Optimal Storage Management Under Uncertainty

By Joachim Geske and Richard Green

Joachim Geske and Richard Green are at Imperial College Business School; j.geske@imperial.ac.uk and r.green@imperial.ac.uk

OVERVIEW

In electrical systems storage has the technical potential to increase efficiency significantly - especially in the context of integrating intermittent renewable technologies. This is achieved by shifting energy from periods of low residual demand to periods of high demand. This raises the utilization of base load power plants and reduces that of peak load power plants. The full gain is achieved if generation capacity is adapted to the "equilibrated" load situation - with a higher base load capacity and fewer peaking stations. In this case, the installed fossil generation capacity might fall below peak load level. Since the amount of energy stored is limited, there is a risk of expensive outages in cases of prolonged demand peaks.

Many previous analyses of storage are based on perfect foresight models in which the operator could ensure that the store always approaches a prolonged peak with just enough energy to avoid an outage. In the real world, it may be impossible to predict the length of a peak, and a different strategy is needed: taking this issue into account, our aim is to derive the optimal way of integrating the storage into the system. Compared to the perfect foresight equivalent, the more realistic storage management strategy includes more "waiting" and "reserve" holding to prevent outages. As result, the storage cannot be operated as efficiently as in the perfect foresight case, reducing the cost savings available. We also find that an increasing risk of reaching peak load further reduces the efficiency potential of the storage. Since the optimal storage strategy is not implemented "naturally" by competitive storage operators, it might be advisable not to adjust generation fully in response to the growth of storage, reducing the difficulty of regulating it.

METHODS

We have derived the expected cost minimizing way of operating energy storage and non-intermittent generation and adjusting non-intermittent capacities for a given storage capacity (300 GWh in our case study). The operator aims to satisfy demand while processing sequentially revealed information about the uncertain residual load. The problem is stochastic and multiscale as it includes short term information processing, storage management and generation decisions as well as long term investment decisions in generation capacities. We develop a dynamic stochastic electricity system optimization model as a Markov Decision Process. A solution is an optimal strategy that assigns each state - defined by the amount of stored energy, residual demand and non-intermittent generation capacities - a probability distribution over possible charging and discharging values. The non-intermittent generators run in merit order to meet the residual demand plus charging (or minus discharging). The model is quantified with an estimated homogeneous Markov Chain representation of the residual load (demand minus wind and solar output) in Germany in 2014 on an hourly basis and with technology cost data. The model is solved for a stationary policy using a linear optimization approach embedded in a hill climbing capacity optimization environment. This strategy and the stationary probabilities are analysed using counter factual experiments and they are compared to the optimal solution derived under perfect foresight of explicit drawings of the stochastic load process. Thus features of the optimal strategy can be derived and the perfect foresight "error" can be quantified.

RESULTS

Figure 1 shows the optimal stationary strategy for the case we analysed. Although the peak residual load is 80 GW, it is optimal to build only 70 GW of capacity (note that our model currently simplifies the actual data to work in multiples of 10 GW). Therefore, the peak residual load of 80 GW cannot be covered without unloading the storage. If the state of charge is zero, it cannot be discharged any further and load is lost. Lost load is valued by the social planner at 100 times the marginal cost of the most expensive non intermittent technology.

For most charging levels, storage is used for arbitrage and charged below a residual load of 50 GW and discharged above – more strongly, the greater the deviation from 50 GW. This increases the utilization of non-intermittent generation capacity and therefore efficiency. Thus an after-storage-load of 50 GW is achieved over a wide range of the states, making an expansion of base load capacity profitable.

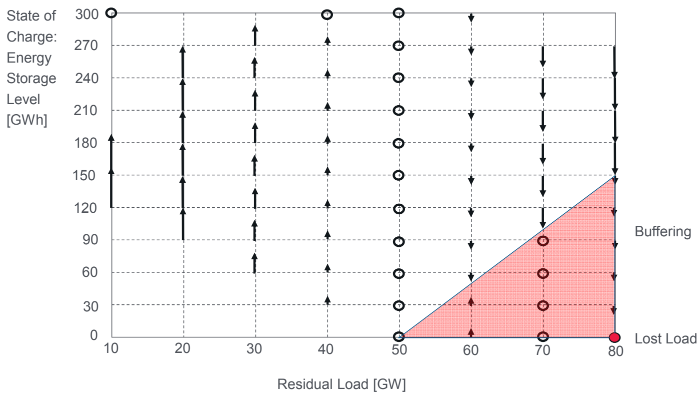

Figure 1: Optimal storage strategy as a function of the state of charge (SOC) and residual load and non-intermittent generation capacities. Black arrows and circles (no operation) indicate the change in SOC.

There is a different pattern in the states included in the red triangle ("Buffering"-area) in the lower right corner. In this area the storage is only unloaded in the case of peak load. Equilibration is limited by three forms of "stabilization actions" to reduce the risk of losing load:

1. At peak load, the storage is discharged in 30 GW steps to keep the load on generators at 50 GW, as long as the charge level is above 130 GWh. Below this level discharging is reduced to 10 GW steps to delay any lost load, which requires all 70 GW of generators to run.
2. At the next load, 70 GW, discharging continues at the load-equilibrating rate (20 GW steps) until a state of charge of 100 GWh is reached. Full load is then accepted to keep a higher "distance" from lost load.
3. With a residual load of 60 GW, the storage would switch to charging, using all the generation available, if the stored energy fell below 50 GWh.

The "stabilizing" actions result in a reserve ("buffering") area with very low probabilities of staying in a state of charge below 50 GWh.

Under the perfect foresight hypothesis with 20 simulated time series from the residual load Markov modelling, system costs can be reduced by 4.4% using 300 GWh storage capacity. The solution with a stochastic residual load without storage is slightly more expensive, but storage replaces peak load capacity and enables an extension of the base load capacity of 10 GW with a reduction in the mid-merit capacity. Therefore, system costs fall by 2.9%, which is one-third lower than with perfect foresight modelling. The consideration of unpredictable changes in residual load and thus holding reserves to avoid lost load seemingly reduced efficiency gains by energy storage.

CONCLUSIONS

It is shown that under uncertainty at high demand an increasing share of the storage is "frozen" in its charged state to avoid lost load (outages). Therefore, a "buffering" share of the storage is not used actively for the equilibration of load any more. Furthermore, this buffer state of charge is established, if necessary, even in periods of high demand when a fully-charged store would be able to de-stress the system. It can be shown that the size of the buffering area rises as the risk of losing load rises. Thus the efficiency gains of storage decrease as uncertainty in the system rises.

This "buffering" does not occur in the perfect foresight analyses that are still the paradigm of energy systems analysis. Estimates of the potential of storage based on perfect foresight are thus overestimated. Furthermore, the welfare maximizing strategy includes "not unloading" in high marginal cost/price cases. The market implementation of this strategy requires the communalization of lost load costs. We propose a contract solution that includes a premium paid in high load cases for not unloading. This contract makes the storage operator indifferent between reserve holding and unloading. A further option to implement the welfare maximizing strategy would be to operate a sufficiently sized store explicitly as a buffer in the public interest.

Such contracts might be difficult to implement in practice, and so a further option might be the operation of the system with imperfectly adjusted capacities such that non-intermittent generation capacity exceeds peak load. In this case it has to be decided whether the storage is operated "inefficiently" with respect to "full" capacity adjustments, or "efficiently" when peak load capacity is not decommissioned "one for one". The challenges of sustaining rarely-used capacity were a frequent topic at the Bergen conference, however.