# Energy-Economic Evaluation of Pumped-Storage Plants

*Dr. Klaus Engels, Michael Brucker, Michaela Harasta und Dr. Tobias Mirbach*

## Summary

Pumped-storage plants participate in two structurally different markets: the market for scheduled energy (also known as the spot market) and the reserve market. The marketing of the available capacity from pumped-storage plants needs to be optimized in both of these markets to achieve the best possible plant scheduling in terms of revenues. Moreover, due to their ability to provide reserve market products, pumped-storage capacities within an existing power plant portfolio can create synergies for the whole portfolio. The optimized combined participation of a power plant in both spot and reserve markets as well as the coherent portfolio effect are considered particular challenges in energy-economic evaluations, e.g. in the light of investment decisions. Based on the Waldeck 2+ expansion project, and in cooperation with RWTH Aachen University, E.ON simulated for the first time an optimized combined participation of a power plant in both markets by applying an integrated optimization algorithm. The same but enhanced evaluation methodology was applied to assess the market potential of pumped-storage plants in Germany. This article presents the complex but comprehensive methodological approach used in this simulation to evaluate the energy-economic viability of pumped-storage plants.

## 1 Technical and economic importance of pumped-storage plants

### 1.1 Future structure of electricity generation

Electricity generation structures are in a state of flux. Whereas in the past electricity used to be generated primarily by large-scale power stations that tended to be located at sites of high consumption, we can expect to see an increasingly decentralized load coverage in the future. In particular the volatile and unpredictable input from wind power will expand as climate protection endeavours gather pace. In such an environment the importance of highly controllable power plants ensuring grid stability will continue to grow. Pumped-storage power plants are technically highly flexible, and it is this quality coupled with their exceptional control capabilities that makes them ideal for the role of a 'grid stabilizer'.

### 1.2 Market opportunities of pumped-storage power plants

The development of the reserve markets will be of major significance for the commercial success of pumped-storage plants. We can already anticipate a rising demand for system reserve that will create a growing market demand for pumped-storage capacities. Besides a rising demand there may appear entirely new reserve products on the reserve market, e.g. a wind balancing product or hourly reserve.

At the same time we can expect an increase in volatility of prices on the spot markets that could be commercially exploited by fully flexible facilities such as pumped-storage plants, creating additional revenue potential in the generation sector.

It follows that pumped-storage projects represent attractive investment opportunities for electricity generators, as witnessed by the large number of projects ongoing in Europe (examples: Atdorf, Waldeck 2+, Jochenstein-Riedl).

Because of their wide diversity of possible applications and resulting high degree of complexity, pumped-storage plants require highly sophisticated calculation tools for the purpose of energy-economic simulation and subsequent commercial evaluation.

# 2 Marketing of pumped-storage capacities

## 2.1 Combined participation on the spot and reserve markets

The complexity of a pumped-storage plant arises from its combined participation in two different markets, the market for scheduled energy ( à spot and futures market) and the reserve market.

For most pumped-storage plants, the bulk of revenues come from participating in the scheduled energy market. The earned contribution margin is not determined by the prevailing price level but by the spread (price differential) between peak and off-peak hours. Water is usually pumped up into the reservoir during the cheaper off-peak hours and then turbinated during the expensive peak hours (also known as process of "refinement").

Beside the market for scheduled energy there is a market for system reserve. This is based on the need to maintain a permanent balance between generation and demand. Based on the rules of UCTE there are three different reserve products in Germany: primary control power, secondary control power and minute reserve, each with a positive and negative direction. In Germany, it is the job of the transmission system operators (TSOs) to tender and procure the control reserve demand.

To maximize revenues, the capacity of a pumped-storage power plant must be optimally split between the two markets depending on prevailing market prices. From a mathematical perspective this poses a complex optimization problem when it comes to evaluating pumped-storage plants.

Another problem involves long-term price forecasting for the different products that are relevant for pumped-storage plants. Although established tools for long-term price simulation on the scheduled energy market already exist, there has so far been a lack of similar fundamental models for the reserve products, as their market mechanisms are extremely complex and difficult to model. This will pose a future challenge as reserve markets grow in importance.

## 2.2 Origin of the portfolio effect

Due to its ability to provide reserve energy in a most efficient way, (additional) pumped-storage capacity in an investor's power plant portfolio can create synergies for the whole portfolio.

This synergy potential is derived from the various technical restrictions of the different power plant technologies, especially in combination with the marketing of structurally different products in the spot and reserve market. Pumped-storage power plants can be operated fully flexible and thereby increase the degree of freedom in an existing portfolio. This greater degree of freedom can be used for a *portfolio-optimized* provision of reserve capacity and reserve energy. By integrating an additional pumped-storage plant into the portfolio, generation capacity – especially thermal power plants – that was previously tied up for providing the marketed reserve capacity can now be freed up for spot market participation. This allows to operate the thermal capacities in a better load point which results in an increase in efficiency. There are therefore two elements to the resulting portfolio effect: the higher spot market earnings of thermal power plants, and the lower specific fuel costs in the thermal sector.

However, this is subject to the assumption that there is a fully liquid spot market in which the capacities that become available can be marketed without impacting the electricity price. Another constraint is an illiquid reserve market, i.e. tradable reserve capacities are restricted and do not increase if additional hydrothermal generation units participate in the portfolio/market. But due to the limited request every reserve market is indeed illiquid.

We should also note that the potential of the portfolio effect is largely dependent on the structure of the existing portfolio. It will be particularly strong in thermally dominated portfolios, while in portfolios with a high hydro component, the portfolio effect will be weak or even nonexistent.

Nevertheless any evaluation of power plants in general – and pumped-storage plants in particular – must take an existing power plant pool into consideration, since the portfolio effect can make a substantial contribution to operating income.

### 2.3 Impact on Market Prices

As well as the value of an individual pumped-storage plant in the portfolio, the overall market potential of this technology may also be of interest to an investor wishing to assess how much commercially meaningful pumped-storage capacity he can put on the market.

Such an assessment cannot ignore anymore the impact that additional capacity has on electricity prices, as it was acceptable for the evaluation of a single additional facility in the portfolio and market (**à** assuming a perfectly liquid electricity market, see above).

Therefore, for this purpose, energy-economic portfolio simulations (power generation and trading) must be combined with market simulation methods. One approach to an evaluation of this type is presented in Chapter 5.

## 3 Energy-Economic Simulations

The contribution margin is determined by applying an approved optimization method for power generation and trading planning that has been developed by the Institute of Power Systems and Power Economics; this method considers markets for scheduled energy (spot market) as well as markets for system reserve [01], [02].

### 3.1 Method for Power Generation and Trading Planning

Power generation and trading planning is a highly complex, multi-dimensional, mixed-integer, non-linear optimization problem for which constraints that apply to all systems and times have to be taken into account. Standard procedures based on mixed-integer linear programming (MILP) might be used to solve the problem if the problem can be linearized. However, given the complexity of this particular problem (large power plant portfolios and simulation period of one year in an hourly granularity), the long computing times and a high demand on hardware preclude such an option as the complexity of the problem rises exponentially with the amount of integer variables, rendering the current optimization problem unfeasible for closed-loop approaches.

Decomposition procedures are practical approaches that break the optimization problem down into smaller sub problems that can be solved iteratively by coordinating their individual solutions. The relevant nonlinear and integer characteristics of each component and market can be taken into account using this approach. The entire procedure consists of several individual optimization stages, each applying the best fitting optimization algorithm – such as dynamic programming (DP), successive linear programming (SLP) and quadratic programming (QP) – to the sub problem of the entire generation and trading planning. At the same time all constraints in the system domain are satisfied due to their coordination by Lagrange relaxation. Lagrange relaxation is a decomposition approach based on the concept of reducing the main problem to less-dimensional sub problems. An overview of the structure of the HERMES optimization method is shown below [03].

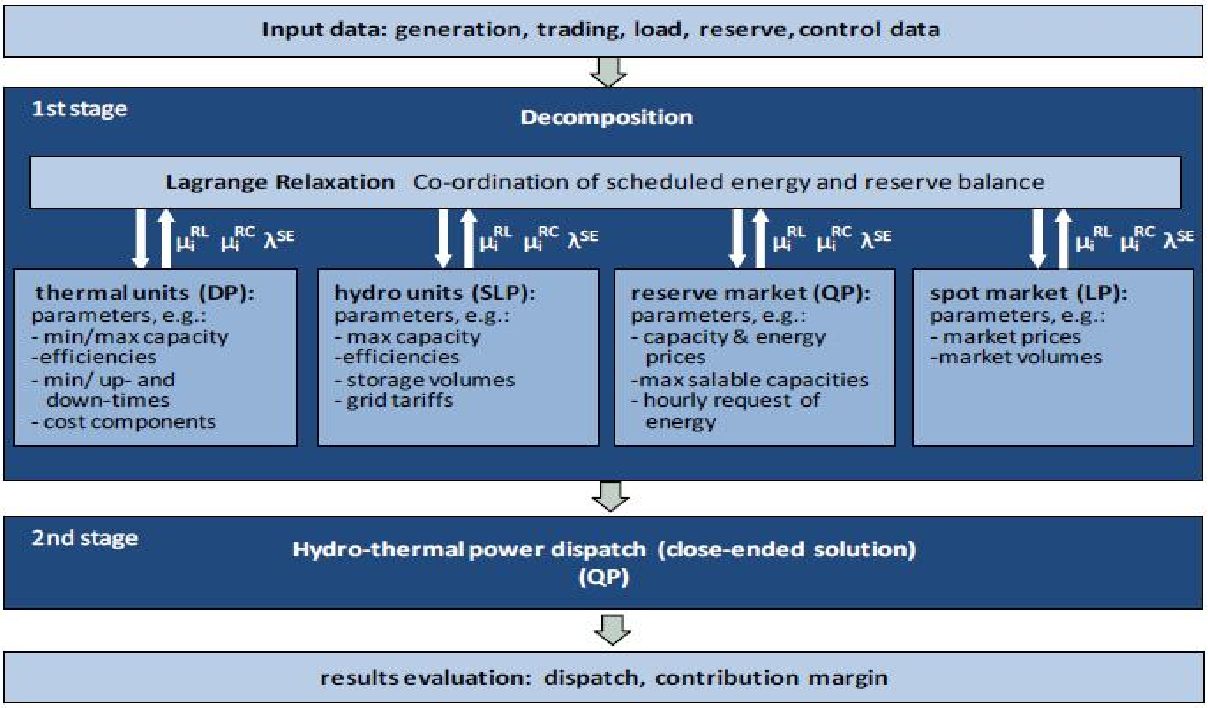


**Fig. 1** Method overview

The result of the power generation and trading tool is the optimal energetic dispatch of all considered power plants on markets for scheduled energy and system reserve taking into account all technical restrictions of the power plants such as minimum and maximum output levels, minimum up and down times as well as organizational constraints of markets (minimum bids). Additionally, the tool determines hourly power plant schedules for each generator divided into scheduled energy, reserve capacity and reserve energy. Consequently the contribution margin of the entire portfolio can be computed. A high solution quality can be demonstrated for short-term problems by comparing simulations which have been conducted for the iterative decomposition approach and closed-loop optimization (MILP) which attains the guaranteed optimum. A detailed quantification of a new power plant's technical and economic impact on an existing power generation portfolio can be determined in this way.

### 3.2 Input Data

The input data for the generation and trading planning comprises the different parameters of the system components. On the supply side of electricity, these specifically include the technical parameters of the power plants and their different generation cost components, whereas prices and quantities are relevant for market modelling. The spot market is modelled by a chronological spot price curve on an hourly basis. Owing to the high observed liquidity of the EEX spot market, no price gradient or limit on the quantity tradable on the spot market are applied to our simulation calculations. The reserve markets are modelled as a function of the reserve quality (primary, second control and minutes reserve) and allowing for the differentiated consideration of the supply of reserve capacity and the provision of reserve energy. Input data include both the prices for reserve capacity and reserve energy and the maximum marketable reserve capacity of the various reserve products due to the limited tender quantities on the reserve markets of German transmission system operators. Because of the low calling signal for reserve energy – especially for minutes reserve – the markets for primary control and minute reserve are modelled as pure capacity markets. An hourly calling signal of reserve energy is taken into consideration for secondary control reserve.

### 3.3 Result – Derivation of the various contribution margin components

The power generation and trading planning tool performs an optimization of the entire power plant portfolio. Because of the interactions within the portfolio, the value of a single plant cannot be determined by simply evaluating the scheduled energy and reserve sold by that single plant on a stand-alone basis. Instead there has to be a comparative analysis of the power plant portfolio that both includes and excludes the power plant that is to be evaluated. The value of a particular plant can then be quantified by a differential consideration of the performed simulation calculations.

In order to be able to analyze the different components of the earned contribution margin of the power plant, various simulation calculations are performed. The total contribution margin consists essentially of three components: contribution market from spot market, reserve market and portfolio effect. Figure 2 illustrates the methodology and the simulations required to determine the different contribution margin components

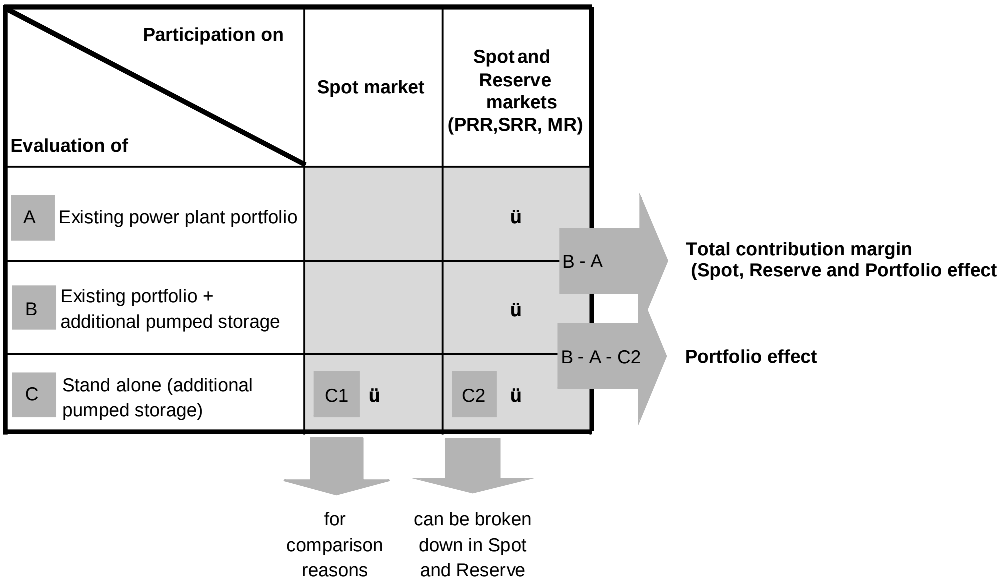


**Fig. 2** Determination of the different contribution margin components

## 4 Investigation based on Waldeck 2+

Taking the Waldeck 2+ expansion project as a concrete example, E.ON has applied the energy-economic evaluation method described in Section 3 for the first time in an end-to-end investigation concept.

### 4.1 Derivation of the optimum level of expansion

The additional pumped-storage power plant Waldeck 2+ was incorporated into E.ON's existing power plant fleet by incrementally increasing turbine and pumping capacity and the various achievable contribution margins (spot, reserve and portfolio effect) were simulated in separate optimization calculations. Because of the size constraint for the existing upper reservoir (à limiting factor in the system) the contribution margin curve is not linear but levels out as capacity increases. A profitability analysis compared the anticipated investment costs of each expansion stage with the attainable contribution margins. In this way it was possible to define an economically optimum capacity range which was then investigated further using smaller simulation steps both upwards and downwards but applying the same methodology.

### 4.2 Derivation of the optimum engine concept

A further step in the investigation involved simulations for determining the optimum engine concept. Three basic concepts are available, differing mainly in their controllability during pumping mode and the possible minimum load of the turbines:

- Pumping turbine with synchronous generator – cannot be controlled in pumping mode, turbine has a high minimum load
- Pumping turbine with asynchronous generator – can be controlled in pumping mode in the upper capacity band, turbine has medium minimum load
- Three-engine set with separate turbine and pump plus converter – fully controllable in pumping mode by running the hydraulic short circuit, turbine has low minimum load

The technical ability to participate in the different reserve markets was defined for each engine concept and operating mode (pumping or turbining mode). Owing to the extreme complexity of the mathematical problem however, this optimization calculation could 'only' be performed in the interconnected Waldeck group and not in the portfolio as a whole. However, comparing achievable contribution margins of the different engine types with related investment expenditure, the commercially optimum engine concept could be derived.

### 4.3 Sensitivity Calculations

The engine concepts that were investigated differ mainly in their ability to participate in the markets for different reserve products. A decision for or against a particular engine concept therefore depends largely on the assumptions about the underlying reserve market prices. Therefore sensitivity calculations were carried out with incremental upward and downward price variations for the individual reserve products while spot prices at the same time remained unchanged.

## 5 Assessment of the Market Potential for Pumped-Storage Plants

Additionally, E.ON has launched a study to assess the overall market potential for pumped-storage power plants in Germany.

The valuation method employed a three-stage investigation process to address the impact on spot market prices, if additional generation capacities are brought into the system.

*Stage 1: Market simulation to determine the electricity price in defined market scenarios*

The market scenarios were defined by their relevant influencing variables, mainly the hydrothermal power plant fleet for each market area, the installed capacity of wind power plants, primary energy and $CO_2$ prices, load, reserve demand and transmission capacities between the market areas. The market simulation calculated the economically optimum, i.e. least-cost power plant utilization needed to cover the demand while allowing for power plant-specific restrictions. On the basis of the hourly power plant utilization determined in this way, generation cost based market prices for scheduled energy could then be estimated.

*Stage 2: Market simulation considering new build capacity*

Since additional power plant capacities affect electricity market prices, market simulations for different new build scenarios had to be performed. These new build scenarios differ from the basic market scenarios only in the *additional* (pumped-storage) capacity introduced into the system. Various new build scenarios representing different expansion stages of the system were defined.

*Stage 3: Contribution margin calculation from portfolio simulation*

To evaluate the market potential of pumped-storage new build units, this third stage simulated their spot and reserve market participation in incremental expansion stages. For this purpose the method described in Chapter 3 was used. To ensure the reliability of the results, the use of the related and hence consistent electricity price is essential when simulating an expansion stage. Result of these simulations was the contribution margins that can be generated with each expansion stage in the portfolio. While additional pumped-storage capacity earns extra revenue on the spot market, the contribution margin of the remaining portfolio decreases. This is because of the negative impact of that additional capacity on the electricity price. By comparing the contribution margins of the various expansion stages, it was possible to identify the expansion level that generates the maximum profit from an overall portfolio perspective.

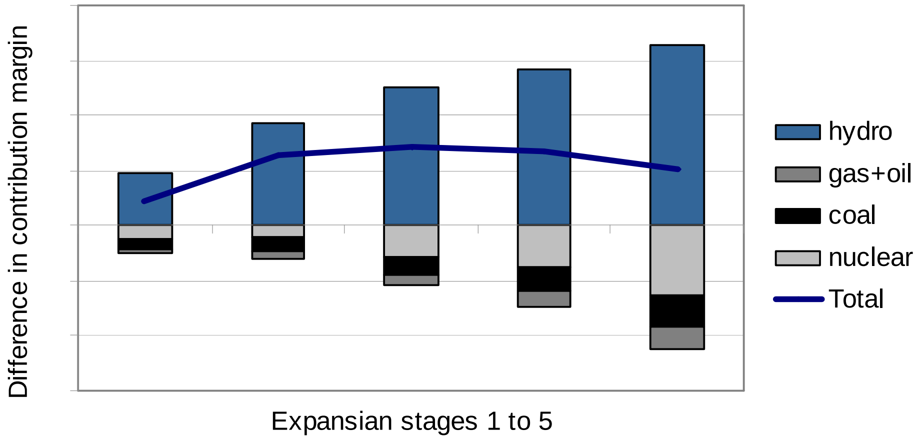


**Fig. 3** Effect of pumped-storage expansion on the contribution margin of the portfolio

## 6 Experience and conclusion for industry

Both reserve revenues and portfolio effect move in orders of magnitude (+92% compared with pure spot marketing in the example of Waldeck 2+) that not only justify the use of complex calculation tools for the solid evaluation of pumped-storage plants but also show it to be indispensable.

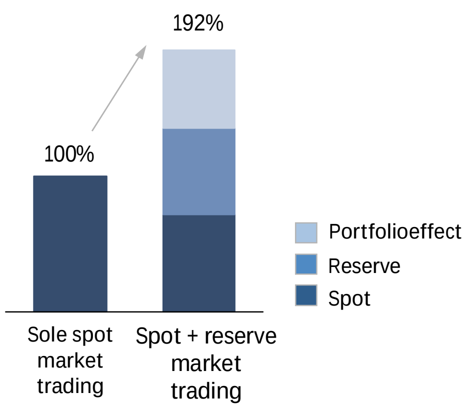


**Fig. 4** Rise in contribution margin when using the evaluation approach described

Assumptions for the development of the reserve markets are of major significance for the evaluation. While established tools are available for long-term predictions on the scheduled energy market, there is a lack of such fundamental models for the reserve markets. Subsequently there is a need for action.

The high degree of detail used by RWTH Aachen in the Waldeck example when modelling systems and markets, and the underlying mathematical methods, involve long computation times. More pragmatic approaches that favour faster computation speeds while still producing reliable results must now be found for an industrially viable use of such tools.

**References**

[01] Hartmann T: "Bewertung von Kraftwerken und Verträgen im liberalisierten Strommarkt" [Evaluation of power plants and contracts in the deregulated electricity market]. Dissertation RWTH Aachen, Aachener Beiträge zur Energieversorgung, Klinkenberg Verlag, Bd. 114, Aachen, 2007

[02] Mirbach T: "Marktsimulationsverfahren zur Untersuchung der Preisentwicklung im europäischen Strommarkt" [Market simulation method for investigating price trends on the European electricity market]. Dissertation RWTH Aachen, Aachener Beiträge zur Energieversorgung, Klinkenberg Verlag, Vol. 128, Aachen, 2009

[03] Hartmann T, Blaesig B, Hinüber G und Haubrich H-J: "Stochastic optimization in generation and trading planning". Proc. Operations Research 2006, pp. 249-264, Karlsruhe, 2007

**The Authors**

**Dr.-Ing. Dipl.-Wirt. Ing. Klaus Engels** is Vice President Asset Risk & Governance for the European hydro fleet of E.ON Generation. Prior to that he was Head of Corporate Development at E.ON Wasserkraft, which is E.ON's German hydro branch. After studying electrical engineering at RWTH Aachen University he worked for another European Utility and an international strategic consultancy before joining E.ON.

**Michael Brucker** studied mechanical engineering at Munich University of Technology and started his career as a design engineer. He joined the predecessor company of E.ON in 1992 and was in a first position responsible for authorisation procedures according to the emission protection law. Afterwards he was Key Account Manager for industrial clients before he became head of the energy economics department at E.ON Wasserkraft.

**Michaela Harasta** works as an investment project specialist within the European hydro fleet of E.ON. She is responsible for economic evaluations and is project manager for the ongoing research studies in cooperation with RWTH Aachen University. After graduating as an industrial engineer she worked for an international plant engineering company and another European utility before joining E.ON.

**Dr.-Ing. Tobias Mirbach** studied Electrical Engineering at RWTH Aachen University where he graduated in 2005. Afterwards he became member of the academic staff of the Institute of Power Systems and Power Economics at Aachen University where he is now head of the research group “Power Generation and Trading”. Besides the ongoing studies with E.ON he has worked on numerous other research and industry projects.