Modelling Transitions to Robust High-VRE Systems

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***Abstract*— Uniper is a major European power producer with around 40 gigawatts of installed generating capacity with a portfolio mix of conventional and renewables assets. In recent years, the power systems of Western Europe have been undergoing a transition towards high levels of renewable generation. Much of the new capacity is provided by wind and photovoltaics (PV). This has led to dramatic changes in how Uniper utilises its coal and gas assets within these markets. New renewable capacity reduces the amount of energy to be served by conventional generators but, as it is both variable and intermittent, conventional capacity is still required to meet demand at all times. Additionally, the reduction in conventional plant load factor reduces the supply of many ancillary services to the system operators.**

The traditional valuation approach of unit commitment to meet projected demand is no longer well suited to understanding the development of these markets. Conventional units are seeing a reduced income from providing energy and a greater income from providing flexibility in the form of reserve, frequency response and system balancing. Uniper has developed a new modelling approach that combines energy and ancillary services requirements into a single model that encompasses the development of energy, reserve products and system balancing actions.

The key features of this model are that demands for energy must be met and the delivery of a range of reserve and frequency response services is simulated. The model operates at high resolution and recognises the temporal profile of PV and the weather-driven uncertainties of PV and Wind production. We also represent the costs and flexibility of each plant type in contributing to each class of ancillary service. The model simulates the short-term balancing actions that the system operator must carry out to respond to transmission constraints and variations in supply and demand.

To enhance access and deliver fast solutions the model has been developed as a cloud-based service that can be accessed through a standard browser. The user experience can be the conventional desk-based modelling experience or in a workshop setting where strategists use the model as a tool to explore the outcomes to a range of scenarios of market development.

I. Introduction

The energy landscape has shifted. Changing customer behaviour, new technology, and increasingly global markets are creating two distinct energy worlds. The classic energy world has the indispensable task of ensuring supply security. Alongside it is emerging the new world of distributed and renewable energy solutions.

The growth of intermittent renewable generation has increased the need for flexible power plants that can meet fluctuating demand at short notice.

Uniper has a significant platform of technologically advanced generation assets across Europe and in Russia. Uniper's portfolio combines large-scale power generation and the effective management of global and regional energy supply chains.

Uniper also specialises in global trading in commodities like natural gas and coal that are bringing energy markets from America to Asia closer together.

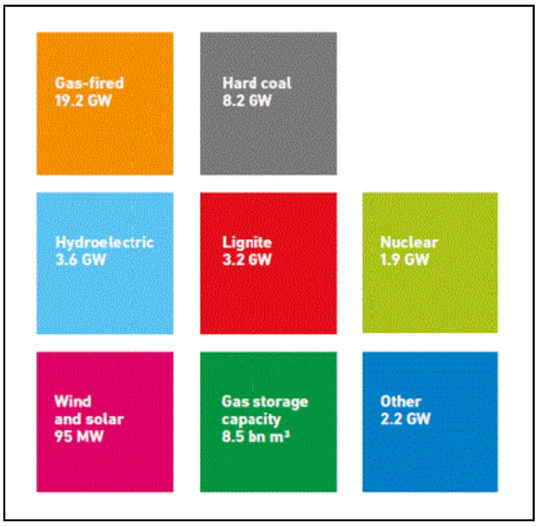

Figure 1. Uniper's Assets in Europe

II. EXPERIENCE FROM THE EUROPEAN ELECTRICITY SECTOR

Over the last decade, the European electricity sector has fundamentally changed. The generation mix now includes significant volumes of intermittent, renewable generation that has very low operating costs. The residual demand on the system has reduced due to the strong rise of embedded photovoltaic (PV) and wind generation, energy efficiency measures and weak economic growth. This has led to a reduction in the demand to be served by conventional generation. This has resulted in lower spreads between electricity prices and fossil fuel costs and environmental legislation such as the European Union's Emission Trading Scheme and the UK's Carbon Support Mechanism has further reduced these margins.

These factors affect the operating regimes of fossil plant as follows:

- Merit order displacement by low variable cost plant pushes gas, and particularly coal, plant to the margins and beyond;
- Greater uncertainty in production from intermittent sources heightens the need for more flexible and responsive generation to balance grids;
- Reduced market share of large generation units presents extra requirements for ancillary services;
- Block product prices are low but volatility is increasing, creating value opportunities for flexible plant.

Market changes mean that conventional utility businesses need to shift from optimising cost and efficiency to reorient towards providing enhanced asset flexibility. This requires both technical and organisation changes. It has also meant changes to plant operations as well as investments in plant flexibility.

Greater uncertainty of demand requires the provision of higher levels of reserve power across all the reserve timescales to ensure that supply and demand are balanced and that grid stability is maintained. In the past, a key supplier of such services was running fossil plant but now there is less capacity operating in general and so this service is gaining value. This also means that Transmission System Operators (TSOs) are calling fossil plant to run out-of-merit to provide ancillary services.

Lawmakers are also concerned that the closure of fossil plant due to end of life and declining revenues are leading to low capacity margins. This is being addressed in European markets through the introduction of capacity mechanisms.

Uniper has prepared for important changes through developing strong modelling expertise and by preparing its employees for industry changes using market simulation events. Simulation events have been used to allow decision makers to experience the effects of changes in the sector *a priori*. This is coupled with detailed market modelling conducted by market analysts using optimisation models that combine the energy, reserve and balancing markets within a single framework. We describe below our approach to modelling and our experience of engaging traders, analysts and strategists in simulation events.

III. MODELLING APPROACH

A. Scope

Our model is designed to capture the price evolution and inter-market dynamics of electricity markets, with a focus on the ancillary services that interact most strongly with the wholesale market. We currently include in the model:

<u>The wholesale market</u>
The wholesale market is used for bulk power purchase from generators in advance of delivery. The exact structure of the market varies between countries from bilateral trading arrangements (UK), to a central clearing (pool) system, to a single regulated buyer with PPAs.

<u>Frequency response, Reserve and Balancing services</u>
Terminology and market arrangements in this area are very diverse, but services typically fall into two broad categories which we treat differently. In each of these categories, payment may be for availability to respond ("reserve"), energy provided to the TSO ("balancing") or both.

Frequency Response or **Frequency Containment Reserve** (FCR) is when generators automatically respond to deviations in system frequency from the target (which is 50Hz in Europe and India). Generator response in most markets must be within seconds and is determined by local frequency measurements without communication from the TSO.

The volumes of FCR required are driven by network dynamics and so TSO frequency containment targets are not typically set to completely counteract system shortfalls or excess power.

Energy volumes are low and remuneration is typically by availability payment. The ability to provide the service is often mandatory.

Frequency Restoration Reserve (FRR) is generator capacity bought by the TSO to relieve the FCR capacity in the minutes or hours after an event has occurred, and to compensate for long-term shortfalls or excess power in the system. The generator should not provide any response until requested to by the TSO, either via an automatic signal or manual communication.

The volumes required are driven by maximum power losses or gains likely to be seen by the system. Energy volumes are higher than for FCR, and remuneration is more likely to be for energy provided instead of pure availability.

Imbalance Pricing and Charging

Most markets have some means for charging back the cost of system imbalances to the generator or demand who caused the imbalance. Likely causes of system imbalances are:

- Demand forecasting errors
- Renewable forecasting errors
- Generator failures
- Interconnector failures

Typically, imbalance prices are indexed to the balancing costs of the TSO and/or wholesale prices. Prices for being long (generating too much or not consuming enough) and for being short (not generating enough or consuming too much) may be identical, or there may be a spread between them.

Cross-Border Flows and Inter-Regional Redispatch

Whatever the market arrangements, the final generation schedule must be physically possible and stable. From a network perspective, this means that it must respect maximum line loadings and the system should be able to continue operating even if some network elements fail. There are two ways to ensure that this is the case, both of which are captured in our model.

The first is to divide a synchronised transmission system into multiple market regions whose boundaries align with major network constraints, and to schedule each market region separately with limits on cross-border flows. This introduces the physical constraint into the wholesale market, and prices in the different regions may converge or diverge depending on whether the desired flow is possible given the imposed limit on traded flows.

The second way is to allow the market to generate a schedule, and then for the TSO to intervene if it is not physically feasible by instructing some generators to change their proposed operating profiles. This is called redispatch, and we model it by dividing each market region into network regions with internal constraints.

B. Traditional Approaches to Market Modelling

The traditional approach to modelling these markets is to treat them as being independent. A wholesale market model is used to predict the wholesale price, and this wholesale price is then used to estimate the opportunity cost for each plant of providing the ancillary service in question. This opportunity cost is applied because a generator must deviate from its economically optimal output level to provide a reserve or redispatch service.

A major weakness of this approach is that it ignores interactions between the markets. A pure wholesale model may choose to shut down as much plant as possible during low demand periods, because the model doesn't need to maintain sufficient fast reserve on the system to maintain stability. Or conversely, it may choose to start as few plant as possible and run them at maximum output, since that is most cost efficient way of meeting demand, again sacrificing system stability to supply expected demand at minimum cost.

Because the price is driven by what is running, ignoring system stability in the wholesale schedule means that the wholesale price forecast is not reflective of true system costs, which in turn means that any separate model which uses that price to predict reserve and balancing prices is inaccurate. These models are not consistent: a model which ignores system stability requirements is used to estimate the opportunity cost of the plant required to stabilise the system.

1) Spinning Reserve Constraints

A common approach to attempt to remedy this drawback is to add spinning reserve constraints into the market model. Such a constraint simply requires that it is possible to increase generation by a pre-specified minimum amount using plant committed to run. If this is not possible, the market model must commit more generators and part-load some of them.

This approach has the advantage that the generation schedule does recognise a need for some flexibility but it still doesn't consider the usage of those reserves. This means the model has an incentive to minimise the availability cost only, even if this would in practice make using the reserve plant to balance the system very expensive. In reality, TSOs try to minimise their total ancillary service costs, including both reserve and balancing, so there is still a large mismatch between the estimated schedule in the market model and the real life decisions of the TSO.

The other major problem with this approach is that the wholesale model doesn't take into account response times. The model meets a capacity target, but it doesn't understand the response profile required by the system and how that fits with the assets it has selected to meet this capacity target. Some assets can change output more quickly than others and the unique capabilities of each asset will determine which mix of ancillary services is most attractive to the TSO.

C. An Integrated Approach to Market Modelling

Our approach is to incorporate a much more accurate model of reserve and balancing into the market model, and to schedule energy, reserve and balancing together. This is more complex but produces a much closer match between actual market and system behaviour than the alternatives we discussed earlier. The model can be broken down into the following phases:

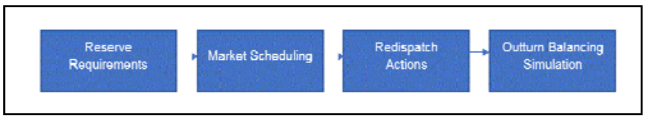

Figure 2. Model Workflow

Because reserve and balancing exist to protect the system from unexpected events, the model is inherently stochastic in nature. The calculation requires that key inputs are specified not just in terms of their expected value, but also in terms of their variability. The entire model is stochastic, with all major price and volume outputs reported as distributions.

1) *Reserve Requirements*

Before schedules can be generated, the model must determine how much reserve of each type is required and how likely that reserve is to be utilised. For Frequency Containment Reserve, the capacity required is estimated using the levels of demand and non-synchronous generation in each hour. Balancing energy estimates are not useful for FCR as the volumes are typically very low.

For Frequency Restoration Reserve, the model performs a Monte-Carlo simulation to calculate the distribution of system imbalances, including amongst other sources generator failure, demand forecasting errors, and renewable forecasting errors. The resulting overall distribution is divided into distributions for multiple response timescales. This allows the model to know how much response must be provided by fast acting units.

From these distributions, the amount of reserve required for each timescale or product (e.g. fast reserve, tertiary reserves) is calculated based on a TSO reliability target, such as to be able to cover all imbalances within three standard deviations of the mean. The distributions also directly give the probability of a plant at any point in the balancing merit order being used by the TSO.

In both the FCR and FRR cases, the model also estimates the impact on reserve volumes of renewable curtailment. This is important as sometimes curtailment of renewables may be the only way to make the system feasible, so this must be included as an option within the model.

2) *Market Scheduling and Redispatch Actions*

Once reserve and balancing requirements have been calculated, the model will generate a schedule for each possible day. These schedules are for:

- A wholesale market trying to meet the *expected* demand;
- Sufficient reserve to cover likely imbalances;
- A merit order of reserve plant which uses energy from the least expensive plant first.

The schedule is generated based on the total system cost of supplying wholesale demand, providing the reserve, and the expected cost of all balancing actions in the day. Because the model optimises the total probability weighted expected cost of all markets, it does not suffer the shortcomings described for the other modelling approaches discussed above.

Redispatching is handled by generating two schedules. The first is a pure market schedule for the case where the region internal network constraints do not exist, and the second is a schedule which respects the internal network constraints. The difference between these two schedules determines which plants are redispatched by the TSO, and their remuneration.

The outputs of these calculations are:

- Operational plans for all generators across the day, including their wholesale sales and their reserve volumes;
- Prices for wholesale, reserve and redispatch markets;
- A cost-based merit order for balancing actions.

This can be thought of as the TSO's plan at the beginning of the day, before any events occur which require balancing actions.

3) *Balancing Simulation*

The final step is to take the operational plan from the market schedule and the balancing distributions and to simulate possible sequences of events and their impact on balancing costs. Combined with the reserve prices from the market schedule, this completes the forecast of ancillary service prices.

Depending on the market-specific methodology for imbalance charging, the simulation of balancing prices also generates distributions of imbalance charges. This is done in a way which captures the correlation of generators with the overall system imbalance, so that for example wind in a renewable dominated system will pay more on average per imbalance MWh than thermal plant.

4) *Results and Outcomes*

The application of this approach has delivered an electricity market simulation including wholesale, reserve, balancing, imbalance charging, and redispatch which informs the analyst for any given future scenario:

- How prices will respond;
- How generation assets and types will be used under that scenario;
- The distributions around predicted prices and generation;
- How feasible the scenario is, including system stability requirements.

D. Case Study 1: UK Market Modelling

We have applied this approach in detail to the UK market to understand the impact of increase wind and PV penetration. The model successfully produces a number of features of the current and future market which more conventional models fail to duplicate, such as:

- Changes in the wholesale price and its daily shape

Correctly accounting for reserve changes which plant are running, which affects the marginal price for energy. Price movements can be up or down depending on the system. On the one hand, more units will run which means on average a more expensive unit is marginal. On the other hand, the reserve constraints may also impose must-run constraints on the marginal plant, which means some of their cost is covered by reserve payments and they need to recover less via the wholesale market. Since the balance between these two factors changes over time, the shape of wholesale prices across the day can shift, in particular the ratio of peak to off-peak prices.

- Mixed reserve provision

A model without knowledge of balancing costs will tend to focus on high cost units such as OCGTs for reserve. Our model produces a more realistic mix of spinning reserve and hydro to cover frequent small volumes, and high running cost plant such as OCGTs to cover the tail of the balancing distribution.

- Increased renewable curtailment

A model without detailed understand of system stability will tend to take as much renewable energy as possible. Our model curtails renewable energy more frequently when it would otherwise be impossible or prohibitively expensive to balance the system.

- Generation type specific imbalance costs

Our model captures the fact that generator types most likely to drive system imbalances tend to pay more in imbalance costs. In the UK, this is the case for wind, since windfarms are often highly correlated with each other and therefore drive the entire system to be long or short. This results in higher charges for wind than you would expect given the average imbalance price.

- Value of units

As Uniper, we are interested in the value of our plants in different future scenarios. As a result of the above changes compared to other approaches, the forecast income by plant differs, which impacts decisions about plant investment.

E. Case Study 2: Market Simulation Events

Uniper has used simulation events to prepare its traders, analysts and strategists for changing markets. Simulation events are organised as a workshop where participants are arranged into small teams. Each team manages a virtual power company over a day of operation. The teams must decide how best to run generators, sell the output and can participate in balancing or ancillary services markets. In the simulation the operation of the market is on an hourly basis but is speeded up to create extra demands on participants and to allow the workshop to complete in typically two hours.

At the heart of the simulation event is a software platform that can facilitate a power exchange to enable players to trade power; can schedule generators to meet demand; and that can balance the system when self-dispatch market rules exist. The simulation is also seeded with uncertainties such as plant breakdown that the participants must respond to at short notice. The simulation environment provides continual feedback on financial and operational performance.

The simulation experience has been used in Uniper’s predecessor companies to gain competitive advantage when markets have changed. Examples included the simulation of the UK’s current self-dispatch market ahead of its transition from a pool-based system and also preparation for the effects of Carbon Trading in the UK market.

The simulations have benefitted Uniper at a number of levels:

- Trading and Operational Strategies can be tested in a safe, environment that replicates the real electricity market.
- Traders can gain intuition about market operation before the system goes live.
- Future working process can be well understood and optimised in advance of implementation. This gives a seamless transfer from learning to doing.
- Market rules can be validated and feedback given to regulators before change is finalised.

IV. IMPLEMENTATION

Uniper is combining market simulation and detailed analysis into a single platform called energyLens. This is a cloud-based platform that can be deployed across multiple device types and only requires internet access to use the service. The core algorithms of energyLens are computationally intensive and the use of Cloud Computing allows the users to benefit from installation-free access to a modelling environment and use of elastic computing resources.

This is delivered as two levels of service using a common data store and optimisation algorithms:

- **energyLens Executive** – A simulation environment where senior decision makers see how the power portfolios will operate in changing markets and the requirements for infrastructure investment. This is delivered in a workshop setting and users focus on high level drivers of portfolio behaviour.
- **energyLens Strategist –** A detailed model interaction that allows understanding on a plant-by-plant basis of future running patterns, revenues,

environmental impact. This is used for in-depth desk-based scenario analysis by strategy analysts.

V. Conclusion

Uniper has seen a renewables transformation in the western European energy sector. This has led to a changed role for fossil plant and a shift in value for these plants away from efficient reliable power to flexibility and the provision of ancillary services.

To enable this transition, we have used simulation and detailed modelling to consider the changes to energy, reserve and balancing in parallel.

We have highlight how standard market modelling approaches do not adequately capture the interaction between energy, reserve and balancing markets and that these give an unrealistic picture of fossil plant running patterns and underestimated the curtailment of renewable generators.

We have developed an optimisation platform that provides an integrated evaluation of these markets and have applied the modelling to the power sector in the UK.

We are now developing this approach in conjunction with our successful experience of market simulation events to develop a platform that can be used to evaluate a broad set of market changes.