OPTIMIZED MACHINE CONCEPT FOR PUMPED-STORAGE PLANTS THROUGH COMBINED DISPATCH SIMULATION FOR WHOLESALE AND RESERVE MARKETS

Optimisation de la conception des équipements d'une station de transfert d'énergie par pompage grâce à la simulation du dispatching pour le marché de gros, de réserve et d'ajustement

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I SUMMARY

In Germany's energy markets of today, pumped-storage power plants offer excellent business opportunities due to their outstanding flexibility. However, the energy-economic simulation of pumped-storage plants, which is necessary to base the investment decision on a sound business case, is a highly complex matter since the plant's capacity must be optimized in a given plant portfolio and between two relevant markets: the scheduled wholesale and the reserve market. This mathematical optimization problem becomes even more complex when the question is raised as to which type of machine should be used for a pumped-storage new build option.

For the first time, it has been proven possible to simulate the optimum dispatch of different pumped-storage machine concepts within two relevant markets – the scheduled wholesale and the reserve market – thereby greatly supporting the investment decision process. The methodology and findings of a cooperation study between E.ON and RWTH Aachen University in respect of the German pumped-storage extension project "Waldeck 2+" are described, showing the latest development in dispatch simulation for generation portfolios.

La grande flexibilité de fonctionnement des Stations de Transfert d'Energie par pompage offre des opportunités de développement exceptionnelles sur le marché allemand de l'énergie. Avant de prendre une décision d'investissement, il est indispensable de réaliser une étude de rentabilité approfondie qui s'appuiera sur une simulation énergético-économique complexe. La capacité de production de la centrale doit être optimisée au sein un portefeuille de centrales et en mesurant les contributions des marchés de gros, de réserve et d'ajustement. La résolution mathématique du problème est encore plus complexe lorsque l'étude doit permettre d'optimiser la sélection des machines qui équiperont une nouvelle construction.

Pour la première fois, il a été démontré qu'il est possible de simuler un dispatching optimal de l'énergie produite par différents types de turbine pompe sur les deux marchés précités, offrant ainsi des éléments de décision pour l'investissement. La méthodologie et les résultats d'une étude conjointe menée par E.ON et par l'université d'Aix La Chapelle (RWTH) dans le cadre de l'extension du projet de 'Waldeck 2+' en Allemagne sont décrits par la suite, illustrant le dernier développement de simulation de dispatching dans des portefeuilles de production d'énergie.

II ENERGY-ECONOMIC EVALUATION APPROACH FOR PUMPED-STORAGE PLANTS

II.1 Combined participation in wholesale and reserve markets

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

To maximize revenues, the capacity of a pumped-storage power plant must be optimally split by its operator 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 issue 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 since their market mechanisms are extremely complex and difficult to model. This will pose a particular challenge in the future as reserve markets will become even more important.

II.2 Origin of the portfolio effect

Due to its ability to provide reserve energy in a very 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. Pumped-storage power plants can be operated fully flexibly, which thereby increases 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 of thermal plants that was previously tied up for providing the marketed reserve capacity can now be freed up for spot market participation. Consequently, the thermal capacities can be operated at a better load point, resulting in efficiency enhancements. All in all, two elements are included into the portfolio effect: the higher spot market earnings of thermal power plants, and the lower specific fuel costs in the thermal sector.

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

II.3 Optimization Methodology

As the power generation and trading planning is a highly complex optimization problem including both nonlinear and integer decisions, a closed-loop formulation is only possible by applying Mixed Integer Programming (MIP) or decomposition approaches [1]. Decomposition procedures are practically approved approaches dividing the main problem into smaller sub problems, which can be solved iteratively by coordinating their individual solutions. Using this approach, all nonlinear characteristics and integer decisions of each component and market can be taken into account. The entire procedure consists of several individual optimization stages, which every time apply the best fitting optimization algorithm to the sub problem of the entire generation planning.

Due to the relaxation of system coupling constraints, it cannot be guaranteed that they are met in each time interval of the optimization unless computation time is unlimited. Therefore, only integer decisions such as thermal unit commitment regarding time constraints and generation boundaries are adapted from the first optimization stage. Accordingly, in the second optimization stage, the remaining continuous optimization problem can be solved in a close-loop approach (energetic dispatch) in order to assure the compliance of time and system coupling constraints.

The result of the power generation and trading tool is the optimal participation of all considered power plants in markets for scheduled energy and system reserve.

Fig. 1 gives an overview on the used multistage decomposition optimization model [2], [3].

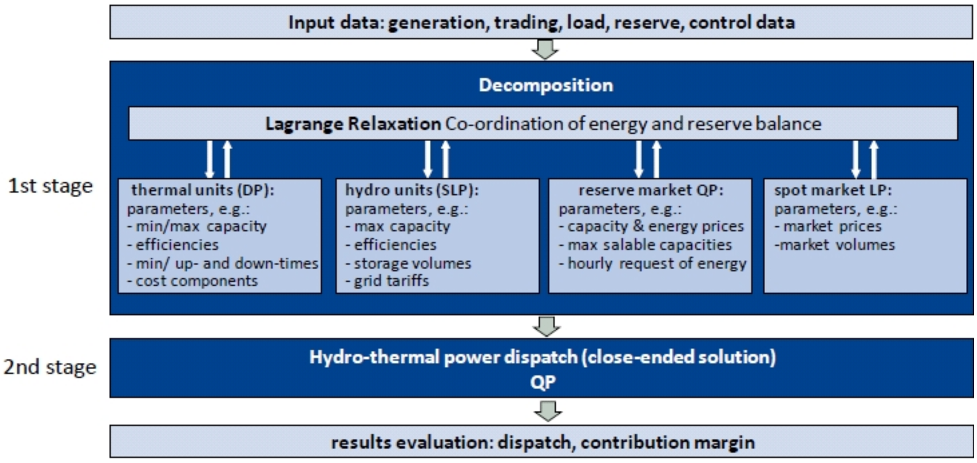

Fig. 1: overview of the optimization method for power generation and trading planning with DP: Dynamic Programming, SLP: Successive Linear Programming, QP: Quadratic Programming, LP: Linear Programming

III EXTENSION OF EVALUATION APPROACH

III.1 Context & Background

The above described approach was used for the Waldeck 2+ extension project in order to find the economically optimal extension stage for capacity and upper reservoir size. An additional question was then which type of machine should be used for the new build option. Basically three technical concepts are available and were considered in the following investigation scope:

- Pumped turbine with synchronous generator
- Pumped turbine with asynchronous generator
- Ternary machine set

The machine type defines major flexibility parameters, which are particularly relevant to the plant's ability to participate in reserve markets. Given the growing relevance of the reserve markets, the decision about the machine type is of crucial importance to the financial success of a pumped-storage investment. However, the mathematical optimization problem becomes even more complex.

III.2 Further development of optimization methodology

The final closed-loop approach of the model described under II.3 is a quadratic formulation of the optimization problem. This formulation lacks the adequate degree of details that is necessary to compare different types of machine. As a result, the optimization model had to be changed into a mixed-integer problem (MIP), in which semi-continuous variables and binary variables could be used. MIP formulations lead to higher computing times so that only the simulation of the Waldeck group from a standalone perspective (not within the portfolio) could be carried out. Two main aspects needed to be changed:

Firstly, the linear formulation always includes the allowance of what is known as the "hydraulic short circuit" (pump and turbine being operated at the same time). However, when a pump-turbine – a turbine that can be operated reversibly as a pump – is considered, the hydraulic short circuit has to be prohibited since it is not technically possible. The prohibition of the hydraulic short circuit directly involves the use of binary variables, as is the case for a decision problem, where two variables are directly dependent on each other.

Secondly, a linear formulation does not allow the modeling of machines with a minimum load higher than zero, since this is a non-linearity in the definition range of the variables. Therefore, turbines and pumps with a minimum load of more than 0 MW cannot be pictured, such as a so called "binary pump," which can only be run at full power.

III.2.1 Avoiding hydraulic short circuit

Two binary variables for each interval and machine are introduced. The binary variables $B^i_{SP,m}$ and $B^i_{ST,m}$, with *m* being the iterator for the machine and *i* for the time period, are supposed to indicate in which state of operation a machine currently is set. Equation (1) and (2) indicate the approach.

Pump-turbine in mode of pumping è $B^{i}_{SP,m} = 0$, else $B^{i}_{SP,m} = 1$ (1)

Pump-turbine in mode of turbining è $B^{i}_{ST,m} = 0$, else $B^{i}_{ST,m} = 1$ (2)

The prohibition of the hydraulic short circuit is ensured by the additional equation (3).

$$B^{i}_{ST,m} + B^{i}_{SP,m} \geq 1 \quad (3)$$

III.2.2 Minimum power of operation

To ensure that a machine is only driven in an operation area between P_{min} and P_{max} , the respective constraints (equations (4) and (5)) were added. The example accounts for a turbine, and the pump is built accordingly. Scheduled energy, reserve power and energy are considered in the equations. Thus, equation (4) leads to the conclusion that in a turbine the sum of scheduled energy, reserve power and reserve energy must either be zero or be in the interval between the machine’s minimum and maximum power output. Conversely, in a turbine the sum of negative reserve power and energy must not exceed the amount of scheduled energy and the resulting operating point must again either be zero or in the interval between minimum and maximum power (see equation (5)).

$$E^{i}_{SE} + \sum_{j=1}^{n} P^{i}_{Res,j} + \sum_{j=1}^{n} E^{i}_{Res,j} - SC_{max,pos} = 0 \quad (4)$$

$$E^{i}_{SE} - \sum_{k=1}^{m} P^{i}_{Res,j} - \sum_{k=1}^{m} E^{i}_{Res,j} - SC_{max,neg} = 0 \quad (5)$$

E^{i}_{SE} Scheduled Energy at the spot market by machine *i*

$E^{i}_{Res,j}$ Energy sold at market *j* for control reserve by machine *i* (demanded reserve energy)

$P^{i}_{Res,j}$ Remaining capacity sold at market *j* for control reserve by machine *i*

n Number of markets for positive control reserve

m Number of markets for negative control reserve

P_{min} Minimum Power of the machine

P_{max} Maximum Power of the machine

$SC_{max,pos}$ $SC_{max,neg}$ Semi-Continuous variables with a domain of $0 \vee \{P_{min};P_{max}\}$

Moreover, additional constraints are added to ensure operation in correct power limits even when running in only reserve mode. The constraint for a turbine and positive reserve is pictured in equation (6).

$$\sum_{j=1}^{n} P^{i}_{Res,j} + \sum_{j=1}^{n} E^{i}_{Res,j} = \{0; P_{max} - P_{min}\} \quad (6)$$

The consideration of all of these constraints allows the correct operation of the plants in compliance with the minimum and maximum power.

IV INVESTIGATION PROGRAM AND RELEVANT INPUT PARAMETERS

IV.1 Investigation program

An integrated portfolio simulation was no longer possible due to the high complexity. For this reason, the investigation was performed in two stages:

- Portfolio simulation with the new PSP being a ternary machine concept without consideration of minimum power constraints that forms the easiest optimization problem from a mathematical perspective. This portfolio simulation provides the portfolio-optimized reserve market participation of Waldeck 2+, which is used as input parameter in the second stage.
- Stand-alone comparative simulations for only the Waldeck Group with maximizing the contribution margin of the Waldeck-Group as objective function. Reserve market participation of the new build Waldeck 2+ from the portfolio simulation (see above) was defined as maximum sellable reserve volume for the stand-alone simulations.

IV.2 Market parameters

The investigation was performed based on the 2009 market environment. Therefore, both, hourly spot market prices and prices for each referring product at the reserve markets observed in 2009 were used as input data in the simulation model.

IV.3 Defined technical engine parameters

In a bid to keep the optimization problem manageable, the focus was directed to the two main flexibility parameters:

- Controllability of load during pump-mode
- Minimum stable load of the turbine

With the machines being defined as follows:

Pumped turbine with synchronous generator: turbine with relatively high minimum load of about 33% of the installed capacity; pump is not controllable, only operation at full or zero capacity is possible.

Pumped turbine with asynchronous generator: turbine with lower minimum stable load of about 22% of installed capacity**;** pump is controllable, but limited to a band between about 70 to 100% of its installed capacity.

Ternary machine set: lowest minimum stable load of about 13% of installed capacity. Pump itself is not controllable (only on or off) but full controllability achievable by running the hydraulic short-circuit.

IV.4 Ability to participate in various reserve markets

Depending on the type of machine installed, the pumped-storage plant can participate in the following markets:

Technology/operation mode		Marketing possibilities						
		Whole-sale	Primary Reserve		Secondary Reserve		Minute Reserve	
			pos.	neg.	pos.	neg.	pos.	neg.
Turbining mode	Pump-turbine with synchr. generator	x	x	x	x	x	x	x
	Pump-turbine with asynchr. generator	x	x	x	x	x	x	x
	Ternary machine set	x	x	x	x	x	x	x
Pumping mode	Pump-turbine with synchr. generator	x	-	-	x	-	x	-
	Pump-turbine with asynchr. generator	x	x	x	x	x	x	x
	Ternary machine set	x	x	x	x	x	x	x

Fig.2: allowed reserve market participation of various machine types

Attractive revenue possibilities were particularly noted for negative control reserve during off-peak hours, when machines are expected to be operated in pumping mode. These products can only be fully offered by a machine type that offers controllability in pumping mode.

The “standstill” mode could not be computed in the model due to the degree of complexity associated with it. As a result, it was omitted, with the consequence that even if a standstill were to occur, the plant would still be able to participate in the primary reserve market, which is not physically possible (a backup by portfolio is required). However, the number of standstill hours was limited so the mistake is negligible.

V RESULTS AND FINDINGS

V.1 Simulated 24 h electricity output of various types of machine

Figure 3 shows an exemplary 24 h electricity output (hours do not represent day time) with wholesale market participation and called reserve energy of the various types of machine as a result of the mathematical optimization:

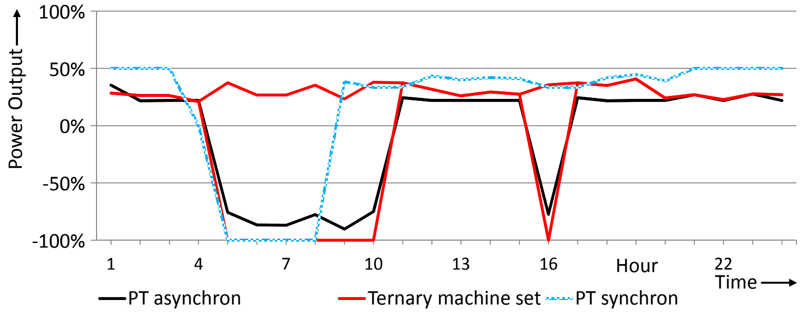

Fig. 3: exemplary 24 h electricity output in % of full load (comparison between types of machine)

Pump-turbine with synchronous generator: pumping occurs during morning hours (hour 5 to 8) with the pump running at its full capacity. Due to the lack of controllability, no other mode is technically possible for the pump. Turbining takes place at a low load throughout the day, but never falls below the defined minimum load restriction.

Pump-turbine with asynchronous generator: pump does not run at its full capacity since it offers limited controllability, turbining occurs at low load but above defined minimum load throughout the day (except hour 16, where pumping occurs)

Ternary machine set: turbine is continuously operated throughout the day far below full load, the hydraulic short circuit is applied in hour 5 to 10 and hour 16. Hence, no classic PSP behavior is observable with pumping throughout night hours and turbining during peak hours.

In summary, it can be concluded from the above that none of the three engine types ever runs at full load at the wholesale market, which suggests that a high amount of capacity is held back for reserve market participation. The turbines run at minimum load even during off-peak hours in order to be able to participate in the very lucrative primary reserve market.

V.2 Simulated run-of-day schedule for pump-turbine with synchronous generator

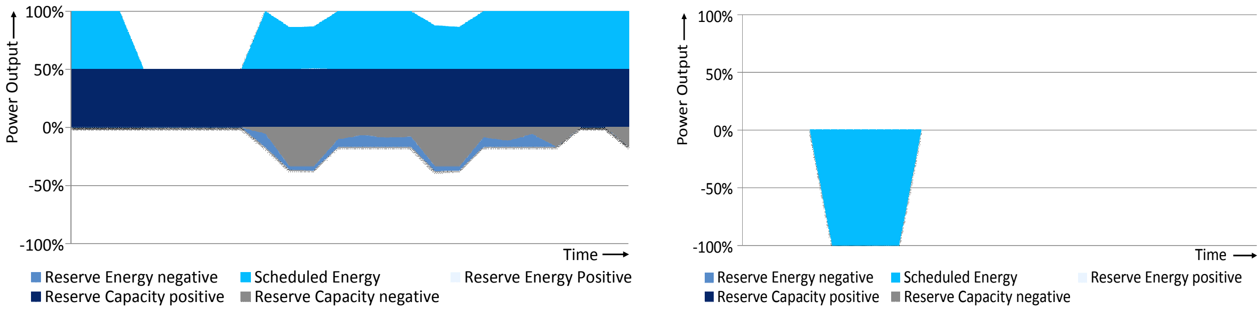

Fig. 4: run-of-day schedule of pump-turbine with synchronous generator (left: turbine, right: pump)

Turbine: A constant band is sold to the market for positive primary control reserve. During pumping hours no positive wholesale and/or reserve energy can be sold due to the use of a reversible pump-turbine. The machine shows a relatively high degree of inflexibility due to its binary pump. Accordingly, there is only limited participation possible in negative control reserve market with no negative primary control reserve sold at all.

Pump: The pump only participates in the wholesale market because the lack of flexibility does not make it possible to participate in markets for control reserve. Positive scheduled energy amounts to zero during pumping hours as the hydraulic short circuit is prohibited in the use of the pump-turbine. However, participation in the positive primary reserve market is possible as indicated on the left side in dark blue, but if called for positive primary energy, the machine has to be supported by other plants of the portfolio potentially leading to fuel costs which are not balanced here. This may lead to a slightly overestimated contribution margin.

V.3 Run-of-day schedule for pump-turbine with asynchronous generator

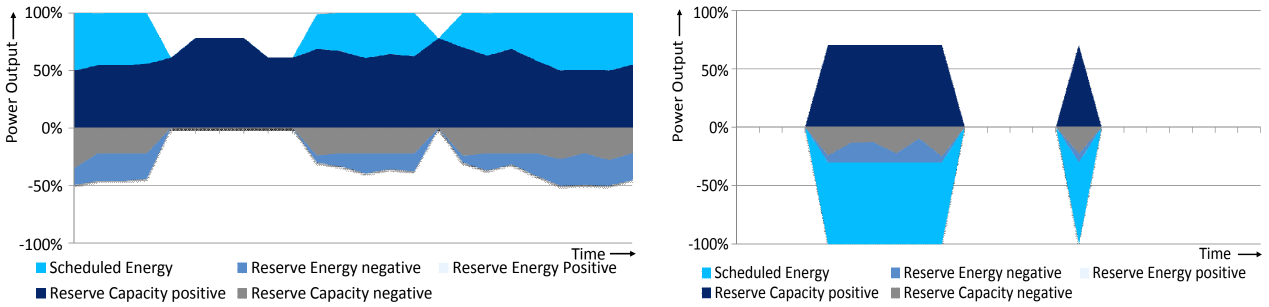

Fig. 5: run-of-day schedule of pump-turbine with asynchronous generator (left: turbine, right: pump)

Turbine: During hours of pumping again no positive spot and reserve energy is sold due to the fact that it is a reversible pump-turbine. The turbine participates to a higher degree in the reserve markets, especially in markets for negative secondary control reserve but also in positive and negative primary control reserve.

Pump: The pump can participate in the negative reserve market within the defined controllability bandwidth. The remainder at full capacity is operated in the wholesale market. If called for positive primary energy, the plant may need to be supported by the portfolio, which leads to a slightly overestimated contribution margin.

V.4 Run-of-day schedule for ternary machine set

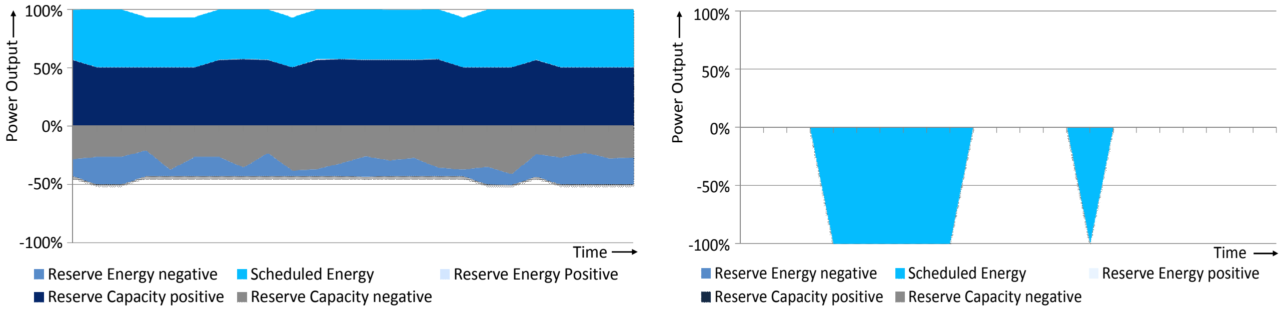

Fig. 6: run-of-day schedule of ternary machine set (left: turbine, right: pump)

Turbine: Participation in the scheduled energy market is well above minimum load throughout the day (even in off peak hours) in order to be able to reduce load when called for negative control reserve energy. Reserve market participation makes up for a larger share than in the pump-turbine options, particularly negative primary and secondary reserve.

Pump: Due to the ability to run a hydraulic short circuit, pumping and turbining can occur simultaneously. The pump itself can only participate in the wholesale market due to its binary nature and the flexibility in turbining mode.

V.5 Comparison and breakdown of achievable contribution margin

Figure 7 shows a comparison of the achievable annual contribution margins between the three machine concepts. The pump-turbine with asynchronous generator and the three machinery set reach virtually the same level of achievable contribution margin, whereas the pump-turbine with synchronous generator shows significantly lower earnings (-20%).

Figure 8 shows the revenue structure for the pump-turbine with asynchronous generator. The pumped-storage plant is, according to simulation results (2009 actual market prices), optimized for reserve market participation (especially primary control reserve) with wholesale market revenues as a side product only.

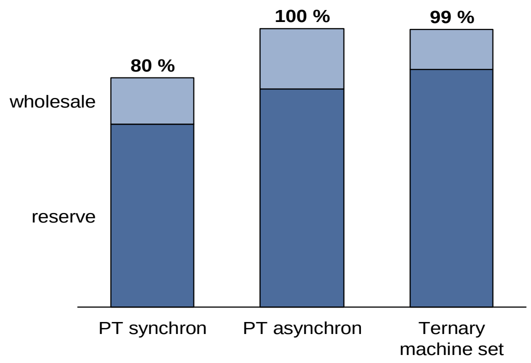

Fig. 7: comparison of achievable contribution margin

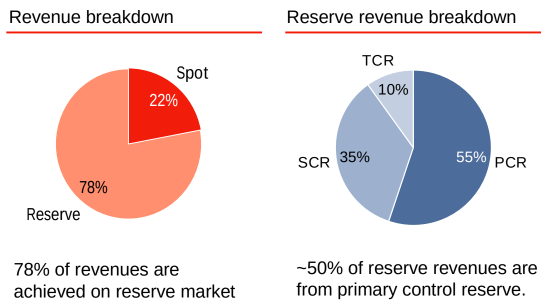

Fig. 8: revenue breakdown for pump-turbine with asynchronous generator

The simulations were performed for different plant capacities. For high capacities the pump-turbine with asynchronous generator was more beneficial than the ternary machine set while for the lower capacities the ternary machine set became more beneficial. In all cases, the pump-turbine with synchronous generator showed a significantly lower contribution margin.

Sensitivity analyses were also carried out regarding reserve market prices. In an environment with even higher reserve market prices than in 2009 (assuming same wholesale price level) the machine concepts showing high flexibility became even more beneficial compared to the inflexible pump-turbine with synchronous generator. In a low reserve price scenario, the pump-turbine with asynchronous generator showed higher contribution margin than the ternary machine set.

Comparing the simulated achievable contribution margins with the respective investment costs for the various machine concepts in cost-benefit analysis it could be concluded that the pump-turbine with an asynchronous generator is the most beneficial concept for the Waldeck 2+ project.

VI CONCLUSIONS

The mathematical optimization of a pumped-storage plant between both markets – wholesale and reserve – suggests that, at least in the German market environment, most revenues can be achieved in the reserve market, irrespective of the type of machine selected.

The differentiation between machine types shows that a certain degree of flexibility, whether in the ability to run a hydraulic short circuit (ternary machine set) or to vary the power output of the pump (pumped turbine with asynchronous generator), is a key factor and leads to significant gains in contribution margin.

Expanded reserve market participation will lead to different run-of-day schedules for pumped-storage plants in the future. Instead of today's traditional schedule with pumping during off-peak hours, turbining during peak hours and longer stand still times in between, it can be expected that plants will instead be run according to the mathematically optimized schedule (see above).

The results of the study are valid only for the German market environment with its specific reserve market structure and products. Simulated revenue breakdown and most beneficial machine type may be different in other markets, such as the French market, which is subject to investigation during project development.

Investment decisions in highly flexible power plants must be supported by the use of very sophisticated simulation tools to adequately reflect the respective plant's full abilities in the underlying business case.

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