Evaluating the Benefits of Stochastic Optimization for Hydro Assets

Florian Kämpfer and Eric Winnington

***Abstract*-- The optimal position planning and dispatching of flexible power plants is based on a daily optimization against the electricity spot market. The basis of pricing flexible assets (either for internal transfer prices or for the valuation of possible investments) is also an optimization. Deterministic optimization approaches lack the possibility to deal with uncertainties in prices and inflows. This study focuses on the advantage a stochastic optimization offers in the two fields dispatching and pricing. The focus lies on the commercial tool TS-Energy from Time-Steps AG. The study examines two plants: a very simple virtual pump storage and a real plant in the Alps. Based on historic price forward curves and inflow prognosis of BKW Energie AG, a realistic backtesting simulation was carried out. For both plants the stochastic method provides several advantages over the deterministic approach.**

***Index Terms* -- Computational modeling, Energy, Hydroelectric power generation, Power industry, Stochastic processes**

I. Introduction

FOR the optimal position planning and dispatching of its flexible hydro and thermal power plants, BKW Energie AG (BKW) is presently employing a daily deterministic optimization based on the current price forward curve (PFC) and inflow/weather forecast. This method lacks the possibility to deal with uncertainties in prices and inflows. In order to determine internal transfer prices and to carry out valuations of possible investments, BKW has built up a framework for pricing flexible assets based on the deterministic optimization of a large number of BKW-made spot scenarios. Aside from facing long calculation times, this approach suffers from the “perfect foresight problem”.

BKW is presently engaged in an applied research study to estimate the benefits a stochastic optimization could offer in the two fields dispatching and pricing. The focus lies on the commercial tool TS-Energy from Time-steps AG as it is readily deployable on BKW’s flexible assets. The study is divided into two parts. First, a very simple power plant without inflows is considered – a virtual pump storage (VPS). This synthetic plant allows to consider the effect of price-uncertainties isolated from inflow-uncertainties. Although being a bit academic, a VPS is a very interesting instrument as it is nowadays often used by energy companies as a means to hedge the energy production and consumption of a real pump storage. The second part of the study focuses on a real plant of BKW’s portfolio. Here the problem of combined inflow- and price-uncertainties is addressed.

In the field of dispatching we have carried out backtesting-calculations to compare the marginal returns that result from either stochastic or deterministic daily optimization of the two plants and bidding at the spot market. The calculation is based on archived PFCs and inflow-prognosis of BKW of five recent years (2007 – 2011). The backtesting simulation includes the bid-process (price-dependent bids) at the Swiss Energy Exchange to generate the realized profile for the plants after market clearing. Price-dependent bids from the stochastic and deterministic optimization are generally different. One of the main difficulties of dispatching a real plant in the Alps is the large uncertainty of inflows. Especially with small storages in combination with large inflow quantities, optimal allocation at the spot market and yet at the same time managing the risks associated with extreme water levels in basins is a though problem.
In the field of pricing based on spot price scenarios we have addressed the “perfect foresight problem”. We have also worked on a coherent understanding of how pricing and dispatching must be interlinked.

II. Methodology: Stochastic Optimization

The Time-steps TS-Energy software is a valuation and risk analysis application for complex power assets and contracts [1][2]. The approach uses stochastic processes to describe uncertain inputs such as electricity price and water influx to optimize assets without the requirement of perfect foresight imposed by standard linear programming software. TS-Energy uses a two-step process (Fig. 1), a backwards integration step which determines an optimal operation strategy for an asset and a forwards integration step which applies this strategy to a set of scenarios to determine fair value and risk information for the asset.

Hydropower assets are described by basins and operating units (generators and pumps), as well as by stochastic processes describing the net water influx for each basin. During the valuation step, the backward integration method is carried out in order to derive the action-grid which holds the information

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about the best action at each settle date (e.g. to hold, generate or pump) given the market state (e.g. the electricity price) and the product state (e.g. volume of the basin). The modeling of the optimal dispatch strategy implies the determination of the value-maximizing decisions for all states at each point in time in order to determine the right time for generation or pumping. In the forwards integration step, this optimal dispatch strategy is applied to spot price scenarios (stochastic mean reverting jump process) generated by means of Monte-Carlo simulations. An adequate number of scenarios for convergence are in the range of 100 to 10'000 which can be used to derive the expected earnings, the probability distribution and the value at risk of the asset.

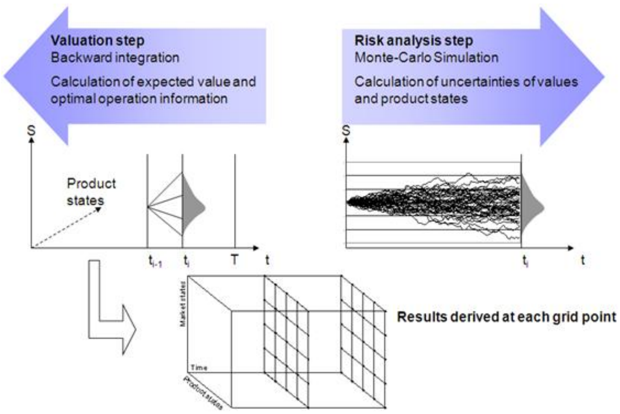

Fig. 1 Two step approach for stochastic optimization

The two step dynamic programming approach used by TS-Energy to solve stochastic problems brings added advantages over the commonly used linear programming solutions to optimize hydroelectric power plants.

Price in €/MWh	0,0	10,0	20,0	30,0	3000,0
Energy in MWh	20,0	10,0	10,0	-20,0	-20,0

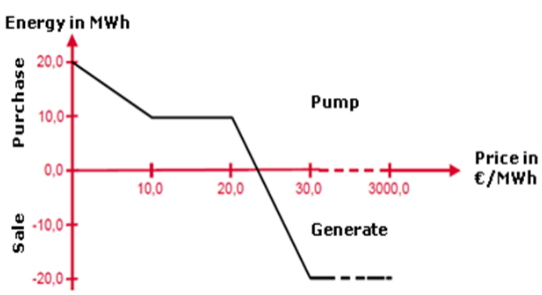

Fig. 2 Example of a price dependent bid for a hydropower plant

The determination of the value maximizing action for each market state at a particular basin state generates the information necessary to create optimal price dependent bids (Fig. 2) for each settle date. For each generator and pump in the system an optimal price dependent bid curve can be extracted, this curve is given in pairs of €/MWh and MWh. This provides an optimal bidding strategy for the electricity exchange day-ahead power auctions.

Additionally since each combination of possible basin volumes is examined at each settle date, pressure dependencies in power and throughputs in the generators and pumps in the system are taken into account automatically at no extra complexity cost.

Stochastic inflows are also taken into account, with the inflows occurring inside a time-step modifying the state of the basins in the next time-step, the TS-Energy method is very resilient to inflow variations, continuing to give optimal actions in the context of a volatile inflow.

For the pricing of assets, the stochastic valuation method gives a fair value which can be used to assess, in conjunction with the value at risk (VaR), the price for purchasing the asset. The fair price provides the information how much income is generated on average with the asset in a risk neutral environment, but it does not contain information regarding the risk that is involved in purchasing the asset. For the investor it is necessary to have a quantification of the risk as well, so that he may purchase the asset for a price that is the difference between the fair price and an appropriate risk premium.

III. Case Study I: Virtual Pump Storage

The parameters and topology defining the simple VPS are given in Fig. 3. The efficiency of the generator-pump cycle is 0.7. The (upper) basin holds a capacity of 15'000 MWh and hence can be used for 600 hours of energy production without pumping.

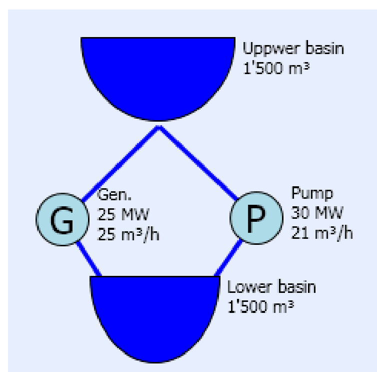

Fig. 3 Topology of a virtual pump storage VPS. Power and throughput of the generator and pump are indicated.

A. Position Planning and Dispatching

The backtesting calculation simulates the dispatching process of the VPS based on a defined optimization methodology. The only time dependent inputs of the optimization runs are the daily updated PFCs of BKW. The simulation provides the possibility to test under "laboratory conditions" which marginal returns could have been earned using either the deterministic or the stochastic optimization. An absolute benchmark is the margin resulting from one single deterministic optimization run on spot settlements: the perfect foresight value. It is clear that neither the stochastic nor the deterministic method can reach the perfect foresight value as the PFCs generally do not perfectly predict the outcome of the spot settlements. It should be noted that our approach assumes the realized settlements at the energy exchange would not have been affected by the bidding process of the VPS (price taking).

The simulation was made for five individual years 2007 to 2011. Boundary condition on the upper basin was a 80 percent filling fraction at the beginning and end of the year. The steps for the simulation of a single day are the following:

1. Determine filling fraction of basin
2. Read historic PFC of that day
3. Perform optimization (deterministic or stochastic) based on updated PFC
4. Determine margin prices and volumes for generator and pump (price-dependent bids)
5. Determine realized profile for the plant after market clearing by comparing settlements and margin prices
6. Calculate new effective basin filling fraction

This process is repeated 365 times for a simulation of a single year. Note that the margin prices in the deterministic method are calculated by comparing PFC and optimal profile of the optimization while in the stochastic method they can be directly extracted from the action grid.

Fig. 4 shows the proportion of the perfect foresight value realized using the two optimization methods for the years 2007 to 2011. In each individual year the stochastic approach generated larger marginal returns. It is interesting to note that the advantage of the stochastic method is more and more pronounced in recent years (where the peak – off-peak ratio in electricity prices decreased). Most extreme was the year 2011, where the surplus makes 6.6 percent of marginal returns.

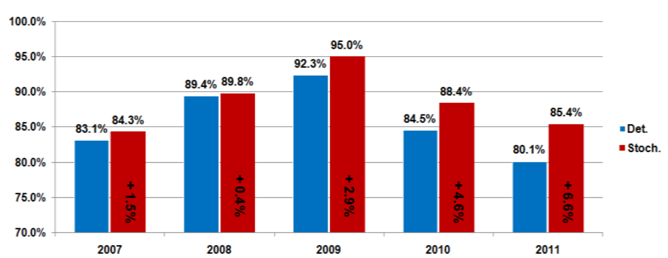

Fig. 4 Proportion of perfect foresight value realized using daily deterministic (blue) or stochastic (red) optimization for bidding at the spot market. Vertical numbers on red columns indicate the additional marginal returns earned by using stochastic optimization (surplus).

The differences of the two methods in daily dispatching have a clearly noticeable effect on the evolution of the storage levels. As an example, Fig. 5 shows the storage levels resulting from daily bidding at the energy exchange by using the two methods (red and blue) for the year 2011. As reference the optimal storage evolution for the perfect foresight case is also shown (black). The stochastic method leads to filling levels generally closer to the perfect foresight case than the deterministic method.

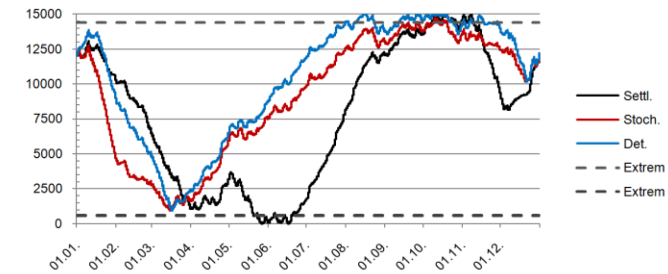

Fig. 5 Evolution of storage levels from daily stochastic (red) and deterministic (blue) optimization together with perfect foresight case with deterministic optimization on settlements (black) for the year 2011. Also indicated are extreme basin levels (dashed grey).

Since the deterministic optimization has no possibility to deal with uncertainties, it is trying to earn as much as possible even when the strategy may result in quite risky storage filling fractions. Being at the very top or bottom of the basin lowers the possibility to optimally adapt to new price developments, hence extreme basin filling levels should be avoided. Filling level needs to be considered "extreme" if the basin could overflow or be totally empty in less than 24 hours of generation or pumping. In order to quantify such risks, we report the number of hours (in proportion to the number of hours in that year) that the storage was in the extreme condition. The results are shown in Fig. 6. Except in the year 2008, the stochastic method manages to avoid extreme filling levels much better than the deterministic method, in average over the years considered the amount of time is reduced by 34 percent.

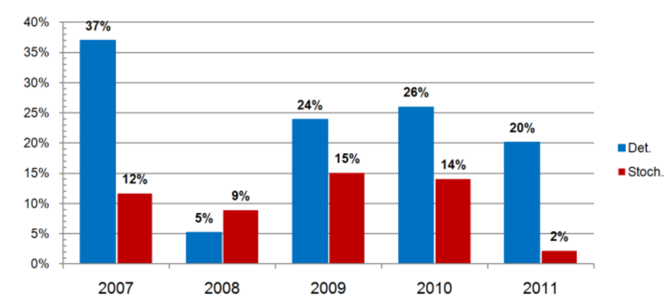

Fig. 6 Proportion of the number of hours in individual years where storage is in extreme condition.

B. *Pricing*

As a test case the estimated value of the VPS at the spot marked was calculated for the period of one year using both the deterministic and the stochastic method. Basis for the valuations are 500 spot price scenarios with hourly resolution. In average the scenarios reproduce the PFC of the valuation date.

With the deterministic method each of the 500 spot price scenarios is optimized individually, hence for every scenario the perfect foresight value is calculated. The arithmetic average of the 500 perfect foresight values defines the value of the plant, also called deterministic option value OV_{det}. In the example considered we find OV_{det} = 1.268 m €. The intrinsic value IV is given by the value of the optimal profile to the PFC. In the example IV = 0.747 m €.

With the stochastic method the PFC is used to perform the backward integration. The thereof resulting action grid is used to perform the forward integration with the same 500 spot price scenarios as in the deterministic case. Again, the arithmetic average of the 500 calculated margins determines the stochastically calculated option value OV_{stoch}. In the example we find OV_{stoch} = 0.961 m €.

The two option values differ dramatically. This is due to the fact that the methodologies are totally different and cannot be directly compared. The deterministic value has no relation to the real dispatching of the power plant, it is calculated from perfect foresight values. We have seen in the backtesting calculation that the realized margin in proportion of the perfect foresight value varies considerably in each year (80.1% in 2011 – 92.3% in 2009). From backtesting we have a history of five years only but it seems well possible that in years where the prices at the electricity market are very volatile the realized proportion of the perfect foresight value may be very small (in extreme cases even negative for a VPS). In contrast to the deterministic value, the stochastic valuation contains a well defined and testable dispatching strategy (contained in the actions of the grid). It therefore does not suffer from the perfect foresight problem. The large difference between the two values has to be seen in that light. The ratio OV_{stoch}/OV_{det} = 0.76 can be seen as a mean (and expected) realized margin in proportion of the perfect foresight value.

IV. Case Study II: Real Plant in The Alps

The second case study deals with a real plant in the alps. The parameters and topology defining the complex plant are given in Fig. 7. The efficiency of the generator-pump cycle is approximately 0.6. The upper and middle basins hold a capacity of 83 GWh and 7 GWh respectively. The dispatching of the plant is strongly influenced by the inflows; especially as the middle basin gets large amounts of inflows compared to its size (regular inflow in summer is about 1/4 of basin volume but can double on extreme days). The basin at the bottom cannot be used as storage as it merely channels a river in a lower valley; in the model we use zero volume.

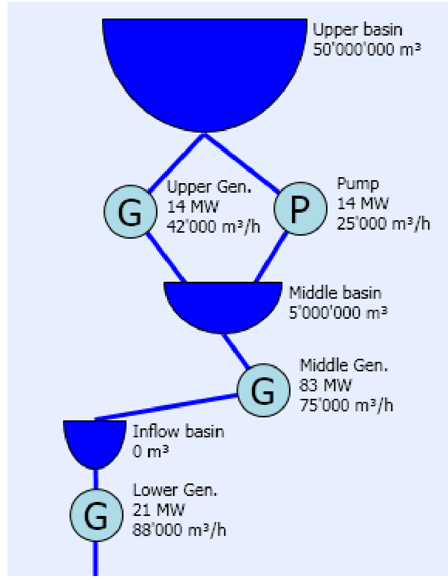

Fig. 7 Topology of complex plant in the Alps with three generators and one pump. Power and throughput of pump and generators are indicated.

A. Position Planning and Dispatching

As for the VPS a backtesting calculation was set up to simulate the dispatching process of the complex plant based on a defined optimization methodology. Boundary condition on the upper and middle basin was a 80 percent filling fraction at the beginning and end of the year. In addition to the daily updated PFCs a daily updated inflow prognosis generated in a hydrological model serves as input for the optimization runs (deterministic and stochastic). The basic idea of the backtesting simulation is the same as that for the VPS and consists of the 6 points described earlier. The only difference for point 5 is that the realized profile together with the real inflows is used to determine the effective basin volumes at the end of each day in the simulation.

Compared to the case of the simple VPS, the dispatching of the complex plant is not so much driven by making use of prize differences but by managing the inflows such that spills can be prevented. In other words, the real problem to solve is not “earning as much as possible” but “dealing with the water as well as possible”. In that light it is not very surprising that differences in the values obtained from the stochastic and deterministic method are minimal. In fact we do not find a significant surplus from one method if we consider only the calculated marginal returns. However, we find huge differences in the behavior of the two methods when looking at storage level curves. The deterministic method generally produces storage filling curves that are much more fluctuating and often cannot avoid extreme filling fractions. In contrast to that, the stochastic method leads to a solution with a comfortable safety margin, yet earning the same amount of money. The difference is most pronounced in the middle basin, where the volume to inflow ratio is small. An example of the evolution of the filling fraction for the middle basin is shown in Fig. 8. In extreme cases (as in Fig. 8) the filling fraction may approach zero if price and inflow develop differently than the inputs of the optimization from which the margin prizes were derived. The stochastic method includes uncertainties and hence leads to less extreme basin filling fractions when real inflows and prizes deviate from the prognosis.

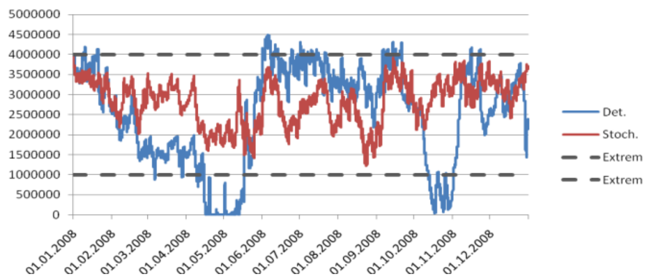

Fig. 8 Evolution of storage levels for middle basin from daily (red) and deterministic (blue) optimization for the year 2008. Also indicated are extreme basin filling levels (dashed grey).

B. *Pricing*

As a test case the estimated value of the complex plant at the spot marked was calculated for the period of one year using both the deterministic and the stochastic method. Basis for the valuation is exactly the same price information as for the valuation of the VPS.

As previously, the arithmetic average of the 500 perfect foresight values from the deterministic optimization defines the deterministic option value OV_{det}. In the example considered we find OV_{det} = 13.093 m €. The intrinsic value IV is given by the value of the optimal profile to the PFC. In the example IV = 11.906 m €. The arithmetic average over the values resulting from 500 forward integrations determines the stochastically calculated option value OV_{stoch}. We find OV_{stoch} = 11.889 m €.

Again, OV_{stoch} is smaller than OV_{det}, however the gap between the two is smaller than for the VPS. A difference between the two values is expected as the methodologies can generally not be compared. The ratio OV_{stoch}/OV_{det} = 0.91 is much larger than in the case of the VPS.

V. Conclusions

In conclusion, in both test cases, the stochastic valuation method provides several advantages over deterministic valuation. The price dependent bids generated by the stochastic optimization allow assets to be operated in a more optimal way, increasing marginal value and simultaneously reducing the number of extreme operation hours and volume of spills. This has a considerable impact for the operation of a VPS or of a hydroelectric power plant. The application of a defined strategy (the action grid) to an asset allows the determination of a value at risk over a set of scenarios. This gives valuable additional information over the deterministic approach which only considers maximal a posteriori margins and as such does not provide VaR numbers.

VI. References:

A. *Technical reports*

[1] E. Zuur, *TS-Hydropower, Approach document*. Technical report, Time-steps AG, Switzerland 2004

[2] E. Zuur, *TS-Energy 2012, Technical description*. Technical report, Time-steps AG, Switzerland 2004

VII. Biographies

Florian Kämpfer graduated and received his PhD in theoretical physics from the Institute of Theoretical Physics at the University of Bern in 2007. Before joining the trading department of BKW Energie AG in Bern in 2010, he worked as a postdoctoral research fellow at the Massachusetts Institute of Technology and at the University of California in San Diego. Within the trading department of BKW he is responsible all themes related to optimization.

Eric Winnington was born in Lausanne, Switzerland, on March 12 1980. He graduated and received his Master of Computer Science from the École Polytechnique Fédérale de Lausanne. He has been working with Time-steps since 2005 in the field of stochastic optimization applied to energy and finance.