Developing PSP integration strategies – A decision-making tool by means of power system optimisation modelling

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Introduction

In 2015 a study was initiated focusing on the optimization of Vietnam's power system through the deployment of pumped storage power plants. The study has examined eight candidate pumped storage plants (PSP) sites which had been identified in the course of a country-wide screening carried out in 2004 and, apart from two sites approved for development, were suggested for further investigation. The study provides an overall assessment of the demand for storage capacity within each of the three interconnected national HV networks (north, central, south), as well as the identification of priority candidate PSPs. The approach introduced in this paper represents a general tool for the identification and prioritization of candidate PSPs, using the project in Vietnam for demonstration purposes, and thereby provides a valuable decision-making basis for both regulatory public entities as well as private investors.

Developing detailed recommendations for the implementation of PSPs requires a thorough understanding of the power supply system(s) within which the individual PSP will operate. A PSP is a storage facility for electrical energy; it generates revenues by storing low-cost base-load excess electricity, and selling it at higher prices during peak-load periods. A PSP may additionally provide balancing and ancillary services, which may also create additional revenues.

A numerical model was developed for the purpose of optimizing the operational dispatch with and without PSP facilities. The model clears power markets on an hourly basis, and is capable of simulating the entire power system on a per unit basis while considering all technical restrictions of units and the system – this permits a determination of the optimum generation and ancillary services which are expected to be provided, assuming different PSP characteristics (i.e. generation and storage capacity).

Similar to a generation expansion plan, the gap between the present situation and an optimum PSP deployment is then bridged by adding available candidate PSPs. The optimum PSP deployment is derived from a cost/benefit comparison of penetration rates, simulated in the power system optimization for individual years over the study period.

The basic performance criteria used to assess the suitability of the candidate PSPs are the required installed turbine capacity and energy storage capacity derived from the power system optimization. The suggested sites are tested to determine whether they can meet these basic requirements; those sites which fall short of meeting the capacity requirements are respectively score-marked. The sites are also checked for any exclusion criteria, which may comprise severe environmental or social impacts, loss of important cultural heritage, and the like.

The assessment continues with a scoring exercise, in which each site is tested against suitability criteria such as the distance to transmission and road networks, ease of access to the site, the type of land used, etc. For each criterion a score is assigned, and the combined score is derived by weighting the individual scores and adding the weighted scores. Sensitivity tests complementing this assessment are carried out by modifying the individual weighting factors.

On the basis of the results of the assessment a group of technically "best sites" can be selected. The weighted score-based ranking may further be used to define the most suitable sequencing of the PSP implementation by evaluating the estimated investment costs, the associated economic indicators and the implementation plans.

1. Power system optimization modelling

The aim of the power system optimization modelling was to determine and quantify the optimum pumped storage potential within the individual network areas of Vietnam. This rationale pursues the aim of reducing thermal power plant operational costs (i.e. fuel and variable costs) and potentially delaying further power plant investments for one or more years.

The applied model is based on a mathematical optimization method in which the operational costs (i.e. fuel and variable operation costs) of the power plant dispatch are minimized while ensuring that both load and reserve requirements are still met. The model works as a mixed integer linear optimization problem (MIP) and is implemented in GAMS (General Algebraic Modelling System) using the solver CPLEX. Microsoft Excel is used for input alternation as well as for visualization purposes. The dispatch is obtained by finding the market equilibrium where the highest incremental cost of the units committed determines the market clearance price.

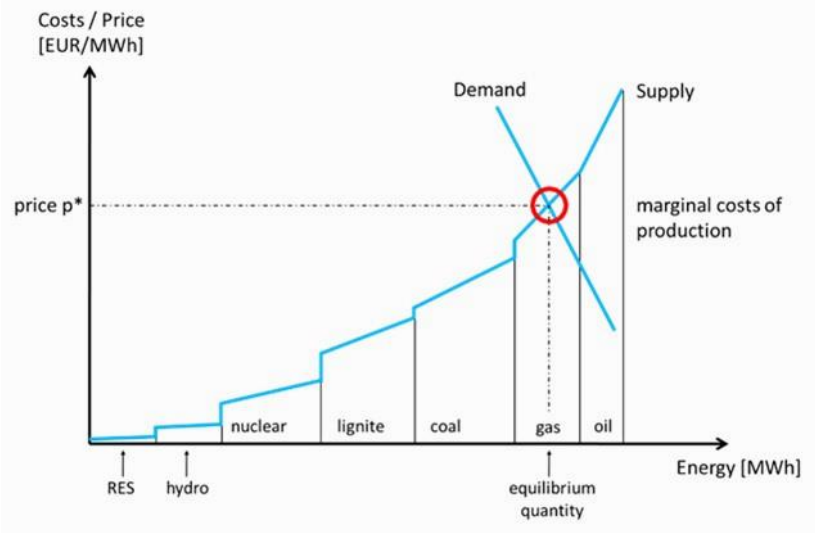


Fig. 1.   Simplified spot market price formation

The table below presents the restrictions and boundaries within which the model operates, as well as the results which are obtained.

Restrictions/Features

- Economic dispatch
- Unit commitment
- Grid node flow capacities
- Minimum up & down times
- Start-up & shut-down costs
- Partial load behaviour (incremental heat rate functions)
- Provisioning of primary & secondary reserves
- RES induced reserve requirements
- Seasonal hydrological conditions
- Hydro-thermal coordination
- Carbon emission consideration

Outputs/Results

- System Marginal Price (SMP)
- Units' operation and plant factors
- Units' cost and profit figures (spreads)
- Fuel consumption and emissions
- Share of technologies and energy sources
- Reliability characteristics (e.g. LOLP)
- Avoided fuel consumption
- Exchange of power and reserve capacities

Based on a multi-scenario analyses, the following questions can be answered:

- When should new generation units be commissioned?
- Which technologies should be applied for future generation, considering costs and the system's technical requirements?
- What investments, operation costs and variable O+M costs will occur at the unit, plant and system level?
- How will long-run marginal costs and short-run marginal costs develop over time?

1.1 Determining the optimum virtual storage potential

By simulating incremental virtual storage sizes and capacities, the model derives individual operation costs and unit commitment in order to determine both operational as well as investment benefits. Potential benefits comprise:

a) avoided generation costs – either due to improved operation of thermal power plants or avoided provision of thermal reserve;

b) avoided variable operation costs; and

c) delayed annualised investments in conventional thermal power plants, due to operation below a defined operational threshold.

The highest avoided costs of thermal power plants quantify the gross benefit of the virtual storages. Annual benefits are compared to the annualised costs of the respective PSP storage and generation capacities in order to derive the net benefits and the optimum virtual storage potential for individual system scenarios and years.

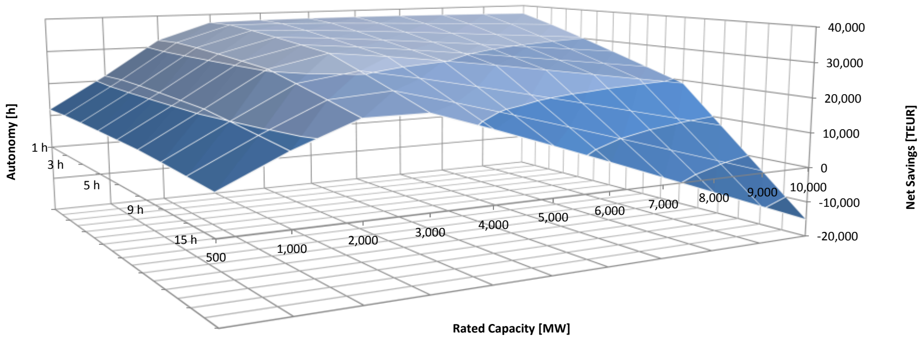
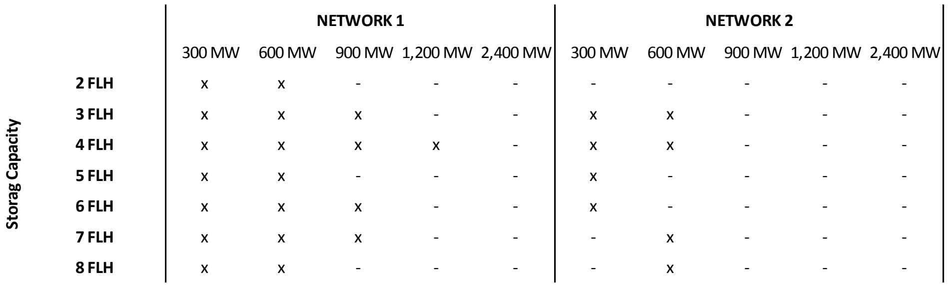


Fig. 2. Indicative annualised net benefits for incremental PSP capacities.

This modelling approach provides a particular quality of results, incorporating the broader – system and market – point of view as well as an isolated view of individual power generation units and individual virtual storages.

1.2 Quantifying the optimum virtual storage potential

Particularly when analysing systems with multiple interconnected networks, such as in Vietnam, the number of possible combinations of different storage capacities in each network may become very large. In order to reduce the number of possible combinations and to minimise computation time, the virtual storage potential is quantified for each network separately. Once the positive net benefits of individual PSP capacities in the individual networks have been identified, a further analysis step combines the potential for deriving specific economic and operational benefits of specific preferred combinations which exceed a set threshold of net benefits which has been determined.



Storag Capacity	NETWORK 1					NETWORK 2				
	300 MW	600 MW	900 MW	1,200 MW	2,400 MW	300 MW	600 MW	900 MW	1,200 MW	2,400 MW
2 FLH	x	x	-	-	-	-	-	-	-	-
3 FLH	x	x	x	-	-	x	x	-	-	-
4 FLH	x	x	x	x	-	x	x	-	-	-
5 FLH	x	x	-	-	-	x	-	-	-	-
6 FLH	x	x	x	-	-	x	-	-	-	-
7 FLH	x	x	x	-	-	-	x	-	-	-
8 FLH	x	x	-	-	-	-	x	-	-	-

Tab. 1. Illustration of preferred storage combinations in individual networks

The operational and investment benefits are then again compared with the estimated costs of investment by means of an economic analysis. Individual combinations are ranked according to their economic net benefits, thereby constituting the actual PSP potential which complements the technical and environmental ranking.

2. Introduction into decision criteria/matrix for the initial PSP project ranking

2.1 Basic performance parameters used for sizing of the PSPs' reservoirs

The sizing of a PSP is principally determined on the basis of a set of performance criteria which are expected to be met by the project. These basic performance criteria are usually derived from studies focussing on the demand and supply of electric power, for example in a national grid, and especially on parameters of supply shortages characteristic for the grid. The shortages can commonly be described by (i) the peak shortfall in power, and (ii) the duration of shortage, or – with respect to the PSP concerned – by the installed generating capacity to cope with the shortage (ability of peak power supply) and the project autonomy (ability of continuous generation at peak power).

For the Vietnam PSP Development Strategy, the JICA Master Plan Study specifies the maximum peak generation capability of a single PSP under consideration to be 1,200 MW, and the duration of continuous generation to be 7 hours, irrespective of the overall power demand of the grid which has to be covered by several PSP in combined operation. From these two parameters, the maximum energy storage capability of a single project is derived to be 8.4 GWh, which requires corresponding storage capacities in the upper and lower reservoirs – for a project with a smaller installed capacity, the respective energy storage capacity is determined to be smaller, whereas the project's autonomy is not varied.

Generally, the reservoir size increases with increasing installed capacity and energy storage capacity, whereas it decreases with increasing head. Since the reservoir depth is usually limited because of stability considerations, an increase in the reservoir volume is predominantly reflected through an increase of the reservoir area – i.e. the surface area 'footprint' associated with the construction of the reservoir. For this reason, projects with higher heads and smaller reservoirs are generally considered to be more environmentally friendly.

The diagram below demonstrates the interdependence between the installed capacity, the net head and the reservoir volume required for the storage of energy. This diagram has been developed assuming a PSP autonomy of 7 hours, i.e. the specified power must be continuously supplied to the grid at full installed capacity level over a period of 7 hours. The graph is valid for supply of the stated power at the transformer high voltage terminals; hydraulic losses in the power waterways were not considered.

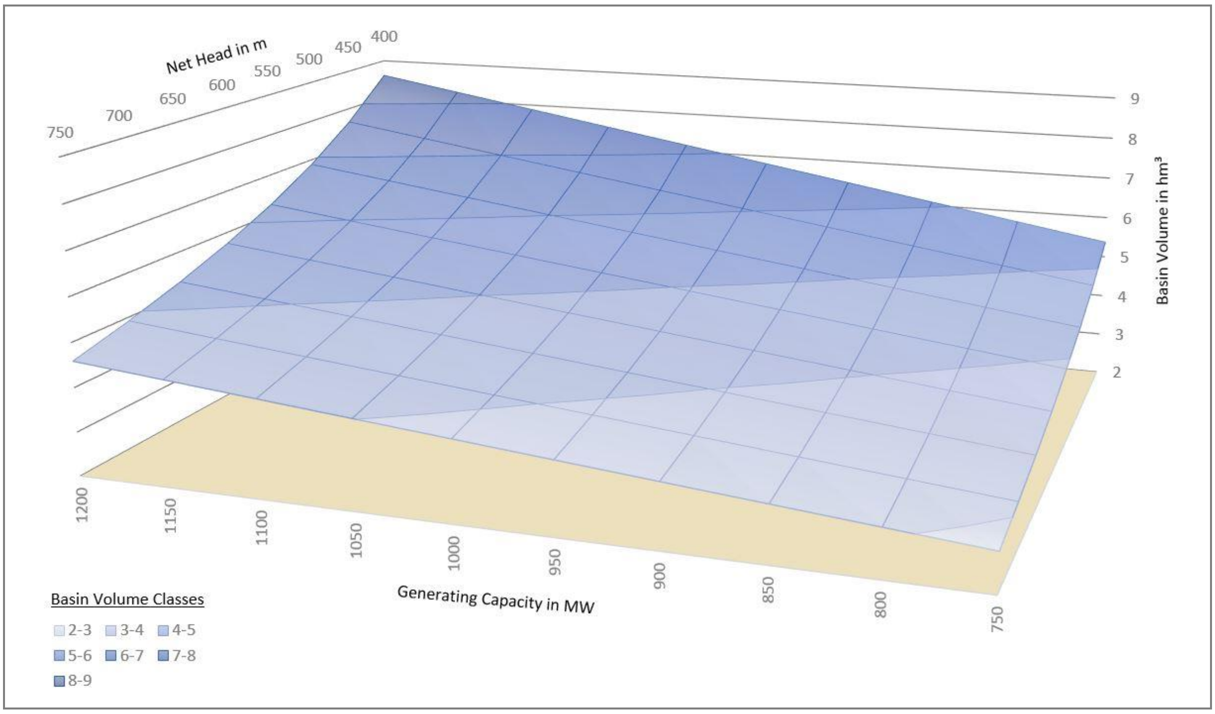


Fig. 3. Reservoir volume for generation at given installed capacity and head (Example: continuous provision of power for 7 h assumed, overall efficiency = 89.7%)

2.2 Assessment and ranking of the potential project sites

Given the fact that the sites have been identified earlier as being generally suitable for the implementation of a PSP, it is no longer necessary for the assessment of the potential PSP sites to re-examine the basic feasibility of the projects. The approach focuses rather on the evaluation of individual technical and environmental criteria and assigning positive or negative scores to the projects with the ultimate aim of allowing a differentiated assessment of the projects to be made and eventually the establishment of a project ranking.

A number of criteria are listed below which can be used to assess individual project features. The listed criteria are complemented by short background explanations.

- Technical aspects:

  The potential PSP sites will be assessed for their specific siting conditions. Among these conditions are included the total area occupied by surface structures, the distance to the nearest source of water, the distance to the nearest connection point to the power transmission grid, and the distance to the nearest connection point to the existing road and railway networks.

  For all potential PSP sites, the relevant key data are provided for the criteria, and the appropriate weightings then applied.

- Social and environmental aspects:

  Whereas many of the structures associated with a PSP can be arranged underground, and therefore do not occupy much surface space, for the construction of a PSP land areas have to be made available for the location of the upper and/or lower reservoirs. It has been assumed that the actual site conditions for these identified projects are more or less suitable for allocation as locations for PSP reservoirs. With respect to the specific conditions in Vietnam, such conditions are assumed to include land used for settlements such as agricultural or farm land, national forest reserves or similarly protected areas.

  Depending on the kind of land use recorded in any potential reservoir areas, varying suitability scores may be assigned to the project.

The individual weightings determined for each potential PSP site are combined to obtain a final overall weighting for the site. This overall weighting system, and the individual weighting factors applied, have to be agreed as representing the various impact factors satisfactorily in order to compare the various identified PSP sites.

Sensitivity checks may be computed by modifying the impact factors with the aim of increasing the impact of selected criteria on the overall result. A ranking is then established for the identified PSP sites based on the results obtained from the combined overall weighting.

The weightings applied in the course of the above procedure are defined by means of a weighting matrix, which is to be agreed in advance of the site evaluation process. A typical weighting matrix is shown in Table 2.

Cat.	Parameter	Symbol	Unit	Range	Scoring	Score Range	Weighting	
							ind.	**comb.**
Technical	Head	H	m	250…750	$100 - \frac{(H-500)^2}{2500}$	75…100	5%	42%
	Head vs. Distance	H/d	-	(theor. 0…∞) 0.0…0.6	$500 \times \left(1 - \sqrt{1-(H/d)^2}\right)$	0…100	3%	
	Installed Capacity	P	GW	0…6	100 x P/P_{max}	0...100	12%	
	Energy St. Capacity	ESC	GWh	0…20	100 x ESC/ESC_{max}	0...100	12%	
	Spec. Costs	C_{sp}	EUR/kW	-	100 x $C_{sp,min}/C_{sp}$	0...100	10%	
Site	Geology	-	-	-	as per geol. assessment	0...100	8%	8%

Cat.	Parameter	Symbol	Unit	Range	Scoring	Score Range	Weighting	
Connections	Water Supply	d_{WS}	m	zul d = 50,000	(zul d – d) / 500	0...100	6%	22%
	Exist. Roads	d_{Ro}	m	zul d = 25,000	(zul d – d) / 250	0...100	8%	
	Ex. Railways	d_{Rw}	m	zul d = 50,000	(zul d – d) / 500	0...100	3%	
	Transmission Network	d_{TN}	m	zul d = 25,000	(zul d – d) / 250	0...100	5%	
Social/Env.	On-Surface Coverage	A_S	m²	-	100 x $A_{s,min}/A_s$	0...100	8%	28%
	Type of Land Use	-	-	-	housing = 25, forest/farm land = 50, others = 100	25…100	8%	
	Settlements	n	No.	-	$(100 – n)^2 / 100$	0...100	12%	

Tab. 2. Typical weighting matrix for ranking of identified PSP sites

3. Derivation of optimum storage potential

The optimum PSP expansion plan can then be defined based on the economic ranking in accordance with technical and social/environmental aspects. Through the selection of the best PSP projects to bridge the virtual storage potential, an indicative project development pipeline can be developed.

It should be noted, that the identified economic PSP potential and shortlisted project candidates may differ in terms of exact storage and generation capacity. The final selection therefore requires a thorough review of project-related costs and construction schedules by means of a financial risk analysis, in order to avoid any unnecessary costs or losses due to too early or too late investments.

References

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The Authors

Klaus Moeller graduated in 1983 in civil and hydraulics engineering from the Technical University of Berlin. He was subsequently engaged as an assistant scientist at the Institute of Hydraulics and Water Resources Engineering, Technical University of Berlin. In 1990 he concluded his research work related to the behaviour of a thermally stratified water storage and submitted his Ph.D. thesis. Since then he has been employed by Lahmeyer International, where his work focussed on the project management for planning and developing of hydropower projects. During the last ten years his engagement has increasingly been directed towards the planning of pumped storage projects, comprising, among others, the 1,060 MW Goldisthal PSP in Germany (commissioned in 2004), the 1,000 MW Siah Bishe PSP in Iran (commissioned in 2013) and the 1,050 MW Lagobianco PSP in Switzerland (currently undergoing the governmental approval process). Presently he is involved in PSP definition and site identification studies in Vietnam, Sumatra and Egypt.

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