ISSN (e): 2250 – 3005 || Volume, 06 || Issue, 03||March – 2016 ||
International Journal of Computational Engineering Research (IJCER)

# Market Challenges for Pumped Storage Hydropower Plants

Milan Ćalović[1], Dejan Mandić[2] and Miodrag Mesarović[3]
[1, 2, 3] Energoprojekt Entel Consulting Engineers Co.,
Bulevar Mihajla Pupina 12, Belgrade, Serbia

**Abstract**

*For power system development planning, a thorough valuation of each of its components is carried out with an objective to improve the system reliability and economy. This paper deals with energy storage technologies with particular emphasis placed on the pumped storage hydropower plants (PSHs). For the long-term development planning of a system with different generating facilities, PSHs still play the major role in the implementation of intermittent renewable energy sources into a future generation mix. For planning of a generation mix with PSHs we use the concept of "Levelized Cost of Electricity" (LCoE) to compare the economic indicators of a system in order to make a fair and unbiased selection of new plants intended to cover customer demands. Being based on the monetary indicators, the LCoE concept is able to help in making investment decisions in view of technology and size of any new generating sources proposed for a defined time horizon. Owing to their excellent operational flexibility PSHs may also be good players on the electricity markets, offering both, capacity and energy services.*

***Keywords:*** *Energy storage technologies, Flexibility, Generation mix, Levelised cost of electricity, Market profitability, Net present value, Power generation cost, Renewable energy sources, Security of supply, Selling prices*

## I. Introduction

The storage of electrical energy is an old research challenge since the early beginning of industrial development of applied technologies for its wide use. The variability of customer demands, as well as unpredictable events on both generation and demand sides, influence the reliability, security and quality of supply, required by markets of high operational standards. One of the common means to provide necessary reliability and security of supply is to ensure sufficient generating capacities and energy reserves by means of energy storage, not only in electrical, but also in other forms, capable to be easily and fast converted back to electrical form of energy, whenever the available generation is not sufficient to satisfy system demand.

The energy storage systems may be connected to either the transmission or distribution network (or even on the customer side of the meter), and they have characteristics that sometimes bring value to generation and other times to transmission or distribution. Besides the utility size storages connected to the transmission and distribution grids, there are small size storages at the household level. The functions of particular energy storage systems are presented in Table 1 [1].

**Table 1: Storage purposes in contemporary power systems [1]**

| Application in power system / Function of storage | Transmission grid central storage (national level) | Distribution grid storage (city level) | End user storage (household level) |
|---|---|---|---|
| Balancing demand and supply | • Seasonal/weekly fluctuations<br>• Large geographical unbalances<br>• Strong variability of wind and solar | • Daily/hourly variations<br>• Peak shaving | • Daily variations |
| Grid management | • Voltage and frequency regulation<br>• Complement to classic power plants for peak generation<br>• Participate in balancing market<br>• Cross-border trading | • Voltage and frequency regulation<br>• Substitute existing ancillary services (at lower $CO_2$)<br>• Participate in balancing markets | • Aggregation of small storage systems providing grid services |
| Energy efficiency | • Better efficiency of the global mix, with time shift of off-peak into peak energy | • Demand side management<br>• Interaction grid-end user | • Local production and consumption<br>• Increase value of local solar and wind |

Presently, there are several different types of storage technologies and systems, which seem to be hopeful for serving the above purposes. The energy storage technologies can be based on different storage methods, including electrochemical (batteries, flow batteries, fuel cells), electrical (capacitors, super-capacitors, super-conducting magnetic energy storages-SMES), mechanical (compressed air energy storage-CAES, flywheel energy storage, pumped storage hydropower plants - PSH), and thermal storage (molten salt, cryogenic liquid). However, very few of them are suitable to fulfill operation or cost requirements currently set by large utility systems, as seen in Table 2 [2].

**Table 2: Performance of major energy storage technologies [2]**

| Energy storage technology | Status of development | Unit sizes | | "Round trip" energy efficiency |
|---|---|---|---|---|
| | | Existing | Potential | |
| Compressed air | Commercial | 100-300 MW | <30 MW | ~80% |
| Pumped hydro | Commercial | 5-2100 MW | <2000 MW | 75-80% |
| Batteries (conv.) | Commercial | >1 kW | <10 MW | 50-90% |
| Flow batteries | Limited commercial | <20 MW | <1000 MW | 70-75% |
| Magnetic | Limited demo. | <10 MW | <100 MW | ~90% |
| Fly-wheels | Limited demo. | <1 MW | <1-1000 MW | ~80% |
| Fuel cells | Commercial | 50 kW-1 MW | >100 MW | 40-80% |

Following rapid cost reductions and significant improvements in capacity and efficiency, the global energy sector is captivated by the promise of deploying energy storage alongside renewables. Storage is promoted as the game-changer which could contribute to solving the volatility challenge of wind and solar electricity generation. Whilst there is plenty of visionary thinking, business models are not always fully understood and there are not many studies on cost data. Figure 1 presents the current maturity level of different storage technologies as related to the capital requirements and development risks associated with them [3].

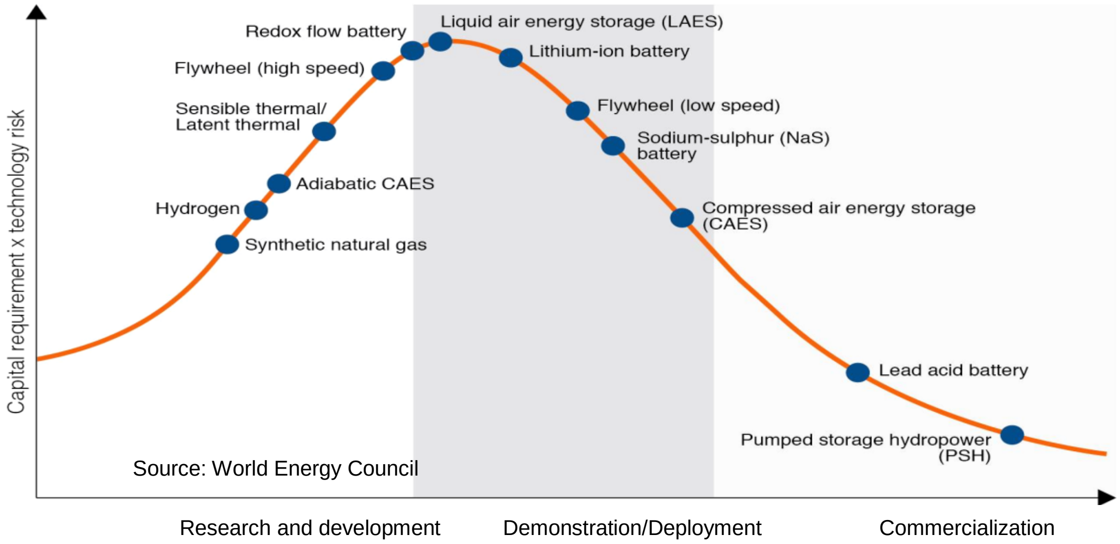


**Figure 1: Current maturity level of different energy storage technologies [3]**

As evident from Figure 1 above, among the current energy storage technologies considered, the most promising is the PSH technology, representing the systems for storing the electrical energy in the form of potential energy of water, easily transformable to the electrical form when needed. This type was primarily represented by conventional hydro power plants (HPPs) with large water reservoirs. Unfortunately, such natural hydropower potentials are limited and already exhausted in many parts of the world. Thus, the only possibility is to build new PSHs on convenient locations satisfying administrative, environmental, and operational conditions [4, 5]. The main conceptual difference of PSHs from the conventional HPPs is the existence of two water reservoirs (upper and lower ones) and two operational modes: pumping (motor) mode and generating (turbine) mode [5]. The PSHs can be of suitable capacities, adapted to the system needs and operational conditions, providing the existence of cheap energy for pumping the water from the lower to an upper reservoir.

It should be emphasized that PSHs are now the only mature technology for transformation of electrical to hydraulic energy and *vice versa*. This means that the presence of PSHs in a system does not increase the energy production. Contrary, they are inherently consumers, with negative total energy balance, having the efficiency coefficient of the overall energy transformation process of the order of 70% to 85% [5]. In addition, it should be noted that PSHs alone are not able to permanently satisfy customer demands, so that they must always be integrated in a real power generation system.

The use of PSHs is convenient, or justified, in the following situations [6,7]:

- Short-term storage of the excessive generation during low-loads to enable it to be used in high-load hours, within daily or weekly customer load-demand diagrams.
- Seasonal storage in certain cases when an excessive generation exists, either from thermal power plants or from run-of-river HPPs during over-flow, and can be saved for use in high load seasons.
- Integration of renewable energy sources (RES) into existing power systems, particularly so when their penetration in the system is high, requires storage means to accept all disposable, but unpredictable and uncontrollable generation (such as wind and photovoltaic). The stored RES generation in the system is used when required, either for the quantity or the fast power response. The use of PSHs for these purposes is rising fast in recent times, as a convenient solution to modern intermittent RES integration to the power grid.
- PSHs with high speed response inherently increase the required system flexible reserves (primary, secondary and tertiary) to a great extent, thus releasing the cheaper generation by conventional plants of this duty.
- If available, the excess storage capacities of reservoirs of PSHs could be rented to interested clients in the neighborhood providing the existence of joint tie-lines in between [7].

Technical aspects of the use of PSHs in generating regime for any of the above applications are almost identical as in case of conventional high-head HPPs. HPPs are not dealt with in this paper, which is devoted to the questions of utilization and economy of PSH operating in synchronism with conventional and new RES power plants within large power systems.

This paper is divided into 8 sections. After the introduction in this Section 1, Section 2 presents short review of main technical characteristics and operation parameters of PSH. Section 3 gives a brief overview of the use of PSH in actual power systems, as important factors to achieve their security, reliability and economy in the operation. Section 4 is devoted to the valuation of main features of PSH in the operation, to be dealt with in the planning stage. In the consideration of economic effects of PSH, the concept of "*Levelized Cost of Electricity*" (*LCoE*) is applied when ranking competitive projects. Section 5 discusses the possible role of the PSH on the energy market and pricing of furnished energy via appropriate composite tariffs. Section 6 presents the case study of the proposed valuation method applied to a proposed PSH project. Finally, Section 7 presents the conclusion, while Section 8 lists the literature used for preparation of this paper.

## II. Pumped Storage Hydropower Plants (PSHs)

PSHs are presently the only practical energy storage principle available for utility size use. Their configurations primarily depend on geographic limitations at the site, such as water availability, topography, and morphology constraints [5-7]. The most important energy-wise characteristics of a PSH are machine rated capacities in both, pumping and generating regimes. Also, the power consumption $P_p$ (in pumping regime) and generation $P_g$ (in generating regime), as well as construction parameters (heads, flows, capacity, etc.) and water availability are basic operational characteristics of the PSH. The energy consumption (in pumping regime) and output of the plant (in generating regime) are calculated by using the plant design parameters. The following formulas (Equations (1a) and (1b)) are used to calculate values of $P_p$ and $P_g$ respectively:

- Motor consumption in pumping (motor) regime

$$P_p = \rho g Q_p H_p \frac{1}{\eta_{pum}\eta_m} = \frac{\rho g Q_p H_p}{\eta_p} \ [MW] \tag{1a}$$

- Generator output in generating (turbine) regime

$$P_g = \rho g Q_t H_t \eta_t \eta_{gen} = \rho g Q_t H_t \eta_g \ [MW], \tag{1b}$$

where $\eta_{pum}$, $\eta_m$, $\eta_t$, and $\eta_{gen}$ are partial efficiency coefficients of pump, motor, turbine, and generator, respectively, while $\eta_p = \eta_{pum}\eta_m$ and $\eta_g = \eta_t\eta_{gen}$ are corresponding overall efficiency coefficients of sets pump-motor and turbine-generator, respectively. Likewise, $\rho$ is the specific mass of water, $g$ is gravitation constant,

$Q_p$ and $Q_t$ are water flows in pumping (upward) and generating (downward) regime respectively, while $H_p$ [m] and $H_t$ [m] are the corresponding water heads.

The corresponding energy parameters are calculated by integrals of plant input/output power within the time of the operation. Also, the stored energy ($W(H_t, H_p)$) in the upper reservoir of the water volume $V$ [m$^3$] = $V(H_t)$ is given (when generating regime is considered) by the formula:

$$W_g = \rho g V H_t \eta_g \ [\mathrm{MWh}]. \tag{2}$$

For $\eta_t = 0.85$; $\eta_{gen} = 0.95$ follows $\eta_g = 0.81$, so that the formula (2) gives $W \approx 2.2 V H_t \, 10^{-6}$ [MWh] (similar formula could be also derived for pumping regime, by the use of corresponding parameters of the plant [5].).

The duration of filling up of an empty upper reservoir ($T_f$) and discharge of a full upper reservoir ($T_d$) are related to the maximum storage of the upper reservoir $W_{max}$ to the rated flows $Q_p^r$ and $Q_g^r$ i.e. to the rated power of the plant $P_p^r$ and $P_g^r$ for pumping and generating regimes, respectively:

$$T_f = \frac{W_{max}}{P_p^r} \ [\mathrm{h}] \text{ and } T_d = \frac{W_{max}}{P_g^r} \ [\mathrm{h}]. \tag{3}$$

The overall efficiency coefficient of the plant within a time period $T$ is:

$$\eta_p^r = \frac{W_g^T}{W_p^T} 100 \ [\%], \tag{4}$$

where $W_g^T$ is the production (in generating regime) and $W_p^T$ is consumption of energy (in pumping regime) within the same time period $T$. The efficiency in modern PSHs is between 70 % and 85 % [5-7]. With such facilities, fewer plants in the system would have to be built and the available plant capacities in operation would be better used with higher capacity factor and efficiency [6]. However, they must be shut down for pumping water up, when a minimum shut-down time is about 10 hours [8].

An attractive operation-wise feature of the PSH is their excellent flexibility (the ability to follow the system load). This is evident from Table 3, presenting comparative flexibility parameters of the main types of generating units, which are used in modern power systems [8].

**Table 3: Flexibility of conventional power generation technologies and PSH [8]**

| Parameter | | Nuclear power plants | Thermal power plant | | | Pumped storage plants |
|---|---|---|---|---|---|---|
| | | | Cool fired | Lignite fired | Gas fired | |
| Start-up time | Cold | ~ 40 h | ~ 6h | ~ 10h | <2h | 0.1h |
| | Warm | ~ 40h | ~ 3h | ~ 6h | <1,5h | 0.1h |
| Load gradient at nominal rate t | Raising | ~ 5%/min | 2%/min | ~2%/min | 4%/min | <40%/min |
| | Lowering | ~ 5%/min | 2%/min | ~2%/min | 4%/min | <40%/min |
| Minimum permanent load | | 50% | 40% | 40% | <50% | ~15% |

Data listed in Table 3 above show that the flexibility parameters of PSHs are superior to all other types of generating plants (nuclear, coal or gas fuelled). This fact emphasizes the technical advantages of PSHs when operating with variable loads and their use (in the absence of conventional storage plants) to provide power system reserves (primary, secondary, and tertiary) [5]. It should be noted that Table 1 does not show flexibility parameters for conventional HPPs, as they depend on particular HPP type: the high-head HPPs are the most convenient in this respect, while the low-head run-of-river HPPs are not [5].

## III. Long Term Development Planning of a Generation Mix Including PSHs

The long-term development planning addresses the economic selection of new technically suitable generation and transmission additions, necessary to meet forecasted load requirements. It is therefore based on the long-term load forecasts, as well as on the analyzing the role of any new power plant in the power system, with known characteristics. The decision on construction of a new plant depends on its operational and cost parameters, as well as on the structure and features of all other plants in operation within the power system. This is mainly based on the principles of economic evaluation with reference to minimum overall costs within the system in a specified time period. The expected contribution of any new power plant-candidate to the overall operational goal is the base for their valuation for a final investment decision to be made. However, the valuation of a new individual plant only on the basis of its investment and other costs and possible generation may not be sufficient, except in small number of cases such as projects with subsidized generation costs (e.g. „feed-in tariffs“), or particular clauses of power purchase agreements (PPAs) in cases when only a specific operational criterion (e.g. maximum generation) is used for decision-making in the planning stage. For other cases a more sophisticated approaches are needed to enable less risky investment decisions be made.

During the last few decades, serious changes occurred in technology, organization, and market aspects of the power industry. Deregulation and market liberation, regional power associations, reinforcement of mutual transmission tie-lines, measures for the reduction of harmful gas emissions, subsidies for the use of renewables etc., create a new environment and new challenges, seeking for new methods of solutions [9]. Substantial changes in planning approach are therefore required. Besides the common criterion of costs minimization, the new approach for the evaluation of future investments and future operation of power systems some novel criteria must be included as well.

Power deliveries to customers are not anymore the only subject of their load demand and forecasts on a defined territory, but mainly on contractual business with respect to corresponding market-agreed energy prices. On the other side, the energy infrastructure is of strategic importance for any country, so that the future development in this subject area cannot be exclusively entrusted to the market. Therefore, the energy development strategy should be an important guiding document for all players inside the investment process in the sector of electrical energy, within an overall development strategy.

The European power sector is undergoing drastic changes as it intends to reach $CO_2$ neutral electrical energy supply by 2050 [10]. This goal is meant to be achieved by simultaneous implementation of several measures. The most important among them are the increase of share of RES within total power generation mix and decrease of $CO_2$ emissions from thermal power plants by improving their efficiency and enabling removal of $CO_2$ from the flue gases ( by the use of carbon capture and storage – CCS technology or otherwise). In this context, the planned solar and wind power generation increases rapidly [7]. The remaining energy production based on RES would be realized by conventional HPPs and distributed generators based on biomass, waste and other sources of primary energy [11].

These projections will surely call for a fast increase of new pumped storage capacities in Europe, as the best enabler of the integration of new energy resources in future power systems [12]. There are plans in Europe for the construction of 60 new PSHs by the year 2020, with the total installed capacity of about 27000 MW [5,6]. However, the potential for further conventional hydropower in Europe is limited because of environmental considerations, lack of adequate sites and certain social acceptance issues. New PSH schemes are subject to similar limitations, but this is likely to be easier done by transformation of non-hydropower dams and reservoir hydropower schemes into pumping hydropower schemes [13].

## IV. Valuation of Services of Pumped Storage Hydropower Plants in a Power System Mix

Energy storage valuation for grid use cases has historically been challenging, due to unique technology attributes, technology uncertainties, and regulatory challenges. The cost-effectiveness of a storage system providing a combination of grid services is dependent on an array of inputs. Generation is deregulated, and generation companies make their business cases in the market, where transmission and distribution assets are allowed a regulated return on investment [14]. The result could look very different when there are changes in the technology cost, configuration, market conditions, and many other factors [15].

Presently, the selection criterion for new plants is the minimum of total expenses, subject to adopted level of security of supply [16]. Similar criteria in the local long-term strategic development projects will be probably used by individual companies, regions and countries. These criteria could be adjusted to specific conditions, resulting from the own strategic policies (fuel import dependency, high level of penetration of renewables, etc.), or due to environmental constraints.

From previous considerations, it is possible to conclude that the approach to the valuation of investments in the power industry, as well as the way of the evaluation of operational effects of power plants in new market conditions, depend on goals posed by the task order and on particular interest of involved subjects (government, business) that should invest the money in new additions. There are strategic regional development studies, directed towards investigation of possibilities for joint regional use of the available energy potentials in an area. They should look for the most favorable plans for new generation capacities within the integrated power networks in participating countries in the region.

The generating cost of electrical energy is not the only decision factor influencing the valuation and ranking of new power plants. While the optimization criterion in the former practice was the minimum of the overall generation expenses (investments plus operation and maintenance as well as other costs), the question is could today such an approach be appropriate for the selection of new capacities by a power generation company engaged in the open energy market? It is reasonable to expect such an approach to be applied in the long-term planning of the power generation mix including PSH as well.

The cost to benefit analyses (CBA) is often applied for the selection of new power plants, where better ranking within the whole individual entity have plants with more favorable benefit to cost (B/C) ratio [8]. For valuation of the grid energy storage, different services, technologies, locations, and future electricity market scenarios should be analyzed. A wide range of energy storage cases can be developed by the CBA. An economic valuation of energy storage systems was carried out by calculating the economic benefit to the grid of replacing natural gas “peaker” plants with energy storage. Such a comparison of three grid size energy storage technologies with “peaker” plants is presented in Table 4 including breakeven capital costs with “peaker” plants [17].

**Table 4: Economic performances of grid size energy storage technologies, 2020 [17]**

| Storage technology | | PSH | CAES | Flow battery |
|---|---|---|---|---|
| Input Data | Nameplate capacity, MW | 300 | 100 | 50 |
| | Nameplate duration, hours | 8 | 8 | 4 |
| | Capital cost, $/kWh | 166 | 211 | 443 |
| | Capital cost, $/kW | 1325 | 1684 | 1772 |
| | Project life, years | 100 | 35 | 20 |
| | Roundtrip efficiency, % | 82,5 | - | 75 |
| | Variable O&M cost, c$/kWh | 0.10 | 0.30 | 0.025 |
| | Fixed O&M cost, $/kW-year | 7.5 | 5.0 | 15.0 |
| Results | Breakeven Capital Cost, $/kWh | 223 | 232 | ..675 |
| | Breakeven Capital Cost, $/kW | 1783 | 1853 | 2699 |
| | Benefit to Cost (B/C) Ratio | 1.32 | 1.27 | 1.23 |

From recently, the concept of economic value of projects is used in planning stage for consideration of the economy of power plants of both dispatchable and undispatchable technology categories. It is defined as the ratio of net present values of the net costs during the working life of the plant and electrical energy generated during the same period, both discounted to the initial year of investment [18,19]. This ratio is called the "*Levelized Cost of Electricity*" (*LCoE*), which, by definition, is calculated as:

$$LCoE = \frac{\sum_{k=1}^{K} \frac{\left[C_I + C_f + C_{om} + C_{ot} - (RV)\right]_k}{(1+i)^k}}{\sum_{k=1}^{K} \frac{W_k (1-d)^k}{(1+i)^k}} \quad , \tag{5}$$

where:

$K$ - years of operational life of a generating plant;

$C_I$ - investment cost calculated as $C_I = A(k,i) \cdot c_I \cdot P_i$ , where $A(k,i)$ is the annual installment of loan repayment for $C_I$ , with $c_I$ being specific cost per unit of capacity and $P_i$ the installed capacity;

$C_f$ -fuel cost calculated as $C_f = c_f \cdot W_a$, where $c_f$ is the specific fuel cost and $W_a$ actual or planned annual generation. Since the *LCoE* concept (5) was originally developed for thermal power plants, in case of their application to HPPs and other renewables, except biomass and geothermal, $c_f = 0$, while for the PSH it is equal to the specific cost of pumping, $c_f = c_{pump}$;

$C_{om}$ - operation and maintenance costs calculated as sum $C_{om} = C'_{om} + C''_{om}$ of constant $C'_{om}$ and variable $C''_{om}$ maintenance cost, calculated as $C'_{om} = c'_{om} P_i$ and $C''_{om} = c''_{om} W_a$ , where $c'_{om}$ and $c''_{om}$ represent specific costs for power $P_i$ and energy $W_a$, respectively;

$C_{ot}$ - other cost that include all expenses not mentioned above (e.g. network upgrade costs, congestion costs, $CO_2$ abatement cost, integration costs, transmission costs, etc.);

*(RV)* - residual value of equipment and other properties in the possession of plant owners after expiration of theoperational lifetime of the plant;

$W$ –energy delivered to the system;

$d$ - coefficient of annual degradation due to plant ageing and wear; and

$i$ - annual discount rate.

By analyzing the equation (5) and all its constituents, it could be concluded that there are as many parameters needed to calculate *LCoE* as in CBA and other methods. In many publications a comprehensive set of parameters is used in *LCoE* calculations [20]. The levelized costs used for case studies based on *LCoE* are found in the available literature for different plant types and technologies, but rarely for the PSHs, and when done so, without cost of energy spent for pumping, like in [8] (cf. Figure 26) or in [17] and Table 4 presented herewith) and elsewhere when CBA method is applied. We therefore decided to adapt the *LCoE* method for use in comparative assessment of various energy storage projects [21]. It is our belief that the method may equally well be applied for evaluating the role of PSH in the long-term planning of a power system generating mix, being based on the inputs not different from those used by CBA and other planning methods.

The value of *LCoE* is considered to be a useful information for investors about new prospective project costs, assuming the certainty of future forecasted revenues and stability of prices of the plant construction and operation costs and of the electricity price on the market. However, *LCoE* does not represent the value of generation from all power system plants during a specified period, e.g. within a year [22]. It is important to note that, while *LCoE* is a convenient measure of the overall competitiveness of different generation technologies, actual plant investment decisions are also affected by the specific technological and regional characteristics of a project under consideration. This involves numerous additional entries (e.g. forecasted utilization rate, the existing generation mix, specific system load characteristics, availability of intermittent resources, etc.) [23].

For this reason, in planning stage, it is necessary to provide many other information, beside investment and operating costs, for all plants and technologies participating in the competition (for their ranking with regards to reliability, flexibility, availability of services, environmental impacts, etc.). Not all of the relevant features is possible to express directly in monetary values. It is therefore apparent that there may be many trade-offs that must be made in determining the correct resource base for planning future power generation, which sometimes can only be addressed verbally, as an expert opinion, or as descriptive constraints only.

Nevertheless, the application of *LCoE* concept in the long-term development planning of power systems must take due account of possible twofold role of PSH in the operation of power systems (as large consumers or generators of electricity) [21]. These facts have motivated authors of this paper to contribute with their own experience and results relative to the application of *LCoE* concept to PSH in the procedure of new plants selection within the process of long-term generation planning.

## V. Pumped Storage Hydropower Plants on the Market

A majority of contemporary power systems operate in deregulated and competitive environment. Their goal is to make the revenue as high as possible. In other words, with known generation costs, the operation criterion of individual entities participating on energy market moves to the maximization of profit instead of minimization of cost, otherwise common in the planning process. The profit obtained by selling the electrical energy is the difference between corresponding revenue and cost. The revenue from market transactions of selling electrical energy depends on cost component shares in services defined contractually (by the Power Purchase Agreements –PPAs, for example), or by the market transactions. Three main components in common traded services of the PSH are:

- Provision of the capacity of generation supply during peak-load conditions (capacity component);
- Supply of the energy according to an agreed upon time schedule.
- Provision of system operation and balancing reserves.

The viability of a new plant project should be defined by analyzing forecasted market prices for the above service components for the whole period of plant life $k$=1,2,…,$K$ years. Presently, the business organized at the markets of electrical energy and/or capacity is based on PPA documents which regulate the contractual conditions of power supply, agreed upon between parties in a country, or between all participants in the interconnection. Their practice could be used for the analysis of market prices. It lies on forecasts of two main traded components (capacity and energy) in the revenue price formula for each of above services, of the form

$$R_k = p_k \cdot P_k^M + w_k \cdot W_k^d, \; k = 1, 2, \ldots K \, , \tag{6}$$

where $p_k$ is the unit price for the maximum contracted capacity $P_k^M$ and $w_k$ is the unit price for the supplied energy $W_k^d$, delivered during contracted period for each of the market transactions. Values of coefficients $p_k$ and $w_k$ are usually different, depending on parts of the day or year (for short-term market transactions), while the differentiation among individual contracts for various parties is also possible. Then, the total revenue of a participant in the trade on energy market for $K$ years from $J$ market transactions is

$$R_K = \sum_{k=1}^{K} \sum_{j=1}^{J} (p_j P_j^M + w_j W_j)_k, \quad j = 1, 2, \ldots, J \; ; k = 1,2,\ldots,K, \tag{7}$$

where $J$ represents the number of the contracted agreements in $K$ years. The corresponding average market price for the services supplied at the market during period of $K$ years through all $J$ contracts is

$$r_K = \frac{R_K}{W_K} \; , \tag{8}$$

where the total energy delivered for $J$ contracts in $K$ years is

$$W_K = \sum_{k=1}^{K} (\sum_{j=1}^{J} W_j)_k \, ; k = 1, 2, \ldots, K \, ; \; j = 1, 2, \ldots, J \tag{9}$$

When $r_K \geq LCoE$ , i.e. when the average revenue of the power plant project under consideration is equal or higher than *LCoE*, it means that the project, with the revenues from the sold services, covers all its own current expenses with the annual rate of return equal or higher than discount rate $i$ used for the calculation of the *LCoE*. In that case, the project is considered economically justifiable from the profit view-point, and *vice versa*. Figure 2 demonstrates how the profitable operation range may be determined based on loss and profit margins within the overall operation range of a PSH.

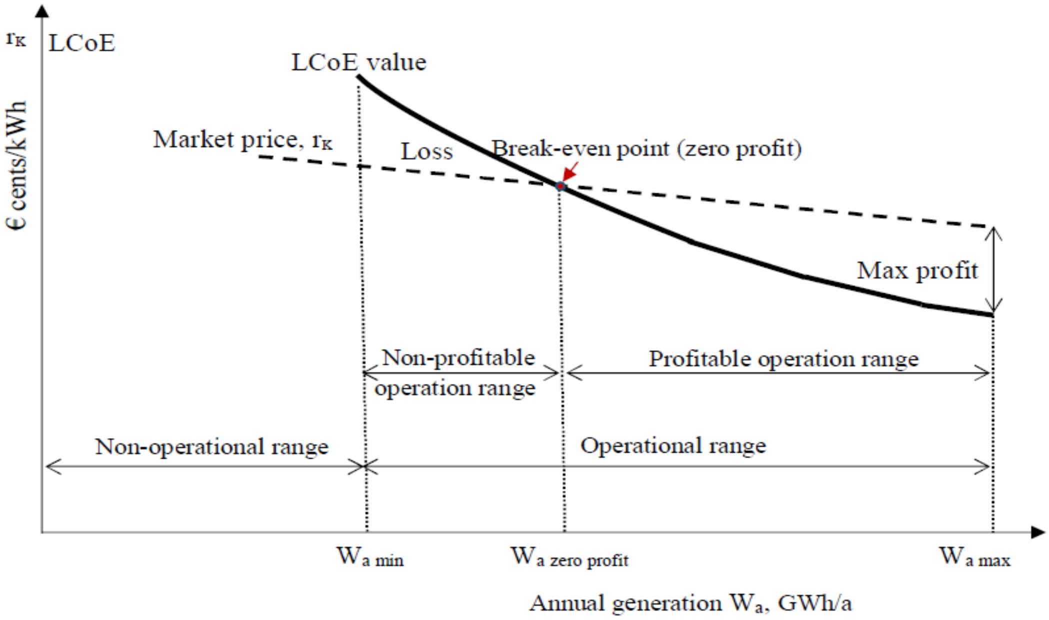


**Figure 2: Levelised cost approach to storage technology assessment**

The renewables industry has become accustomed to technology assessment based on investment costs, which are then translated to levelised cost, where only the lowest cost technologies are rewarded. This *LCoE* assessment is then used to inform policy development, so that the so-called cheapest technologies are promoted. But these two challenges for storage mean that this approach will not work for storage. The cheapest technologies might not necessarily deliver the greatest profit value, and thus it is better to examine storage through holistic case studies in context, rather than place faith in generic cost estimations. It is also important that these case studies are not examined in a geographic vacuum, as it is the local energy market that critically determines the revenue available for each service. Therefore, more system-integration approaches and evaluations are needed to add to the knowledge base.

The growth in deployment of intermittent renewables is creating new urgency around flexible markets, which would include the need to ensure that ancillary services markets are designed so as to be a level playing field for all. The development of flexible markets will help address the revenue risk associated with storage plant. The main value of PSHs is their ability to provide power quality, reliability, and security of supply. This can be in the form of uninterrupted power supply to end-users, providing some reserve margin or initial power to restart the grid after a blackout. In this context, high reliability appears to be more important than the risk of high costs.

## VI. Case Study of a Potential PSH Project

The concept of *LCoE* was widely used for the long-term generation planning based on the conventional hydro, thermal and nuclear power plants, as well as those based on RES such as wind and solar (PV) [19, 22]. However, this concept was not found to be applied so far to the PSH taking into consideration the costs of energy spent for water pumping from the lower to the upper reservoir ($C_f$ in Equation (5)). This fact was a challenge for the authors of this paper to use the *LCoE* method for the evaluation of a prospective PSH project, referring to the cost prices of electricity available in the power system in specific situations that may appear under normal operational conditions.

To demonstrate the application of the *LCoE* method, a case study was undertaken of a $4 \times 175$ MW PSH project, envisaged for construction by the year 2025, when a considerable amount of intermittent (wind and solar) generation is expected to come on line. The overall estimated investment costs of this PSH project are $C_I$=550×$10^6$ € [21, 24]. Primary goal in our case study was to find out economic ranges of the annual generation as a function of the cost of capital. For this purpose we used two discount rates of $i$ = 6 %/year and $i$ = 8 %/year. We also applied the *LCoE* concept for two different prices to be paid for electrical energy consumed by the plant when operating in pumping regime. These were $c_{pump}$=1.1 €c/kWh, which corresponds to generation by spill-over water of run-of-river HPPs (during rainy seasons) and $c_{pump}$=4.0 €c/kWh which corresponds to the surplus of generation from lignite fired power plants during night hours. These costs of energy spent for pumping are the extreme (min/max) values used for analyzing the viability of plant operation. Other parameters needed for calculations have been taken from Table 5, which also presents the main design characteristics of the reference PSH project [21].

**Table 5: Basic design characteristics of the reference PSH project [21]**

| Design characteristics | Dimensions |
|---|---|
| Average elevation of the upper reservoir level | 810.5 m |
| Active storage capacity at head of 365 m | $80 \cdot 10^6 \ m^3$ |
| Stored energy at head of 365 m, assuming efficiency $\eta = 0.81$ | 65 GWh |
| Lower reservoir max/min level elevation | 435.6 m/430 m |
| Maximum net head for 1 turbine operation | 381 m |
| Maximum net head for 4 turbines operation | 315 m |
| Maximum total head for 1 pump operation | 346 m |
| Maximum total head for 4 pumps operation | 397 m |
| Designed water flow at the net head of 365 m for 1 turbine in operation | $54 \ m^3/s$ |
| Designed water flow at the net head of 365 m for 1 pump in operation | $42 \ m^3/s$ |
| Maximum plant output at the head of 365 m (4 units in operation) | $4 \times 175$ MW |
| Designed apparent capacity of generator/motor for 1 unit in operation | 180 MVA |
| Rated power factor of the overexcited machine in generating regime ( $\cos \varphi_G$ ) | 0.95 |
| Rated power factor of the overexcited machine in pumping regime ( $\cos \varphi_M$ ) | 1.00 |

Among relationships drawn from the calculations, of particular interest for this study was the *LCoE* as a function of the annual generation of the PSH plant, explained in Figure 2. Figure 3 shows the calculated variation of *LCoE* with the annual generation $W_a$ within the assumed operational range between 425 and 560 GWh/year for the assumed four cases: case **1** ($c_{pump}$ = 1.1 €c/kWh; $i$ = 6%/year), case **2** ($c_{pump}$ = 1.1 €c/kWh; $i$ = 8 %/year), case **3** ($c_{pump}$ = 4.0 €c/kWh; $i$=6%/year) and case **4** ($c_{pump}$ = 4.0 €c/kWh; $i$ = 8 %/year). The *LCoE* values of the PSH are then compared to the assumed market price $r_K$ of the energy and capacity services (dotted line), expected when the plant will be on line.

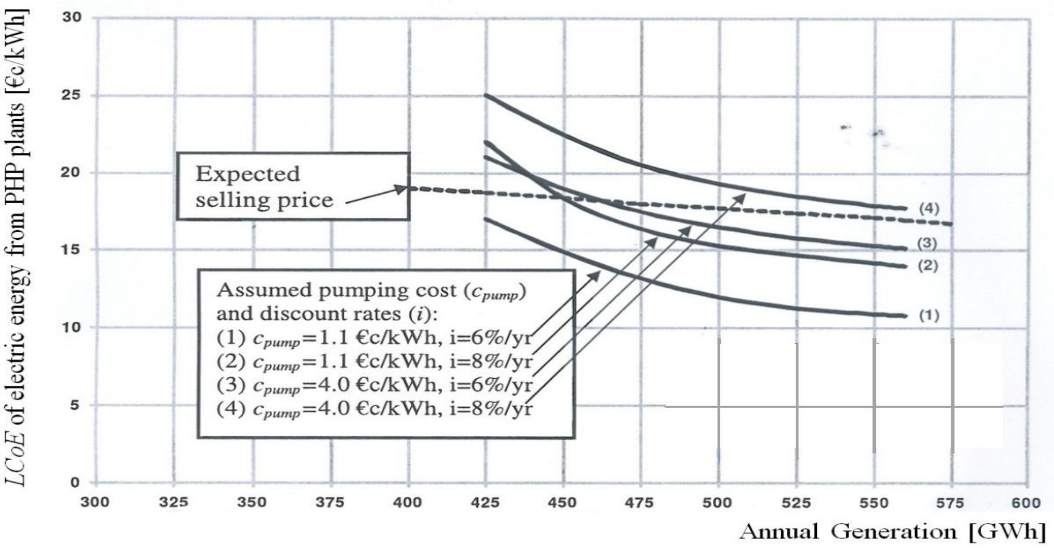


**Figure 3: *LCoE* vs. generation for the evaluation of viable operation of the PSH**

From Figure 3 it is evident that it is not possible to achieve economically viable plant operation in the whole considered range (425–560 GWh/year), but only in cases when the annual generation $W_a$ is above one defined by the criterion $LCoE \leq r_K$. Due to uncertainty of the assumed price $r_K$ for the base assumption, a sensitivity analysis was performed for the market prices $r_K \pm$ 10% an d$r_K \pm$ 20%. Points of intersection of *LCoE* and $r_K$ lines determine minima of annual generation needed for the PSH operation to be economically justified. These values are presented in Table 6. Table 6 shows that the minimum equivalent full capacity operation of the PSH should be between 701 and 921 hours per annum for the most favorable market conditions (market price $r_K$ + 20 %). For a less favorable market price $r_K$ + 10 %, the minimum full capacity operation hours should be between 736 and 863 per year. The operation would not be justified in case **4** if the cost of electricity for pumping is $c_{pump}$ = 4.0 €c/kWh and the discount rate is $i$ = 8 %/year.

**Table 6: Viable annual generation for various *LCoE* cases, GWh/year**

| | Pumping cost | $c_{pump}$ = 1.1 €c/kWh (Hydro) | | $c_{pump}$=4.0 €c/kWh (Thermal) | |
|---|---|---|---|---|---|
| | Discount rate | $i$ = 6%/year | $i$= 8%/year | $i$ = 6%/year | $i$ = 8%/year |
| Market price, $r_K$ | Base $r_K$+ 20% | ≥393 GWh/a | ≥446 GWh/a | ≥443 GWh/a | ≥516 GWh/a |
| | Base $r_K$+ 10% | ≥412 GWh/a | ≥463 GWh/a | ≥483 GWh/a | Not viable |
| | Base price $r_K$ | ≥432 GWh/a | ≥502 GWh/a | Not viable | Not viable |
| | Base $r_K$– 10% | ≥459 GWh/a | Not viable | Not viable | Not viable |
| | Base $r_K$– 20% | ≥507 GWh/a | Not viable | Not viable | Not viable |

For the assumed base price $r_K$, the operation of the plant would not be justified if the cost of electricity for pumping is $c_{pump}$ = 4.0 €c/kWh, while for the lower cost of electricity $c_{pump}$ = 1.1 €c/kWh it would be justified only if the annual equivalent full capacity operating time should be at least 771 hours and 964 hours for the discount rates $i$ = 6 %/year and $i$ = 8 %/year, respectively. If the assumed service prices are below $r_K$ by 10 % and 20 %, the equivalent full capacity annual operating time should be at least 820 hours and 905 hours respectively for the discount rate $i$ = 6 %/year, while the operation of PSH could not be justified under none of other conditions that have been considered.

The above analyses exhibit a considerable decrease of the economically viable operational range with the increase of the price paid for energy consumed for pumping, as well as with the increase of the discount rate. The calculated *LCoE* values for the PSH project are between 17 and 25 €c/kWh for generation of 425 GWh/year and between 11 and 18 €c/kWh for maximum generation of 560 GWh/year. Of particular concern is a high sensitivity of economically viable generation to the market price $r_K$ for services supplied by the PSH at the market. The volatility of this price means high risk for decision-makers in planning the PSH projects. The price volatility between 12 and 20 €c/kWh was therefore assumed with due care, taking into account expected changes at the future open market. It is comparable with the *LCoE* values of about 15 €c/kWh reported for some other generating technologies, planned to go on line by 2020 [22], the same as *LCoE* in Case **3** above for maximum annual generation of 560 GWh.

## VII. Conclusions

At the present level of electricity storage technologies, PSHs are the only practical solution for balancing system supply-demand when dealing with the growth of generation from renewable energy and related increase in share of the intermittent generation of electricity. This is due to capability of PSH to store large quantities of electrical energy for the use when balancing generation and load are needed, as well as to quickly react to compensate the changes in the variable grid conditions.

The PSH plants, as well as of all other plants in operation within an interconnected power system, follow the same operational rules and principles of valuation of their generation as all other plants. This requires a thorough evaluation of the contribution of each individual plant to the overall system security, reliability, and economy. In planning stage, this is usually achieved by using the cost-benefit analyses, while, for the long-term generation development planning, the best solutions could be found taking into account various specific aspects for the evaluation of new PSH investments according to the minimum *LCoE* criterion.

The *LCoE* concept allows comparison of various input parameters of plants-candidates for selection of those that best meet the future generation requirements. When used for PSH plants, the *LCoE* concept proves to be convenient for the evaluation of their levelized energy and investment costs and for comparison of these costs with benefits from selling services that such plant can offer at the market. Calculated for various ranges of investment and costs of energy spent for pumping, as well as of the expected market prices for capacity and energy services supplied by an individual plant, the *LCoE* values make it possible to distinguish between combinations that are economically viable and those that are not. Besides those presented herewith, it is possible to use the concept of *LCoE* for the evaluation of specific modes of the future use of PSH within power systems, such as providing necessary reserve capacities, supply of balance energy, etc.

## References


[1] *** "The Future Role and Challenges of Energy Storage", DG ENER Working Paper, European Commission, Directorate General for Energy, Brussels, 2013

[2] M. Mesarović, "Energy Storage Technologies and Renewable Energy Sources", *Termotehnika*, Vol. 34, No. 1, 2008.

[3] ***"E-storage: Shifting from cost to value - Wind and solar applications", World Energy Council, London, 2016.

[4] G.K. Jones, M.A. Laughton and M.C. Say, "Electrical Engineer's Reference Book", Butherworth- Henemann Ltd., Oxford OX2 8DP, 15th Edition, UK, 1993.

[5] ***"What's so Hard about Licensing a Pumped-storage Power Plants", *Hydro Review*, www.HydroWorld.com, 2011.

[6] *** "Europe's Pumped-Storage Potential", *Hydro Review*, www.HydroWorld.com, 2011.

[7] *** "Hydropower Storage Abroad Could Support the German "Energiewende" – WEC Germany Report, *WEC Inside*, pp. 1-15, August 2013.

[8] ***"Flexible Generation – Backing-up Renewables", Report of Euroelectric Renewables Action Plan (RESAP), Euroelectric, Brussels, Belgium 2011.

[9] J. H. Roh, M. Shahidehpour and L. Wu (2009): „Market-Based Generation and Transmission Planning With Uncertainties“, IEEE Transactions on Power Systems, Vol. 24, No. 3, Aug. 2009 pp. 1587-1598
[10] F. Van Hulle (Principal Author), "Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations"–A Report by EWEA, Brussels, Dec. 2005.
[11] *** "Role of Alternative Energy Sources: Hydropower Technology Assessment", US Dept. of Energy – National Energy Technology Laboratory, DOE/NETL 2011/1519, August 2012.
[12] *** "The European Market for Pumped-storage Power Plants", *Ecopreg*, April 2011, www.HydroWorld.com, 2011.
[13] R. L. Arántegui, N. Fitzgerald and P. Leahy, "Pumped-Hydro Energy Storage: Potential for Transformation from Single Dams“, Joint Research Centre of the European Commission, Petten, the Netherlands,2012
[14] Y. Fu, Z.Li and M. Shahidehpour, "Profit Based Generation Resource Planning", IMA Journal of Management Mathematics, 2004, 15 (4), pp. 273-289
[15] R. Ebrahimi, M. Ehsan, and H. Nouri „A Profit-Centric Strategy for Distributed Generation Planning Considering Time Varying Voltage Dependent Load Demand“, *International Journal of Electrical Power&Energy Systems*, Vol. 44, Issue 1, January 2013, Pages 168–178
[16] A. Mazer, "Electrical Power Planning for Regulated and Deregulated Markets", IEEE Press, Hoboken, NJ, USA, 2007
[17] ***"Cost-Effectiveness of Energy Storage in California: Application of the Energy Storage Valuation Tool to Inform the California Public Utility Commission", Proceeding R. 10-12-007. EPRI, Palo Alto, CA: 2013. 3002001162.
[18] *** "New Power Cost Comparisons - Levelized Cost of Electricity for a Range of New Power Generating Technologies", Report of the Australian Academy of Technological Sciences and Engineering (ATSE), March 2011(Published by the US Energy Information Agency, January 2013).
[19] S. Can Gülen, "A More Accurate Way to Calculate the Cost of Electricity", *Power Magazine*, 17. July 2011.
[20] A. Valasa III, "What is Inside Your LCoE Assumption?" Semi PV Group, The Grid-April 2010, www.pvgroup.org/NewsArchive/ctr_03626.
[21] M. Ćalović, D. Mandić and M. Mesarović, "Including Pumped Storage Hydro in Long-Term Generation Planning“, Hydro Review Worldwide, Vol. 23, No. 2., March-April 2015, pp. 28-32
[22] *** "Levelized Cost of Electricity – Renewable Energies", Fraunhofer Institut für Solare Energie Systeme (ISE), Freiburg, Germany, 2012.
[23] *** "Recent Developments in the Levelized Cost of Energy", US Department of Energy, Report NREL-DOE 2012.
[24] ***"Development of Power Generation in South East Europe – Update of Generation Investment Study", World Bank, Washington DC, 2011.