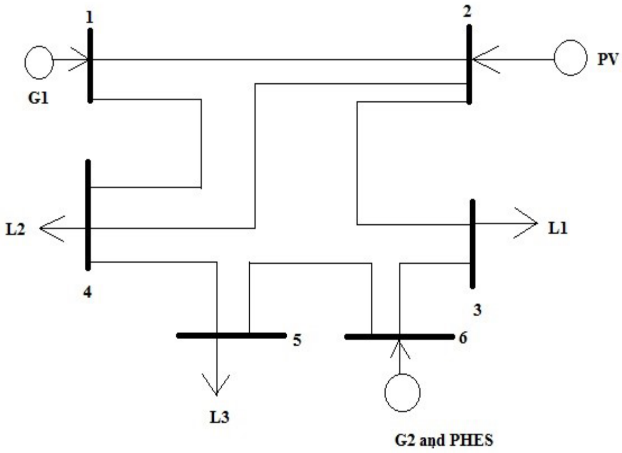



Figure. 2. Single – line diagram of 6-bus test system

Table 1 gives the flow limits and impedance of the transmission lines of the 6-bus test system being considered here. Table 2 gives the generator parameters for the coal and the gas fired generators. The technical and operational parameters of solar PV unit are given in Table 3.

TABLE I. Transmission Line Data

| Line No | From | To | Impedance (Siemens) | Flow Limit (MW) |
|---|---|---|---|---|
| 1 | 1 | 2 | 0.170 | 200 |
| 2 | 2 | 3 | 0.037 | 100 |
| 3 | 1 | 4 | 0.258 | 100 |
| 4 | 2 | 4 | 0.197 | 100 |
| 5 | 4 | 5 | 0.037 | 100 |
| 6 | 5 | 6 | 0.140 | 100 |
| 7 | 3 | 6 | 0.018 | 100 |

TABLE II Generator Specifications

| Generator No | Type of Plant | Bus | Unit Cost Coefficients | | | Pmax (MW) | Pmin (MW) | Min. Uptime (hrs) | Min. Downtime (hrs) | Ramping rate (MW/hr) | Startup Cost (Rs.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **a (Rs. /hr)** | **b (Rs. /MWh)** | **c (Rs. /MWh^2)** | | | | | | |
| **1** | Coal | 1 | 1678 | 1405 | 0.03 | 100 | 20 | 4 | 4 | 1 | 37935 |
| **2** | Gas | 6 | 3600 | 2480 | 0.45 | 120 | 10 | 1 | 1 | 2 | 2480 |

TABLE III. GENERATOR PARAMETERS OF SOLAR PV UNIT

| Gen. No | Type of Plant | Bus | Variable (social) Cost (Rs./MW) | Capacity (MW) | Pmax (MW) | Pmin (MW) |
|---|---|---|---|---|---|---|
| **3** | PV | 2 | 0 | 150 | 110 | 0 |

The generation and capacity data for the PHES unit in the system is given in Table 4. It is worth mentioning that the capacity of the upper and lower reservoirs is calculated in accordance with the capacities of Purulia pumped hydro plant in West Bengal [11].

TABLE IV. TECHNICAL SPECIFICATIONS OF PHES UNIT

| Gen. No | Plant | Bus | Capacity of turbine (MW) | Capacity of pump (MW) | Volume of upper Reservoir ($m^3$) | Volume of lower Reservoir ($m^3$) |
|---|---|---|---|---|---|---|
| **4** | PHES | 6 | 230 | 200 | 4.125e6 | 3.75 e6 |

## *B. Results and discussions*

The SCUC model formulated in Section III was applied to the 6-bus test system. The analysis is carried out on an hourly basis for 24-hour of operation of the described power system. This section presents the result of the SCUC analysis carried out on the 6-bus test system. The results have been presented in two sub-sections. The 6-bus test system without pumping mode serves as a base case for the analysis. Its operational and economic outcomes are compared with that in the case of pumping mode of PHES unit.

## *C. 6-Bus system without pumping action of PHES unit*

SCUC output for 6-bus test system with thermal unit, PV generating unit and PHES unit without pump has been plotted in the Fig 3. The figure depicts the generation output of the two thermal generators. The scheduled and actual generation of PV unit is given and the difference between the two has been plotted as spillage. The output from the PHES unit without pump is also plotted. The load profile considered for the SCUC operation has also been provided in the figure.

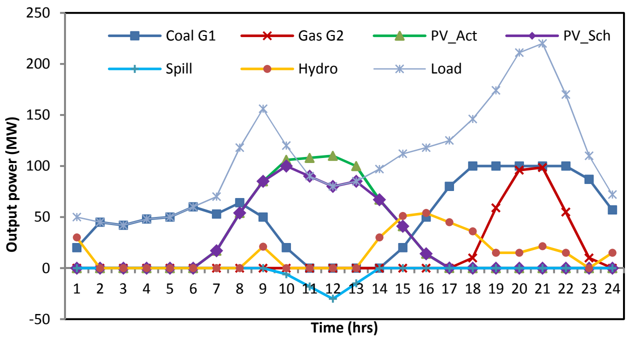



Figure 3. SCUC output for 6 bus system without VRE generation and a PHES unit without pumping

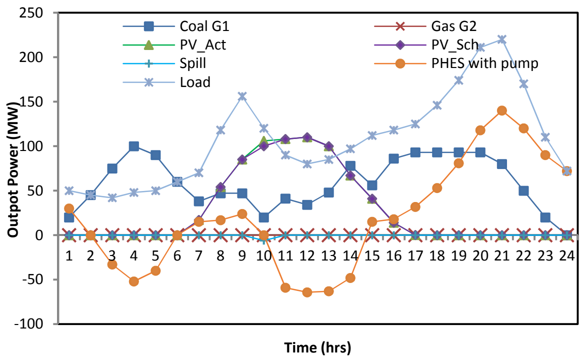
This case of SCUC modelling does not consider the pumping mode of the PHES unit. It is clear from Fig. 3 that even though there is a significant generation from the PV unit during certain hours of day but still a part of it is spilled due to limited load during those hours. It can be noted that the thermal generators do not operate during the hours of PV generation as PV fulfill a significant part of load during the daytime. But they operate during the late evening hours when the demand peaks while a very less amount of power is provided by the PHES unit during that period. This is due to limited amount of water present in the upper reservoir which constraints the generation from PHES unit.

The total cost of operation and the total generation from thermal units is given in Table 5.

## *D. 6-Bus system with pumping action of PHES unit*

The section gives the results for the SCUC analysis done on the 6-bus test system while allowing the pumping action of the PHES unit. The results have been presented in Fig. 4.

Figure 4. SCUC output for 6 bus system without VRE generation and a




PHES unit without pumping

It can be noticed that the pumping action of PHES unit is allows storage of excess solar generation. The pump operates twice during the operation, once during the early hours in morning and secondly when there is surplus PV. The pump stores this surplus generation and utilizes it for generation during the late peak hours. This is the benefit lost to the society due to the pumping mode of PHES unit in presence of a VRE generation source. It is also worthwhile mentioning that the spillage of PV is considerably reduced in presence of PHES unit. The power stored by the PHES unit during its pumping action is utilized to meet demand in the late-night peak hours. Load shedding is completely eliminated in this case and also the costly generator G2 is not generating.

TABLE V. TOTAL COST OF OPERATION WITHOUT PUMPING

| **Total Cost of operation (Rs.)** | | 2877381 |
|---|---|---|
| Total generation from thermal units | Coal Unit G1(MWh) | 1246 |
| | Gas Unit G2 (MWh) | 328.5 |
| Total cost of generation from thermal units | Coal Unit G1 (Rs.) | 1860061 |
| | Gas Unit G2 (Rs.) | 887320 |
| Total load shed (MWh) | | 13 |
| Cost of load shedding (Rs.) | | 130000 |
| Per unit cost of energy served (Rs./MWh) | | 1074.8 |

TABLE VI. TOTAL COST OF OPERATION WITH PUMPING

| **Total Cost of operation (Rs.)** | | 2112753 |
|---|---|---|
| Total generation from thermal units | Coal Unit G1 (MWh) | 1407 |
| | Gas Unit G2 (MWh) | 0 |
| Total cost of generation from thermal units | Coal Unit G1 (Rs.) | 2112753 |
| | Gas Unit G2 (Rs.) | 0 |
| Total load shed (MWh) | | 0 |
| Cost of load shedding (Rs.) | | 0 |
| Per unit cost of energy served (Rs./MWh) | | 822.4 |

Table 6. Gives the cost of the SCUC operation with the pumping mode in the power system. It also gives the output

of the different thermal generators and their respective costs of generation.

The total cost of operation with pumping mode of PHES unit in the system is reduced by Rs. 7, 64,628 as compared to the non-pumping case. The generation from thermal generator G1 is increased which is utilized in the pumping operation of PHES unit. It is observed that the cost reduction is higher than the saved cost of load shedding.

Comparing the total system cost of operation in a non-pumping and pumping mode, it can be said that for the given system characteristics, storage adds a value equivalent to the reduction in cost of system operation i.e. Rs. 7, 64,628.

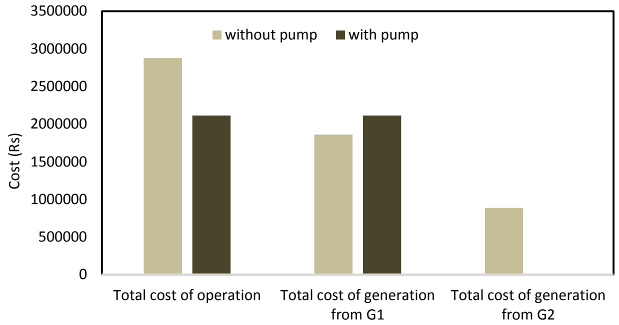



Figure 5. Cost comparison between with pump and without pump operation of the system

The difference between per unit cost of energy served is found to be Rs. 252.4/MWh. In per KWh term, the storage value is estimated to be Rs. 0.252/kWh. This value allows a system planner to consider investment in storage technology (pumped hydro in this case).

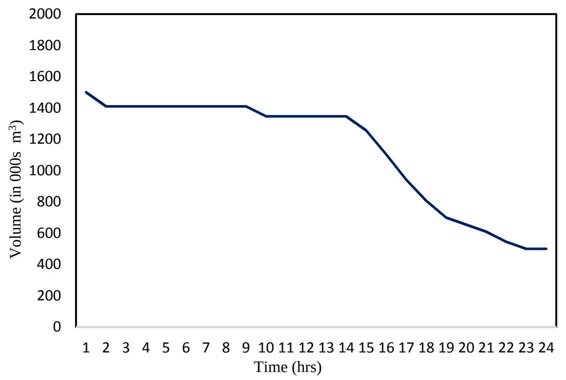



Figure. 6. Volume of upper reservoir without pumping

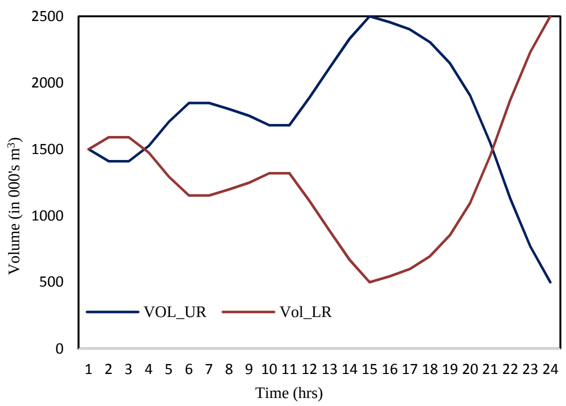



Figure. 7. Volume of upper and lower reservoir with pumping

## *E. Economic Assessement of Pumping Facility of PHES*

From the results presented the SCUC operation on 6-bus test system, it is observed that presence of pumping facility in a pumped hydro unit improves the economic operation of the system and there was a reduction in the overall cost of system operation. Afterwards saving as the value of pumping facility are quantified. We set out to determine the present value of the pumping facility in a system by using certain assumptions. These include:

- The identified 24-hour load pattern each day throughout the year and the same SCUC operation.
- The life cycle of a PHES unit has been assumed as 30 years and a discount rate of 15% is considered to determine the present value.

TABLE VII. ECONOMIC VALUE OF PUMPING FACILITY IN A 6-BUS TEST SYSTEM

| **6-bus test system** | **Overall system operation cost without penalty for lost load** | | **Overall system operation cost with penalty for lost load** | |
|---|---|---|---|---|
| Daily cost of operation (in million Rs.) | Without pump | With pump | Without pump | With pump |
| | 2.74 | 2.11 | 2.87 | 2.11 |
| Savings/year (million Rs.) | 231 | | 279 | |
| Present value (million Rs.) | 1748 | | 2107 | |
| Value of pump facility (million Rs./MW) | 8 | | 9.6 | |

Table VII gives the results for a 6-bus test system. Thus allowing the pumping action of PHES unit adds a value equivalent to Rs. 9.6 million/MW in a system. Excluding the cost of unserved load this value is equivalent to Rs. 8 million/MW.

# VI CONCLUSIONS

Renewable energy, particularly the renewable energy sources like solar and wind, are expected to play a significant role in the power sector basket of the country in the future. Increasing proportion of variable renewable energy generation in a power system remains a cause of concern for the system operator. This can be addressed to some extent by improving renewable energy generation forecast and provision of storage infrastructure connected to the power system. Pumped hydro-based electricity generation projects also provide a role in terms of absorption of excess power generated by the renewable energy sources especially those with zero marginal cost, and make available the same during the peak demand periods. It is found that existing PHES units are not being utilized in the pumping mode leading to a loss of economic value to the power system and the society.

It is found that in the characterized 6-bus test system, the presence of pumping based storage facility translates to a value of Rs. 0.297/kWh in the overall cost with considering the penalty for unmet load. This value is equivalent to Rs 0.253/kWh when the penalty for lost load is not considered. The economic value based on the present value of lifetime benefits of pumped storage is estimated equivalent to Rs. 9.6 million/MW (Rs. 8 million/MW), with (without) consideration to penalty for unmet load. Hence, it can be concluded that a capital cost of a similar proportion would justify additional investment for adding pumping mode with a lower reservoir in a PHES.

In this analysis the present value of the pumping facility of a hydro unit in a power system is also determined. Considering the same 24 hours duration operation throughout the year *i.e.* 365 days and with an estimated life of 30 years of a hydro unit the present value is calculated. The results indicated that in a 6-bus test system the pumping facility translates into a value equivalent to 9.6 million Rs/MW. This value comes out to be 8 million Rs/MW when the penalty cost of not serving load is removed.

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