Department for
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& Industrial Strategy

Benefits of Long Duration Storage

Methodological Annex

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Contents

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AFRY Management Consulting was commissioned by the Department for Business, Energy and Industrial Strategy to undertake this research. AFRY provides leading-edge consulting and advisory services covering the whole value chain in energy, forest and bio-based industries. Our energy practice is the leading provider of strategic, commercial, regulatory and policy advice to European energy markets. Our energy team of over 250 specialists offers unparalleled expertise in the rapidly changing energy markets across Europe, the Middle East, Asia, Africa and the Americas.

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The report contains projections that are based on assumptions that are subject to uncertainties and contingencies. Because of the subjective judgements and inherent uncertainties of projections, and because events frequently do not occur as expected, there can be no assurance that the projections contained herein will be realised and actual results may be different from projected results. Hence the projections supplied are not to be regarded as firm predictions of the future, but rather as illustrations of what might happen. Parties are advised to base their actions on an awareness of the range of such projections, and to note that the range necessarily broadens in the latter years of the projections.

1. Introduction

This document is an annex to the main report "The Benefits of Long Duration Electricity Storage". It provides a documentation of the methodology followed in the study, covering the BID3 methodology and other specifics of the study that are additional to the main report.

1.1 Structure of this report

This report documents the methodology in the study, covering the BID3 methodology and specifics of this study. This is done by providing:

- The methodology of AFRY's power market model, BID3.
    - An introduction and overview BID3.
    - A description of BID3's key features for this study.
- The modelling methodology used for this study.
    - A description of the use of BID3 in this study.
- The methodology for the core scenarios and sensitivity tests.
- The detail of inputs and outputs, and additional explanation not in the main report.

1.2 Conventions

- All monetary values quoted in this report are in GB Pounds Sterling in real 2019 prices, unless otherwise stated.
- Annual data relates to calendar years running from 1 January to 31 December, unless otherwise identified.
- Plant efficiencies throughout this report are defined at the Higher Heating Value (HHV) basis. Fuel prices are similarly quoted on a gross (HHV) basis.

1.3 Sources

Unless otherwise attributed the source for all tables, figures and charts is AFRY Management Consulting.

2. The BID3 Market Model

BID3 is AFRY Management Consulting's proprietary power market optimisation model.

The model provides long-term projections for the physical operation (generator output, emissions) and economic behaviour (electricity prices, system costs) of the market, it handles modelling of 8760 hours with large numbers of countries, power plants, renewables, storage and demand-side management. BID3 has been enhanced to include a unified approach across sectors and co-optimises both power and hydrogen sectors. This accounts for the demand/supply dynamics of each and the price impacts on each other.

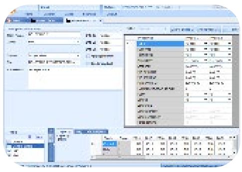
BID3 includes a sophisticated capacity expansion module. The 'Auto Build' module optimises both generation dispatch and investment decisions across the modelled time frame, accounting for the full resolution of weather and demand patterns, reserve and operability requirements and simultaneously optimising all interconnected markets. This runs in such a way to ensure full consistency between dispatch and capacity new build decisions. The result is a scenario where the investment decisions are sufficient to cover the needs to operate the system, accounting for hourly dispatch patterns for all chosen weather patterns and all future years. Running the model in this manner, we ensure our scenarios are internally consistent; with fossil fuels, carbon, electricity and hydrogen reaching a stable equilibrium in terms of price and volume.

2.1 Overview of BID3

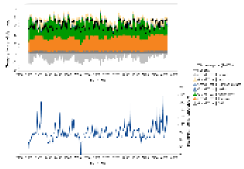
BID3 is our electricity market model, used to simulate the dispatch of all supply and demand in electricity markets as well as the economic new build and retiral decisions by market players.

Exhibit 2.1 – Modelling features of BID3

BID3 projects detailed physical operation and economic behaviour, covering a variety of timeframes.

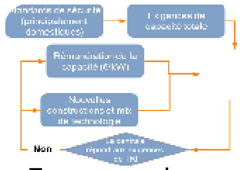


Detailed power station database



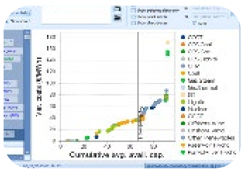
Flexible charting and pivoting of any data

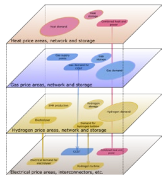
Zonal, FBMC and nodal pricing



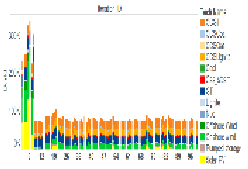
Energy-only and energy + capacity markets

Sophisticated hydro modelling

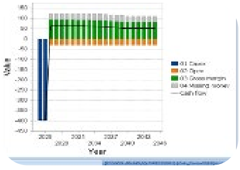




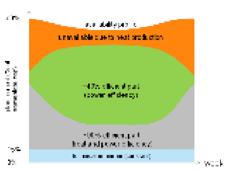
Hydrogen and heat co-optimisation



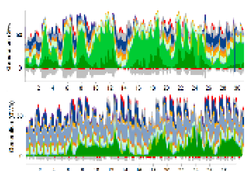
Auto Build module



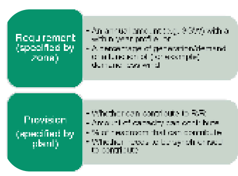
Profitability, IRR calculations



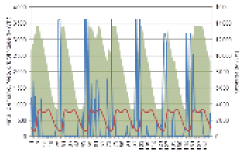
Detailed CHP modelling



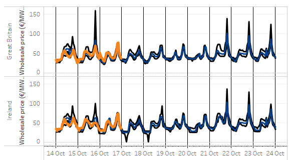
Intermittent generation



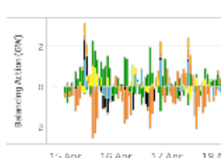
Reserve and response



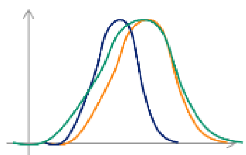
Demand-side management



Short-term modelling



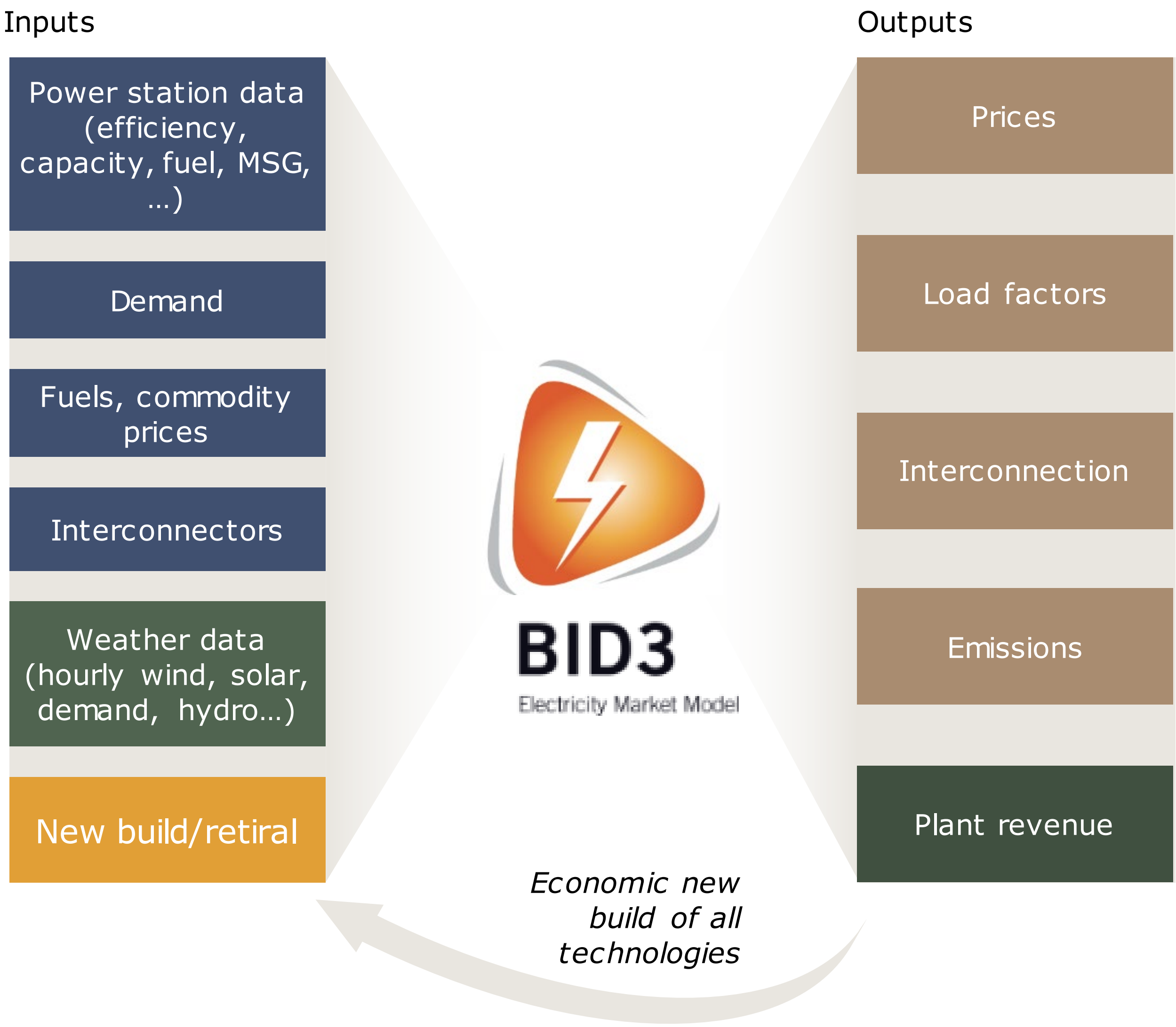
Within-day calculations



Monte Carlo analysis

Exhibit 2.2 – BID3 Overview, Inputs and Outputs

BID3 is an economic dispatch model that simulates the hourly generation of all power stations on the system, taking into account fuel prices and operational constraints such as the cost of starting a plant.



2.2 How does BID3 work?

BID3 is an economic dispatch model based around optimisation. It combines state-of-the-art simulation of thermal and renewable-dominated markets, reservoir hydro dispatch under uncertainty, demand-side response and scenario-building tools. Exhibit 2.1 and Exhibit 2.2 provide an overview of BID3.

It simulates the hourly (or sub-hourly) generation of all power stations on the system, taking into account fuel prices and operational constraints such as the cost of starting a plant.

It accurately models renewable sources of generation, such as hydro, reflecting the option value of water, and intermittent sources of generation, such as wind and solar, using detailed and consistent historical wind speed and solar radiation data. It fully models all sources of flexibility on the system such as pumped storage, batteries and Demand-Side Management, and also new technologies such as electrolysis and hydrogen CCGTs.

BID3 provides a simulation of all the major power market metrics on an hourly basis – wholesale electricity prices, dispatch of power plants and flows across interconnectors. The result of this optimisation is an hourly dispatch schedule for all power plants and interconnectors on the system. At the high level, this is equivalent to modelling the market by the intersection between a supply curve and a demand curve for each hour. BID3 also includes modelling of balancing and reserve markets, providing a simulation of the value of reserve holding, reserve activation, required balancing energy and balancing prices.

BID3 also includes the following features:

- Optimisation of start-up and part loading costs for thermal plant, including start-up and comprehensive plant dynamics.
- Hourly renewable generation based on detailed wind speed and solar radiation data.
- Sophisticated treatment of Demand Side Management and storage, allowing simulation of flexible load such as electric vehicles and heat.
- Sub-hourly modelling with up to 1 minute resolution.
- Co-optimisation of energy and ancillary markets. The hourly holding of reserve and response is co-optimised alongside the wholesale market, and reserve is activated with a subsequent balancing optimisation. Inertia is also co-optimised alongside the delivery of power.

BID3's key feature in this project is the Auto Build module. This is AFRY's endogenous investment optimisation module, used to assess the long-term optimal investment solutions for all assets in the system, producing optimal new build, retiral and mothballing (see 2.5.1).

2.3 Inputs

Good quality inputs that are compatible with the model are important to the simulation exercise. This section explains:

- the main inputs;
- how they are handled in BID3; and
- how they are combined into scenarios.

Inputs in BID3 are expressed by making use of three building blocks: tracks, profiles, and general data. Additional inputs are required for specific modules and scenarios.

Tracks refer to annual values of the corresponding input (plant capacity, demand, interconnector capacity, fuel price, etc.) describing the year-to-year evolution. Tracks are a key building block of a scenario in BID3. A scenario in BID3 consists of tracks which are used to index the relevant data. The tracks are combined to form scenarios. This 'building block' approach enables the model to be flexible in testing a variety of scenarios.

2.3.1 Inputs: Profiles

2.3.1.1 Introduction

Profiles dictate the within year shapes that are used as multiplying factors when generating a time series of the given input, they are a key input in BID3's ability to:

- Model a sophisticated, high resolution 8760 hourly set of results.
- Model a set of results that are internally consistent between all inputs.

BID3 enables the creation of scenarios using specific profiles for specific input data, which ultimately describe how elements change within a year. These can be random changes such as outages and changes influenced by weather. Weather can influence inflows and wind (which affects production) and temperature (which affects demand). More detail on the modelling of weather patterns is described in Section 2.3.1.5.

2.3.1.2 Profiles & case collections

A case collection consists of different profiles and describes how elements change within a year. This feature exists so that profiles from different cases can be combined in a consistent manner. For some time-variant properties, we use sample day profiles (e.g., for fuel prices), but typically use hourly profiles where these are important. Case collections combine the weather driven and average default profiles together appropriately.

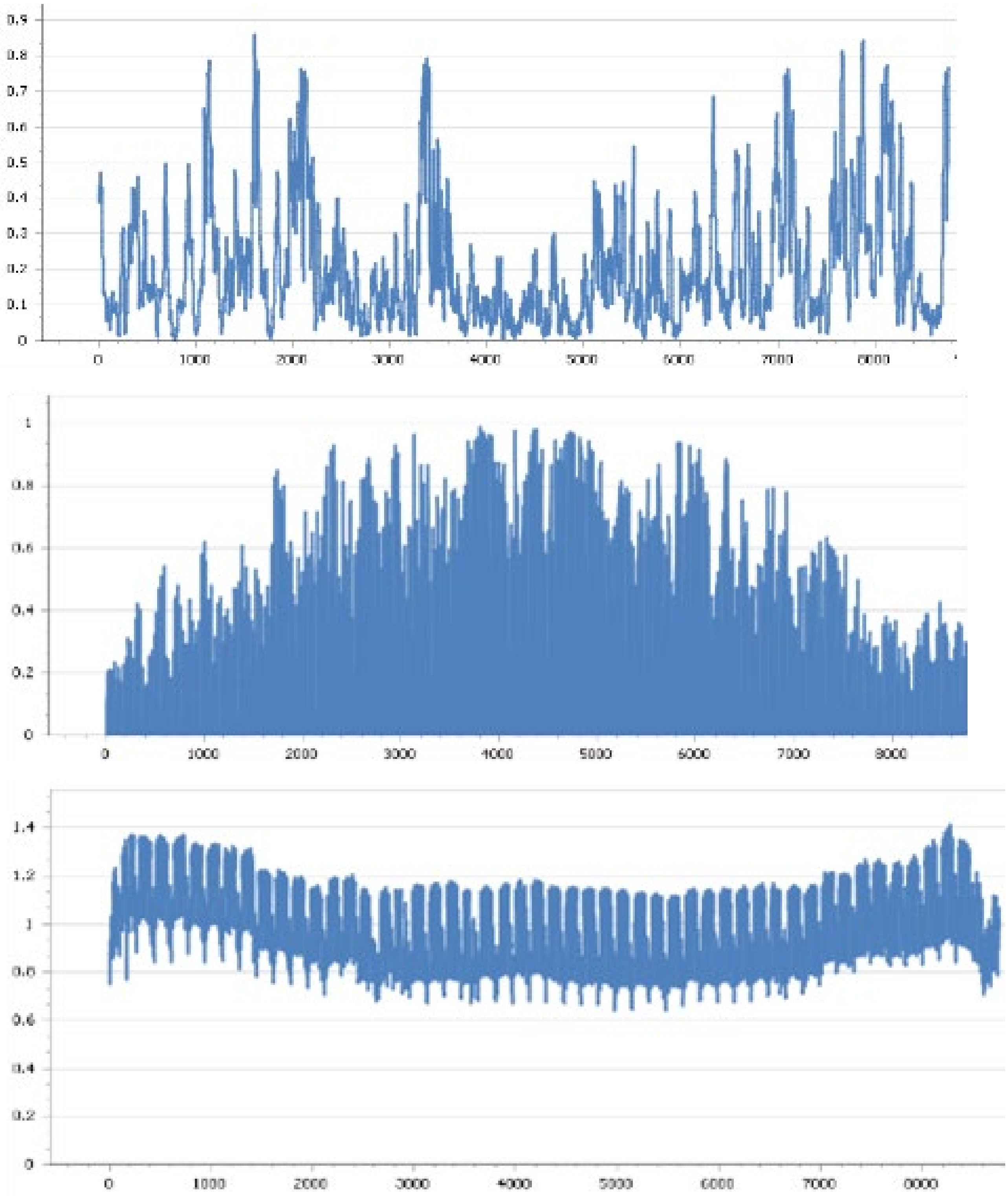
2.3.1.3 Consistent data & modelled scenario

Importantly, we use consistent historical weather and demand profiles (i.e., both from the same historical year) which means we capture any correlations between weather and demand and can also sample a variety of conditions – for example, a particularly windy year, or a cold, high demand, low wind period.

Taking onshore wind as an example (a similar process is used for solar PV), the regional hourly load factor profile is based on the locations of known wind farms within the region, hourly average wind speeds at each wind farm's location, the hub height of turbines at each wind farm, appropriate aggregate power curves for each wind farm, and the capacity of each wind farm

Exhibit 2.3 – 'Profile' sample data for hourly wind, solar and demand

BID3 provides detailed and consistent data.



2.3.1.4 Modelling real weather years

AFRY apply multiple historical years in BID3, to cover a range of different weather outcomes. The modelled weather years represent consistent sets of historical data; they are chosen to capture the range of weather impacts of power markets. Each future year is modelled multiple times and final results represent the average of these independent simulations. Examples of important weather driven profiles used in BID3 are:

- Plant generation refers to the power generation by renewable plants and CHP must run generation within a year.
- Demand (electricity & hydrogen) describes change in demand within a year.
- Hydro inflows: the storable & non-storable inflow to hydro plants within a year.
- Ambient factors specify the impact of temperature on thermal capacity.

Other factors also vary across the year, with other relevant hourly profiles:

- Plant availability: defines the capacity at which plants can produce within a year according to planned and random outages.
- Fuel prices describe the variation in input prices within a year.
- IC availability refers to the variation in interconnector capacity within a year.
- Reserve holding requirements.

2.3.1.5 Weather patterns

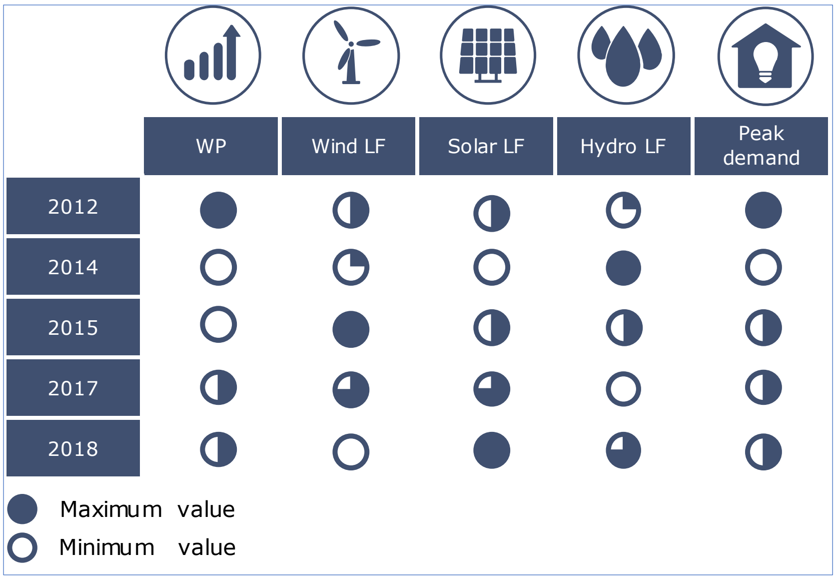
Historical weather patterns used in our modelling influence a large variety of factors that drive hourly and annual wholesale market outcomes. These include electricity demand patterns, hydro inflow patterns and intermittent patterns of renewable generation. For example, a very cold year with low renewable output would lead to high wholesale electricity prices, since the high demand would be covered by increased thermal and peaking generation. By choosing suitable historical patterns, the full range of potential weather-related situations are factored into the modelling.

For this study, there are five weather patterns used: 2012, 2014, 2015, 2017, and 2018. Exhibit 2.4 summarises the average characteristics for each year selected at a pan-European level. Key features of the set of weather patterns include:

- **Demand**: 2012 represents the year with the highest peak demand, reflecting the very cold winter season. 2014 recorded the mildest winter over the last ten years, leading to the lowest demand. 2015, 2017, and 2018 represent more typical European demand levels.
- **Renewable and hydro generation**: the highest wind load factor across the European countries was recorded in 2015. That year also had high levels of solar generation, although not as high as 2017 and 2018. 2012 and 2014 represent more average and lower renewable generation respectively, although 2014 had high levels of hydro generation, being a relatively ‘wet’ year among the set of weather patterns, especially in the Nordics.

- **Scarcity rent**[1]: as high demand leads to tight capacity margins, 2012 is characterised by high scarcity rent while 2014 sees the minimum values for the scarcity rent due its low demand.
- **Wholesale prices**: the combination of high demand and modest renewable generation push wholesale prices up in 2012. 2014 and 2015 are characterised by low wholesale prices due to respectively low demand and high renewable generation, especially from wind power. Similarly, Southern European countries with high solar penetration see relatively low prices in 2018 compared to the average.

Exhibit 2.4 – Weather year characteristics



The impact of each weather pattern in a given market may differ from the wider pan-European picture. This is because: (1) weather patterns may differ across Europe, so for example a colder than average year in north west Europe may not be colder than average in south east Europe; and (2) technology specific installed capacities and load factor vary by market, so for example wholesale prices in southern Europe are likely to be more responsive to changes in solar load factor because more solar capacity is likely to be installed and solar load factors are also typically higher in these markets.

Whilst individual years may exhibit these trends, the combination of running five years has been chosen to ensure that the model captures a sufficient range of extreme weather events, including high demand and low wind periods.

2.3.2 Hydrogen sector coupling

BID3 can be used to provide a multi-sector assessment of the integration between electricity and hydrogen.

[1] The scarcity rent: This represents the additional value of generators bidding in the wholesale electricity market above their variable cost of generation. This mark-up varies by hour depending on the market conditions, with market participants typically able to bid up more in hours when the system is very tight.

The purpose is to reflect the nature of different hydrogen supply, demand, storage and transportation requirements, leading to different (and potentially overlapping) spatial delimitations and zoning requirements.

In BID3, hydrogen supply is assigned zones and price areas which are distinct from the power zones and price areas. Similarly, hydrogen demand is assigned each a hydrogen zone.

Each dedicated hydrogen technology is assigned to a hydrogen zone. Hydrogen technologies with both the electrical and hydrogen interactions (e.g., electrolysers) lie in both co-product electrical price zones.

2.3.3 Geographical setup

The geographical resolution in BID3 is divided into zones, price areas and countries. The zones are the smallest geographical entities in BID3 and define the resolution of all the input data.

The optimisation within BID3 is carried out on groups of zones from one or more countries. This grouping of zones is usually known as a price area. At day-ahead, transmission constraints between such zones are ignored, giving rise to a single price. Transmission and wider system constraints are modelled for the purposes of balancing simulations (see Section 2.3.5).

There is a high level of user flexibility in the creation of price areas and in the assignment of zones to them.

2.3.3.1 Modelling GB and the Continent

BID3 is a pan-European model able to simulate detailed scenarios in GB and the Continent. Electricity interconnectors are key enablers of this modelling capability, helping ensure safe, secure and affordable energy supplies at the least cost solution.

Weather patterns are often correlated across wide geographical regions, and therefore it is important to model both GB and the continent on a consistent basis. BID3 is ideally set up to capture the extent to which low temperatures, high demand, low wind coincide across multiple markets.

In an island market like GB, it is important to have a good modelling approach to embed the impact and contribution of interconnectors. High penetration of wind generation can cause grid stability issues, as wind turbines (and other forms of non-synchronous generation) can limit the ability of the SO to maintain sufficient inertia in the system. This will be an important characteristic of the scenarios and a driver of the optimised solution. Interconnector flows are significant determinants of the system’s operation and therefore it is important to account for these interactions.

2.3.4 General

2.3.4.1 Supply

There are several factors influencing the supply curve. This section gives an overview of the type of power plants in BID3 and the key parameters available for each plant. Some properties of plants are common to each plant specification: e.g., zonal location, nameplate capacity, availability profile, capex/opex, investment type.

Thermal assets. We maintain an extensive database of all thermal assets across Europe, with information on a range of parameters including (amongst others): fuel types; min time on/off, run ramp rate; efficiency; co-firing status; start-up costs; and minimum stable generation (MSG).

Intermittent renewables. Hourly load factor profiles are estimated on a zonal basis and applied to the projections of installed capacity. New capacity can have different load factors to existing capacity, typically as a result of improvements in turbine technology and higher hub heights.

Storage plants. Storage plants are used for load shifting i.e., they consume power and fill up their storage when demand is low and power is cheap and generate when demand is high, and power is expensive. Storage plant specific properties are round-trip efficiency, availability, time to fill, time to empty, variable pumping cost, inflows, modular storage, and minimum storage level profile.

Hydrogen. The model includes both production of hydrogen on a stand-alone basis (e.g., ATR, SMR), production of hydrogen via electricity (electrolysers) and consumption of hydrogen to produce electricity (hydrogen CCGTs).

Hydro. For reservoir hydro, the decision regarding how much water to dispatch for power generation and how much to store in the reservoir for later is associated with a high degree of uncertainty. Consequently, BID3 allows reservoir hydro plants to be dispatched using either a constrained perfect foresight methodology or a water value method.

2.3.4.2 Demand

Annual demand is entered in TWh/year, for electricity and hydrogen.

This is then characterised over the hours of the year according to a demand profile. Annual demand is disaggregated into hourly values via a series of demand profiles that take into account historical weather patterns and demand flexibility (in the case of EVs and heating).

Annual electricity demand is specified according to different elements:

- Electrified transport (electric road vehicles, such as cars, trucks, buses, and rail transport).
- Electrified heat (space heating).

- Residual 'economically sensitive' demand (predominantly driven by GDP growth and assumptions around energy efficiency).

There can also be several tranches of annual hydrogen demand:

- Residential heat.
- Transport.
- Industrial.

Demand response. Demand response refers to changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. BID3 models demand response to capture the impact of electric vehicles, heat storage units, industrial and commercial turn down DSR and other parts of demand response. These can be modelled as price sensitive demand (e.g., I&C DSR) or including restrictions around the storage of power between hours (flexible charging of EVs subject to limits on charging availability and driving of the vehicles).

2.3.4.3 Fuel

Fuel types include coal, gas, biomass, oil products and various others. CO2 prices are also an input.

All fuels also have an emissions content for certain pollutants. This is used to determine how many tonnes of CO2, SO2, NOx, Mercury and Particulates are emitted from burning a unit of fuel.

In the case of hydrogen, the fuel price can either be specified as an input, or more commonly, is an output of the model based on the prevailing production costs at any point in time.

2.3.4.4 Interconnectors

Electricity interconnectors are links that allow the transfer of electricity from one point to another, helping to ensure safe, secure and affordable energy supplies. Pipelines serve the same purpose but for other energy vectors such as hydrogen.

Interconnection. BID3 models both existing and new interconnection between zones. Interconnectors are assumed to be optimally utilised, i.e., equivalent to a market coupling arrangement.

Hydrogen pipelines. Hydrogen pipelines are the equivalent to power interconnectors for each individual hydrogen zone. Their properties are named similarly as power interconnectors and represent the same concept. Losses are considered as a function of the length of the pipeline.

2.3.4.5 Technology costs

We model the evolution of costs (capex and opex) for all generation technology types based on observed data; discussions with our network of industry contacts; and learning rate analyses for battery storage and intermittent renewables.

2.3.5 System Constraints

There are various types of constraints in BID3 that can be modelled for a variety of different system features and specific constraints required to model specific markets.

BID3 has the flexibility to model all of these constraints on an on/off basis depending on the scenario's requirements. These constraints include all forms of reserve and response markets, and other constraints that TSOs may impose as a result of the network. Below a few relevant constraints are described as examples of the model's ability to model system constraints.

2.3.5.1 Reserve holding

System operators keep capacity available, ready to change their output at very short notice in order to maintain system stability. It is possible to model the holding of reserve capacity in BID3. Any number of types of reserve/response holding can be specified, BID3 will 'co-optimise' the holding of this reserve capacity alongside the main plant dispatch.

For each hour of the year, the supply of reserve capacity must be greater than or equal to the requirement for each individual reserve holding requirement. Plants will therefore be constrained to output below their available capacity, and their remaining capacity allocated to the reserve holding requirement. These decisions are determined as part of the main optimisation, and so plant dispatch and reserve holding are 'co-optimised'.

2.3.5.2 Boundaries

A Boundary is a notional line separating one group of zones from another where flows of electricity from one side of that Boundary to the other are constrained by the Boundary's capability. Boundaries in BID3 have a 'Defined' and a 'Reverse' direction.

Zones are allocated to either the 'Exporting' or 'Importing' side of each Boundary.

The concept of boundary and its application in BID3 is derived from the representation of the transmission network, as used by National Grid ESO. The ten most significant boundary constraints – as identified from the latest NG ESO Electricity Ten Year Statement – are modelled in BID3. Although it is possible to model any number of boundaries, AFRY have configured their inputs to capture the main constraints that exist on the GB transmission network today and in the future. All generation, storage, and demand are located in (or disaggregated to) a specific notional zone within GB. Transmission capability is limited at each boundary.

Reinforcement of boundaries is included within the Auto Build investment module.

2.3.5.3 Inertia

AFRY model the GB inertia requirements by looking at the allowed rate of change of frequency, new sources of inertia and faster frequency response. The BID3 modelling looks at the respective costs of inertia management in the BM, synchronous condensers, and fast frequency response to determine future inertia requirements. The cost optimisation will either lead to a reduction in the size of the instantaneous largest infeed, and/or scheduling of additional inertia provision.

2.4 Backcast

BID3 is a fully benchmarked and back tested model. The quality of BID3 and its underlying data is assured with a regular backcast exercise. Every year a full backcast of GB and Europe is run, testing the quality of BID3’s data and modelling assumptions.

In the backcast, all GB and Europe has been modelled simultaneously for 2012-2020, with the aim of simulating day-ahead hourly market prices. The model’s outputs are compared to the market’s outturn data on prices, generation, CO2 emissions, interconnector flows and capture prices by technology.

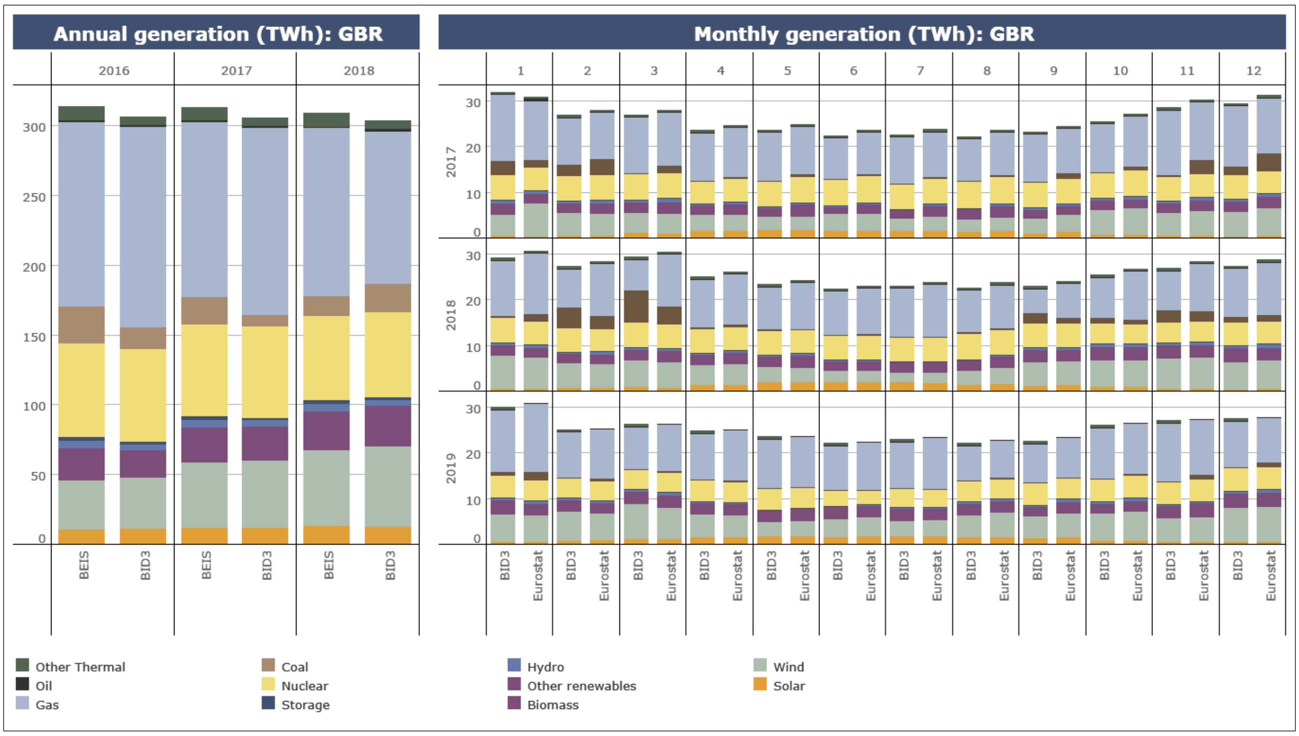
In this section we highlight the quality assurance demonstrated by the back cast, with examples for the day-ahead backcast and Balancing Mechanism (BM) backcast in Great Britain.

Exhibit 2.5 shows the generation in GB from BID3 data against market data, demonstrating a close match at both annual and monthly resolution and an accurate dispatch. The modelling of electricity prices in GB shown in Exhibit 2.6 also demonstrates a strong level of accuracy in the model.

Overall, BID3 has been proven to provide a highly accurate representation of all European markets, with annual errors typically in the range of 2-3%.

Exhibit 2.5 – GB Day Ahead backcast, Generation (TWh)

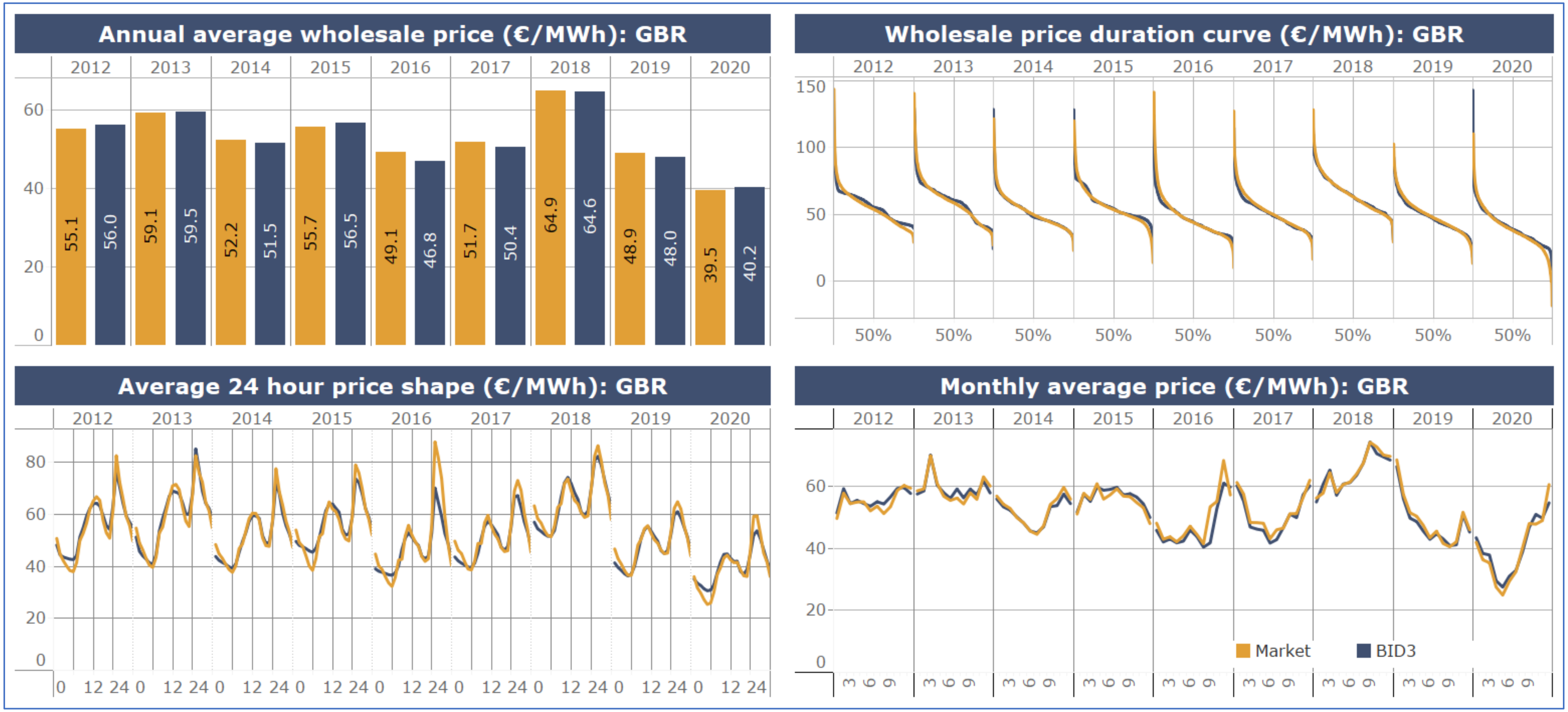
BID3 accurately models the generation by fuel on a monthly and annual level.



For the purposes of this backcast, AFRY's profiles are used for wind, solar, hydro and demand for the relevant historical years. Commodity prices are set based on outturn values, as are annual demand levels. Generator and interconnector availability is calculated from Urgent Marketing Messaging (UMM) data.

Exhibit 2.6 shows the ability of BID3 to backcast historical market prices.

Exhibit 2.6 – GB Day Ahead backcast, Price comparison (€/MWh)



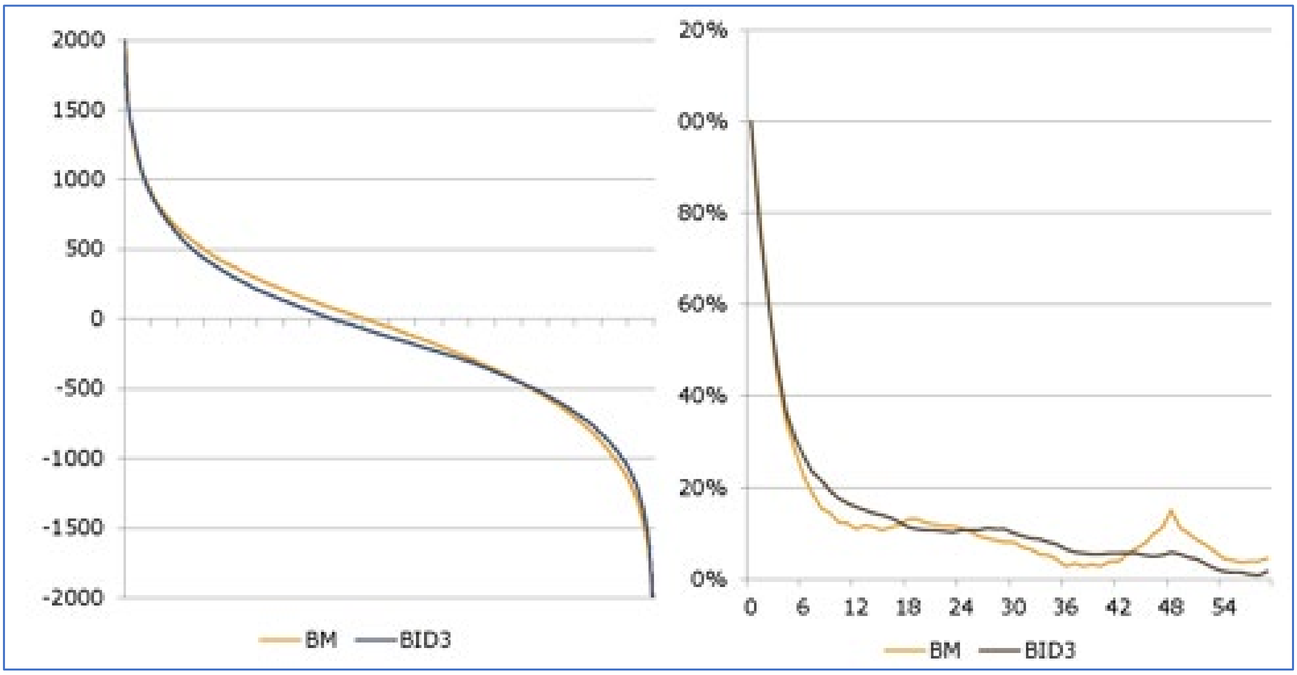
Source: Historical data from N2EX

The backcast of the GB Balancing Mechanism ensures key functions and characteristics in the model accurately reflect reality.

The modelling of the BM also includes energy imbalances and System Operator actions. The latter includes transmission, inertia and voltage constraints requirements. An operating reserve must also be maintained at all times.

BID3 stochastically creates a net imbalance volume based on the forecast of wind, solar, demand and plant outages between gate closure and settlement, including error persistence between periods. A backcast for these values are shown in Exhibit 2.7.

Exhibit 2.7 – NIV Duration curve (MW) and Auto Correlation (2019)



Source: Historical data from Elexon

Parameters such as Bid and Offer prices are calibrated to guarantee that the value of accepted actions reflect reality. Exhibit 2.8 shows the hourly weighted average accepted Bid and Offer price modelled in BID3 against outturn data from the BM.

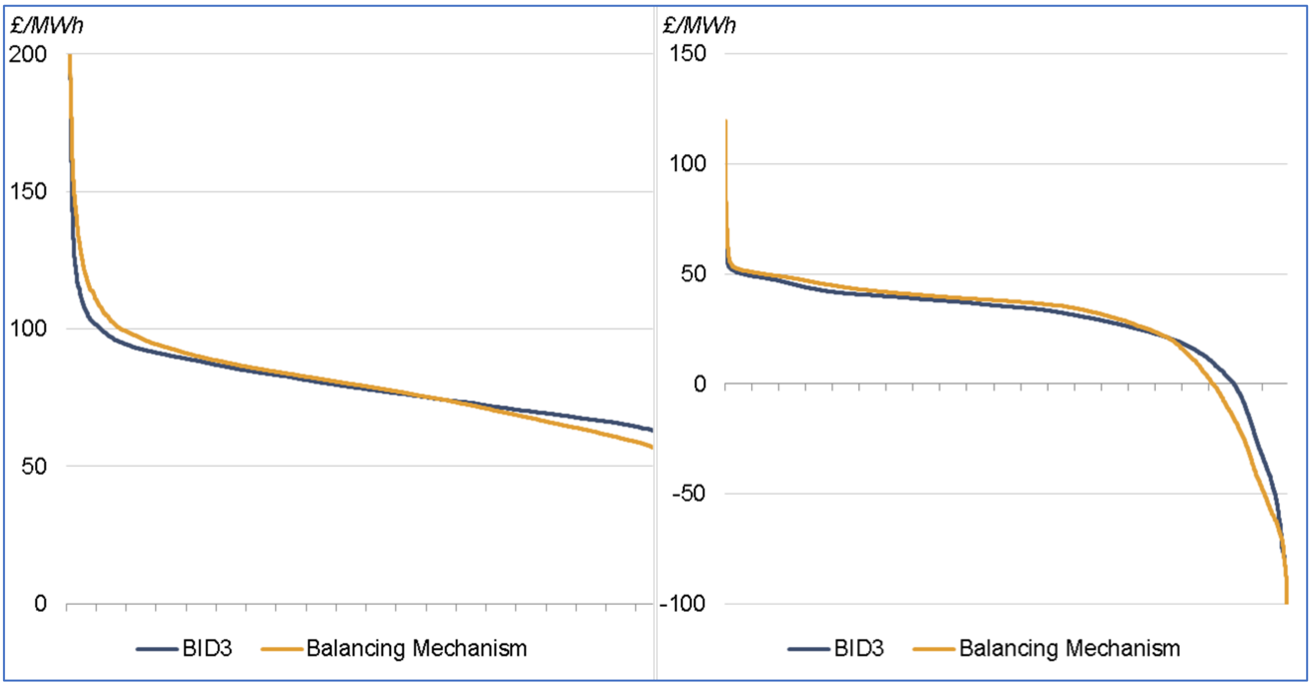
The accurate level of modelled representation in BID3 is also shown in the imbalance price duration curve in Exhibit 2.9, highlighting a good representation of the BID3's range of imbalance prices compared to reality.

In order to accurately model the imbalance price, this shows a number of key features of the BM are well modelled, including:

- bid/offer prices for each generator;
- accepted volumes by generator;
- generator dynamic data (such as MNZT);
- required energy actions;

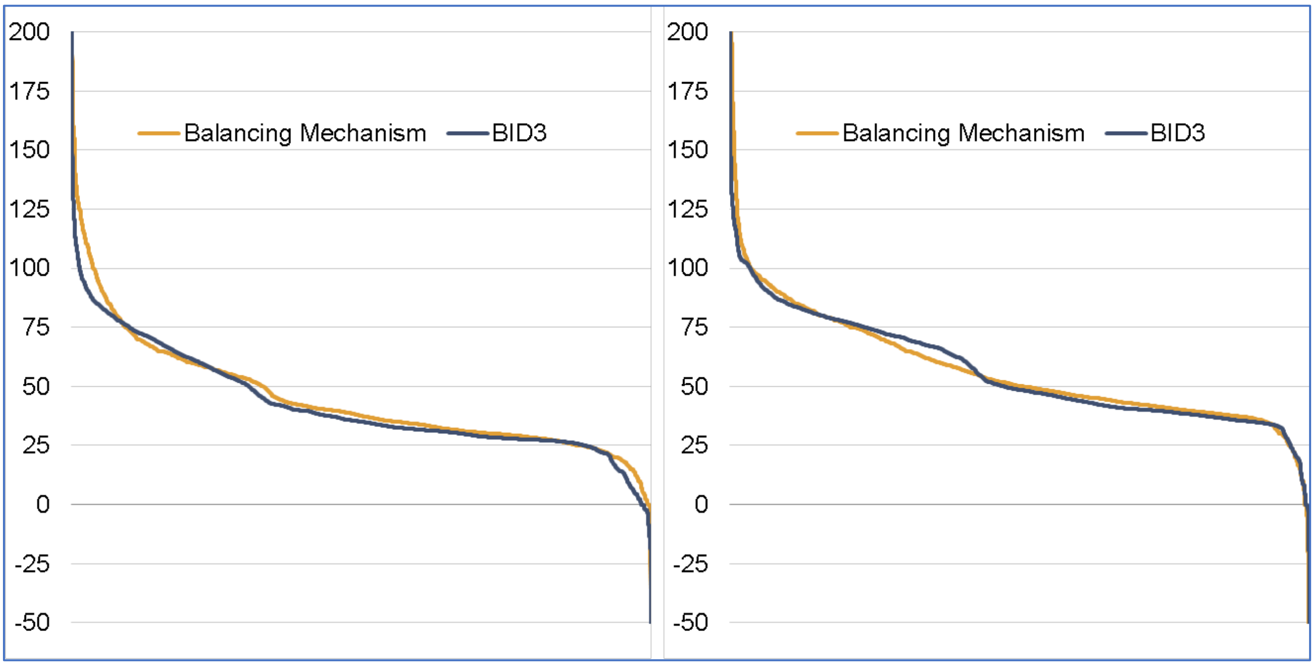
- required non-energy actions; and
- the imbalance price algorithm.

Exhibit 2.8 – Hourly weighted average offer and bid prices, £/MWh (2019)



Source: Historical data from Elexon

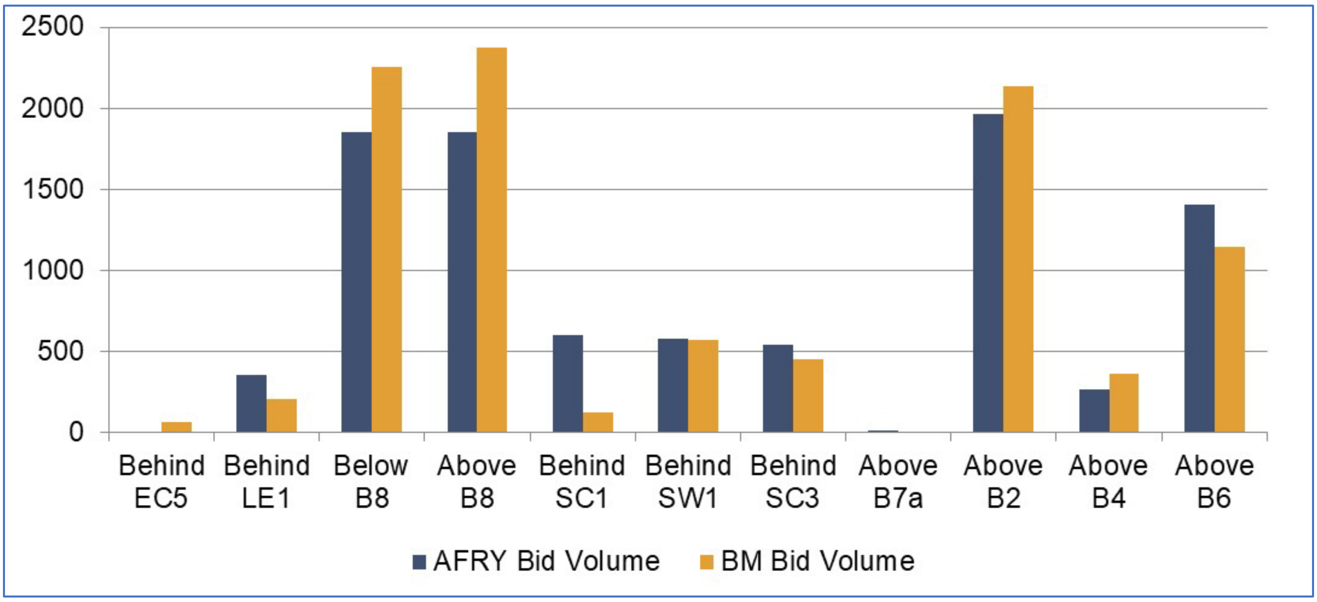
Exhibit 2.9 – Imbalance price duration curve, £/MWh (2017, 2018)



Source: Historical data from Elexon

Further evidence of the ability of BID3 to model locational transmission constraints is shown in Exhibit 2.10. BID3 captures well the main dynamics of transmission constraints, particularly around the key Scottish boundaries B2, B4 and B6. There are few generators bid off in the B7a region, but it is another key constraint. Generation in other regions is typically bid off for energy reasons rather than transmission constraints.

Exhibit 2.10 – Locational accepted bid volumes, 2019 (GWh)



Source: Historical data from Elexon

Separately, bids and offers are also taken on generators on a locational basis for voltage support and inertia management (in the case of location specific constraints arising on groups of generators, which can form the largest infeed risk together on certain occasions).

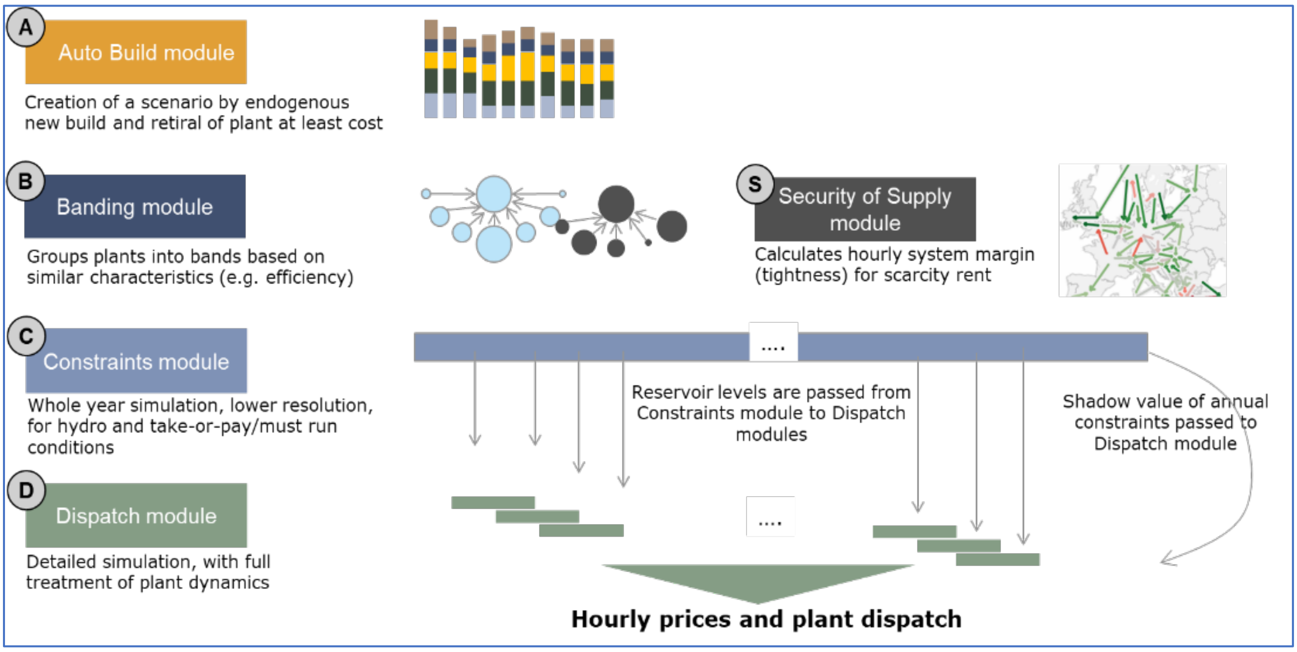
2.5 Modelling principles: main modules of BID3

As a fundamentals optimisation dispatch model, BID3 models the power system:

- from the bottom up;
- optimising generation, storage and transfer of power;
- optimising across timeframes, from sub-hourly to multi-year;
- minimising the cost of meeting demand; and
- subject to relevant constraints.

These principles are at the heart of BID3 and are translated into the core modules of BID3. These cover different timeframes and functionalities, summarised in Exhibit 2.11.

Exhibit 2.11 – Overview of main modules in BID3



Auto Build. The Auto Build module is among the most sophisticated and important optimisation tools, representing state-of-the-art modelling by capturing both dispatch and investment decisions together. It is described in more detail in 2.4.1.1

Banding. Is designed to increase the speed that the model solves. It does so by grouping very similar plants together in groups (or bands). This allows the model to have few bands rather than many plants to consider, which has several benefits: removes degeneracy from the model; reduces the amount of memory used as there are fewer variables.

Constraints. Is an optimisation of the whole year at once, so that annual hydro or take-or-pay constraints can be modelled accurately. It does so by taking all of the main inputs used in the Dispatch, but with some simplifications, so that the whole year can be solved in one go.

Dispatch. Is the most detailed module in BID3 with many functionalities. It solves the weekly dispatch optimisation using linear programming, modelling the dispatch of thermal, CHP, hydro, storage, reserve and DSR technologies.

2.5.1 Auto Build

Auto Build is a sophisticated capacity expansion module allowing the model to develop scenarios of new build, retiral and mothballing automatically. The Auto Build module exists to endogenously determine the future plant capacity of a given scenario. Using the same inputs as the other BID3 modules, the module iterates a market dispatch and a capacity investment optimisation.

In this section an overview of Auto Build's basic architecture is described.

Sophisticated decomposition technique to minimise system costs. This relies on the use of Bender's or Dantzig-Wolf decomposition technique to solve multiple sub-problems and recombine. This is illustrated in Exhibit 2.12. Therefore, the module ultimately minimises the long run cost of generation, by changing the investment in power plants, subject to various constraints. These include constraints such as security of supply, technology build caps and deployment rates, emissions limits, and renewables penetration. These constraints need to be specified as inputs. These two approaches have some important differences, relating to how the capacity is optimised, how plant lifetimes are logical and how the hardware requirements may differ.

Iterative basis. The module runs on an iterative basis. The module successively calculates refined plant build results until the model has converged on the least cost optimal solution. The sequence in which Auto Build runs can be thought of as a loop: a dispatch optimisation, followed by an investment optimisation, followed by a dispatch. The links between the market dispatch and the investment decisions for the iteration process are shown in Exhibit 2.13.

High resolution modelling for renewables and storage. Auto Build is built around the same detailed weather-based modelling of the main BID3 dispatch algorithm. Built on a bottom-up basis, it accurately includes the interactions of differing weather patterns, ensuring consistency between wind, solar and demand profiles with the use of historical weather patterns. This sophisticated approach ensures systems with increasing levels of renewables are modelled accurately. The Auto Build is a high-resolution dispatch solution that is internally consistent with the hourly profiles for generation, demand, etc, and is therefore adequately able to capture the modelling of storage. Unlike many other capacity expansion approaches, the Auto Build is **time sequential**; it links all hours together (intertemporal constraints) and so it accurately represents storage and battery technologies.

New build and technologies. The Auto Build module invests in new plants, considering all cost elements of existing plants, but also the capex required to build the plant. It captures new build across sectors, in particular modelling zero carbon transitions including sector coupling (P2Heat, P2Hydrogen, etc.).

Exhibit 2.12 – The Auto Build iterative process

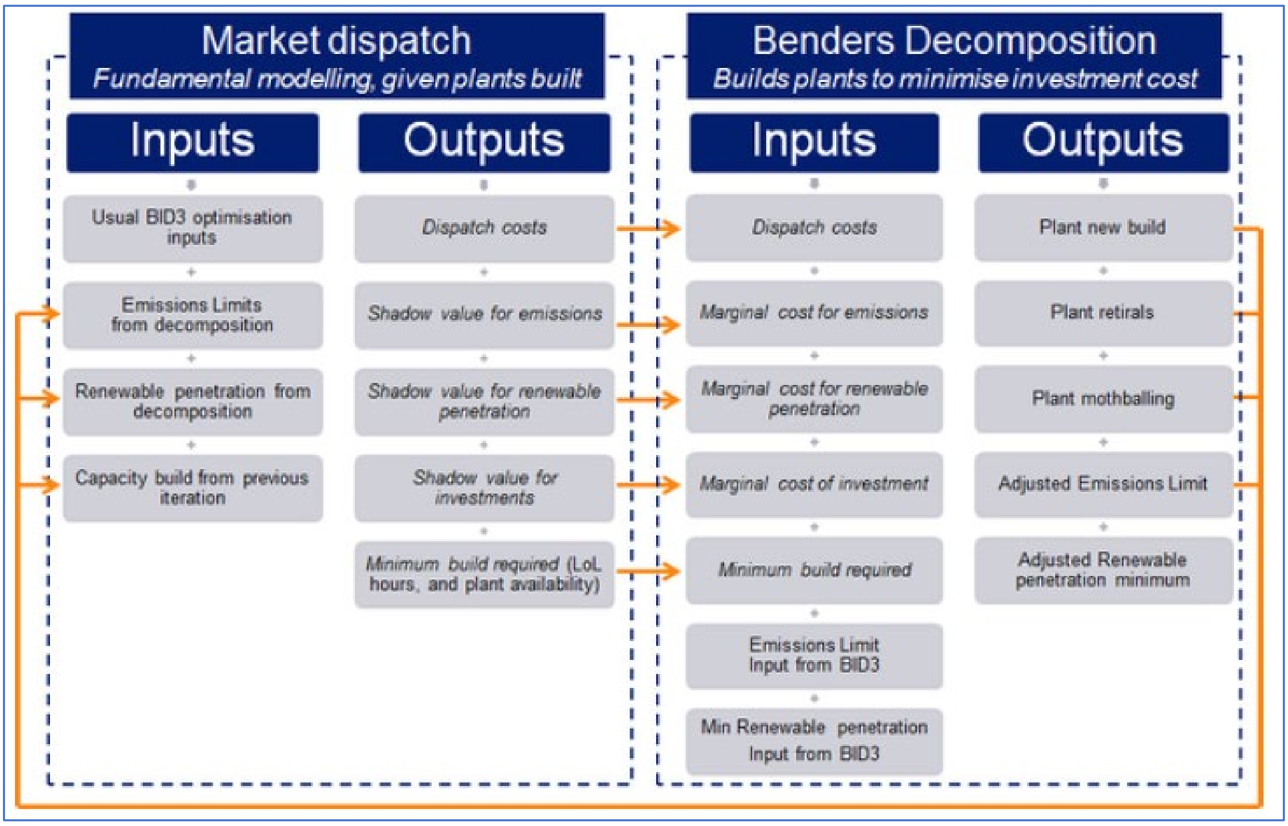
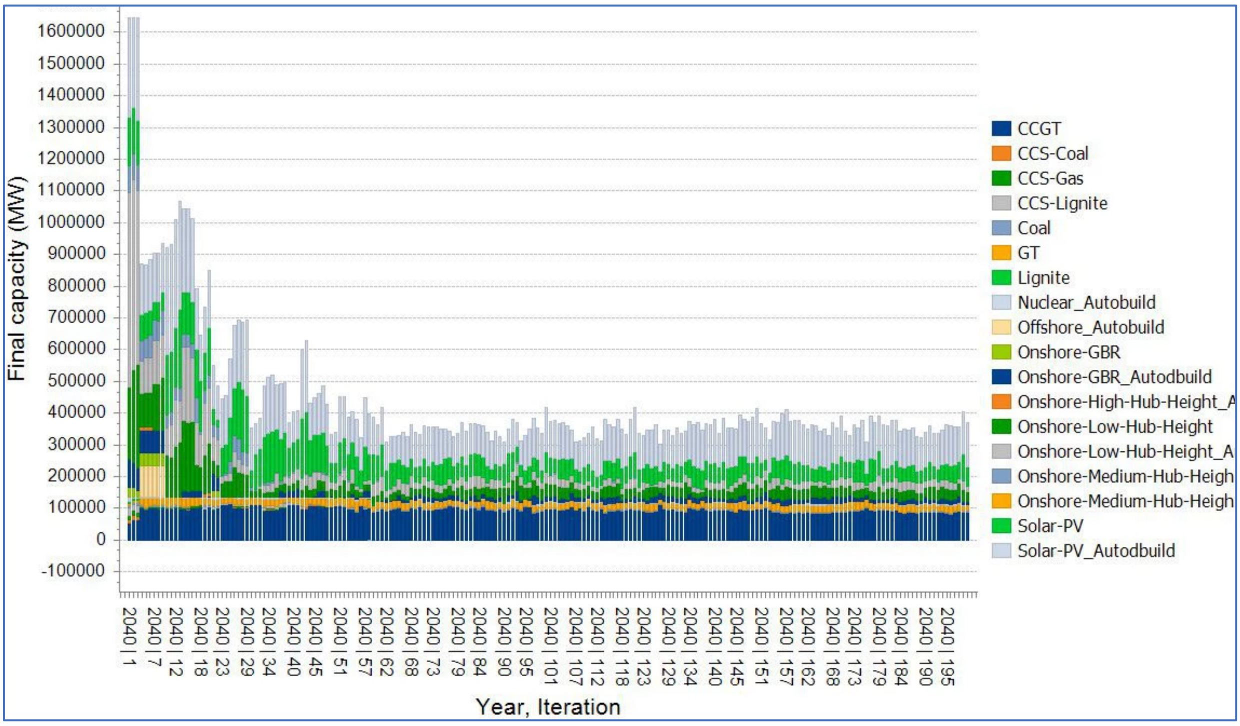


Exhibit 2.13 – Auto Build convergence of model solution (illustrative)



2.5.2 Investments

Investment decisions in the model are taken in relation to power plants, interconnectors, boundaries and hydrogen plants. Defining investments is very important for profitability analysis and to endogenously determine the future capacity of a given scenario. The model requires the following inputs as minimum:

- capex;
- opex;
- hurdle rates;
- build time;
- technical and economic lifetimes; and
- parameters for other revenue streams available to the generator.

2.6 Key outputs (What does BID3 provide?)

BID3 outputs all the key characteristics of the energy system it is modelling. These include **system-wide** outputs such as the System Marginal Price, the marginal plant in each hour, capacity margins and emissions (from system down to the plant level), capacity and generation mix. **Plant-specific** outputs are also available for analysis, these include generation volumes for all types (renewables, thermal, storage, demand-side, etc.), plant revenues and costs. **Interconnection**-related outputs such as flows. **Investment** outputs related to the profitability of investments (power plants and interconnectors) at annual resolution, new build capacity and retirals of existing assets.

Depending on the type of run, different outputs at different resolutions (from annual to sub-hourly) are available.

This section provides an overview of some of these key outputs of the model categorised under dispatch and investment outputs.

2.6.1 Dispatch outputs

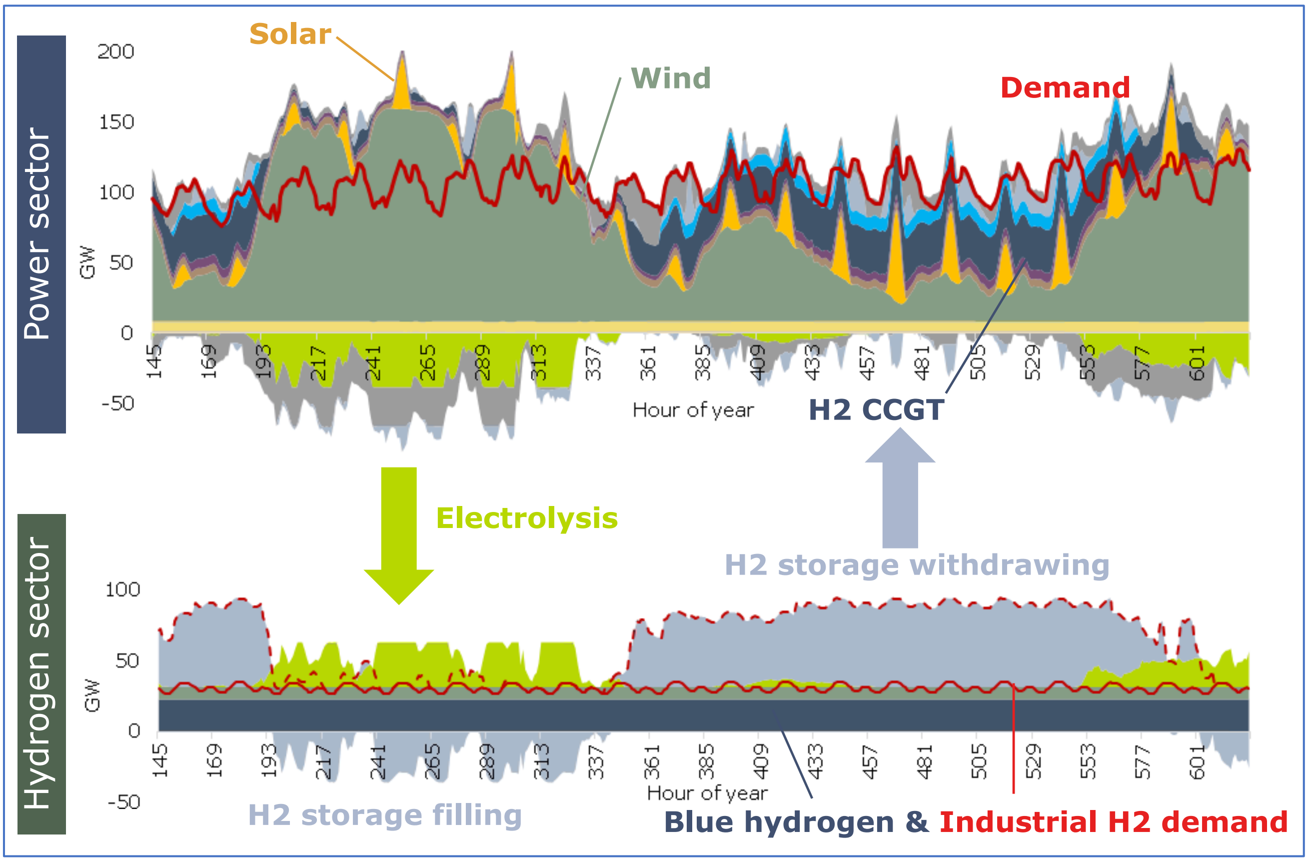
BID3 is able to output all aspects of the electricity market that it simulates, including the physical operation and economic behaviour of all plant types for all 8760 hours of the year. In general, all the input fields described in Section 2.3 will have a counterpart output provided by BID3 from the optimised simulation. These include the generation volume, load factors, the costs of generation (fixed and variable) as well as specific features from the **thermal modelling** (number and cost of hot, warm, cold starts, emissions), **renewable modelling** (curtailment), **storage** (hours of discharge, number of cycles), **DSR** (load shifting, load shedding, energy recovery). BID3 can output the simulation of flexible demand, including the storage, demand and network off-take.

The BID3 dispatch creates a mirror **hydrogen** sector to the power sector, models energy flows between the sectors, and outputs H2 prices.

In order to quantify the role of hydrogen in providing long duration storage to the power sector, BID3 includes modelling of both sectors and the energy flows between them. The final output is an hourly dispatch schedule for both sectors, showing where there are synergies, as shown in Exhibit 2.14.

Outputs for the hydrogen sector include demand, production, storage injections and withdrawals, and hydrogen prices.

Exhibit 2.14 – Illustrative hourly generation



Asset utilisation. BID3 provides useful metrics regarding the utilisation of certain assets. BID3 outputs standard load factor metrics for generating technologies (such as thermal and renewables) based on actual generation and nameplate capacity. BID3 makes use of its sophisticated dispatch data to calculate the asset utilisation for storage technologies as well based on hours of discharge per day and number of charging cycles per day.

2.6.1.1 Emissions

BID3 outputs the dual value of any emissions constraints and the final emissions for each modelled year. The constraint dual reflects the cost of carbon emissions for the given emissions limits for each individual year.

In the case of multi-year emissions constraints, this will show the impact of any banking or borrowing of permits.

2.6.2 Investment outputs

2.6.2.1 Build Summary

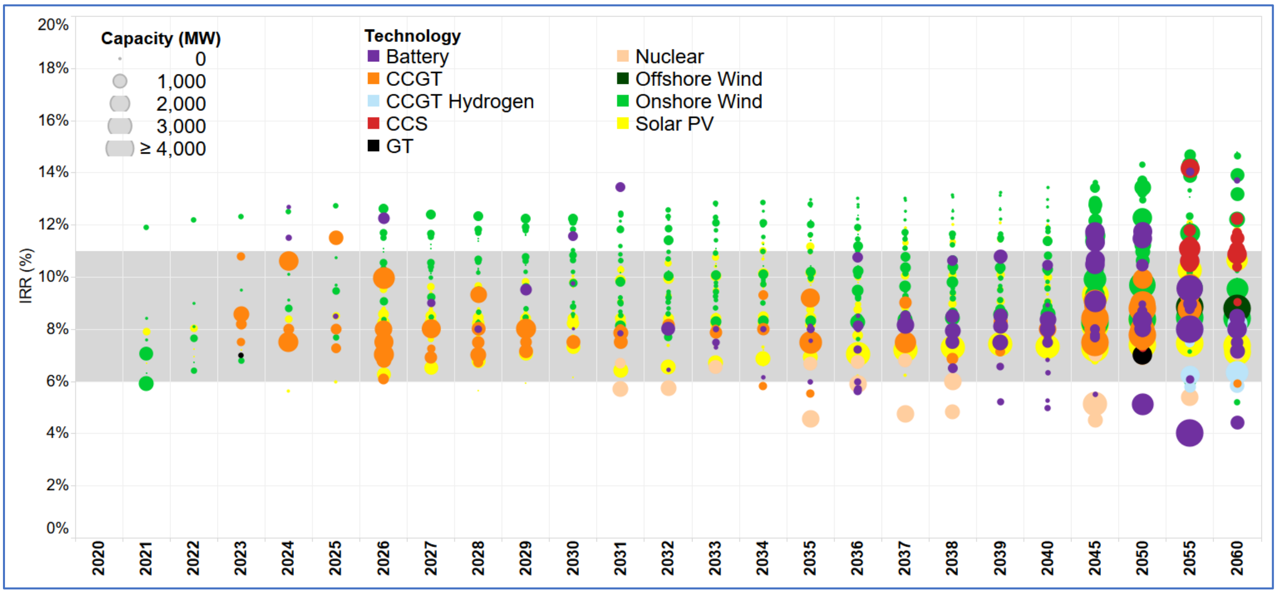
Among the most important output of the model's investment decision (from Auto Build) is the overall capacity results. BID3 can output the build on both an aggregate and plant-specific level. The final amount of capacity built by the module can be seen, alongside the maximum amount possible, the amount retired or mothballed for a given investment type, price area, year and iteration. These are the high-level summary outputs for the module and the simplest way to visualise its results.

Exhibit 2.13 shows an example of the output from this form: the total operational capacity (new build plus plants kept open) for one future year. The results are split by investment type and the evolution of the results by iteration shown.

2.6.2.2 Investment cashflows

BID3 calculates cashflows for any future investment, along with key metrics such as IRRs and shortfall against fixed costs. These investment metrics can be visualised and post-processed from BID3 including the NPV, IRR, missing money of specific plants. Exhibit 2.15 illustrates an example of these outputs.

Exhibit 2.15 – Example of project IRRs



2.6.2.3 LCOEs

The load factor outputs can be processed together with the lifetime costs of the given assets to calculate the levelized costs of electricity in the modelled scenarios.

2.6.3 System cost outputs

The investment costs and dispatch costs from BID3 provide a disaggregated view of the total costs in the system and provide a view on the total system costs. BID3's capabilities in modelling the system dispatch, investment decision in generating plants, transmission and interconnection assets, and storage mean that corresponding cost outputs for these can be provided at a disaggregated level for:

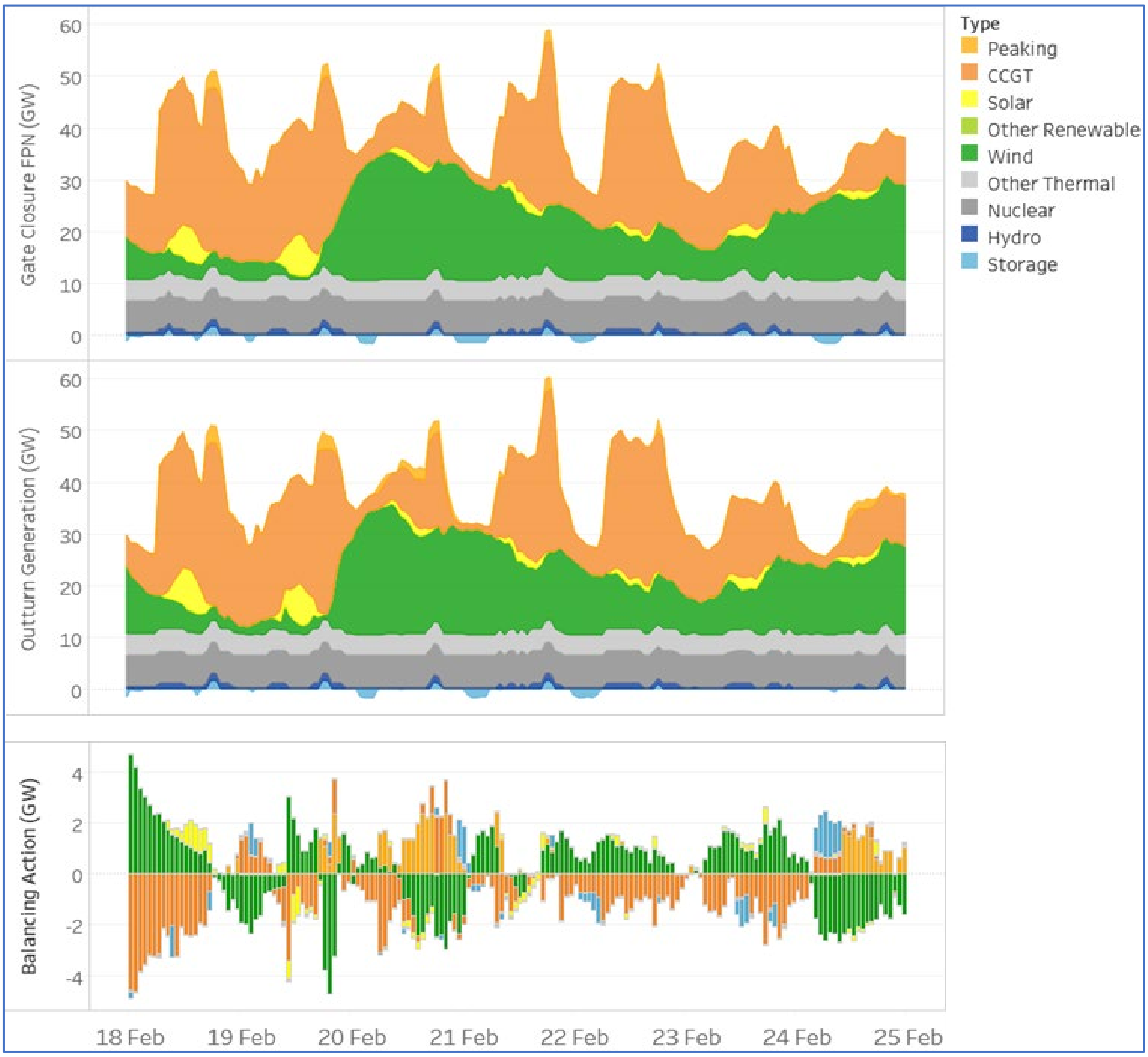
- transmission;
- interconnectors;
- hydrogen storage;
- hydrogen capacity;
- generation capacity;
- fuel; and
- carbon.

2.6.4 Re-dispatch outputs

AFRY has developed the locational modelling of the BM in GB, including the impact of transmission constraints. BID3 is able to output BM volumes and costs, which can also be location specific.

Modelling the full BM, BID3 can provide a greater richness of insight. This can be seen from Exhibit 2.16 showing an example output from BID3 of the balancing needs from a sample week. The overlaying of FPN, outturn generation and balancing actions demonstrate different elements of the Balancing Mechanism such as short and long wind forecast requiring turn up and down of flexible thermal generators, or transmission constraints requiring curtailment of wind.

Exhibit 2.16 – Example FPN, Outturn generation and BOA



3. Modelled scenarios and assumptions

The modelling in this project covers Great Britain and all neighbouring countries.

The optimisation is applied to show how both dispatch and investment decisions are taken for generation and storage technologies, as well as modelling key system operability needs. All the modelling is carried out at an hourly resolution, accounting for key interactions for weather variability, demand and storage.

The model is used to simulate two core market scenarios – each with a counterfactual without long duration storage – and a variety of sensitivities, all testing the research questions in this study.

The scenarios have been designed to illustrate potential pathways to net zero and the role of different potential long duration storage technologies, projected to result from internally consistent combinations of assumptions and drivers.

3.1 BID3 in this project

This section of the report documents the methodology in the study, covering:

- a description of the use of BID3 in this study;
- the methodology for the core scenarios and sensitivity tests; and
- the detail of inputs and outputs, and additional explanation not in the main report.

3.1.1 How BID3 is being used for this project

BID3 is well positioned to answer the research questions of this project.

BID3 is equipped with features that make it flexible in its ability to test the range of scenario and sensitivities in this study, enabling a sophisticated comparison of relevant system costs. In this section key features of BID3 that are important for this project are described in their application.

In this section we explain the methodology in the application of BID3. We highlight:

- the geographical setup for this project;
- the optimisation approach, describing the method behind the optimisation of investment, dispatch decision;
- the project specific constraints applied in the optimisation;
- the specific weather years applied in the optimisation; and
- the long duration storage technologies included in the optimisation.

3.1.1.1 Geographical scope

AFRY has used BID3 to calculate the optimal capacity to meet net zero in Great Britain and Europe.

Geographical setup GB. In this study AFRY models Great Britain locationally, including the modelling of the main transmission constraints in the GB market. This feature enables the integration and evaluation of how constraints will drive flexibility (and by extension long duration storage) needs and system costs in the future. The locational constraints applied in this study include B2, B4, B6, B7a, B8, EC5, SW1, SC1, LE1 and SC3, as shown schematically in Exhibit 3.1.

The thermal capabilities of the boundaries between zones are benchmarked against NG ESO publications of grid reinforcement.

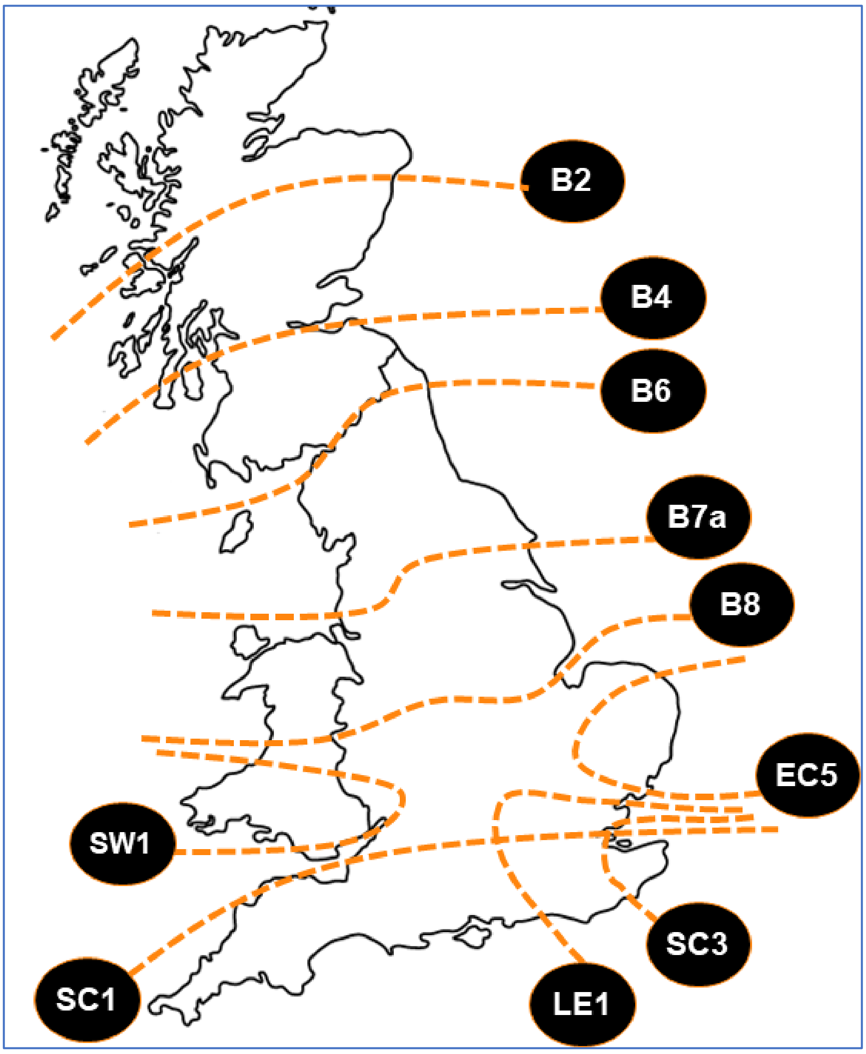
In this study AFRY optimises the level of grid reinforcement along with the rest of the modelled system. The optimal level of network capability is derived in the simulation based on the costs of grid reinforcements, the avoided costs of balancing the transmission constraints and the available commercial alternatives to grid reinforcement (such as long duration storage).

With regards to the zonal configuration of GB, power demand is split according to historical shares of demand in each zone. Existing capacity is allocated to each zone based on known locations of assets. Future capacity can be built in any zone subject to further limitations for storage and renewables. For renewables, the overall capacity caps are disaggregated across the zones. Wind capacity is limited in each zone based on the resource potential, as calculated by AFRY from analysis of wind speeds, land area, also accounting for the existing and future pipeline of capacity. Solar capacity limits are based on land area. Thermal generation and most types of storage can be built in any zone without further limitation than the overall national build caps. Further capacity limits were applied for pumped storage (only available in Scotland), compressed air storage (only available in certain English zones) and salt cavern hydrogen storage (only available in certain English zones). These latter two limits were derived from analysis of the locations of salt caverns.

Geographical setup Europe. Today's electricity interconnection with neighbouring EU countries (at ~7.4GW) plays a significant role in the GB electricity market. With the support of the cap and floor regime and market dynamics, GB has a strong pipeline of interconnection projects which is set to increase the overall level over the next decade and beyond. It is therefore important in this study to model the future system on a pan-European level, accounting for interactions and impacts on the GB system and by extension the role of long duration storage.

In this study AFRY model European countries, including hourly interconnector flows both optimised (for neighbouring countries) and fixed (based on the modelled AFRY High scenario, net zero compliant). Exhibit 3.2 shows which countries (and flows) have been optimised together with GB, and which ones have been modelled using fixed flows.

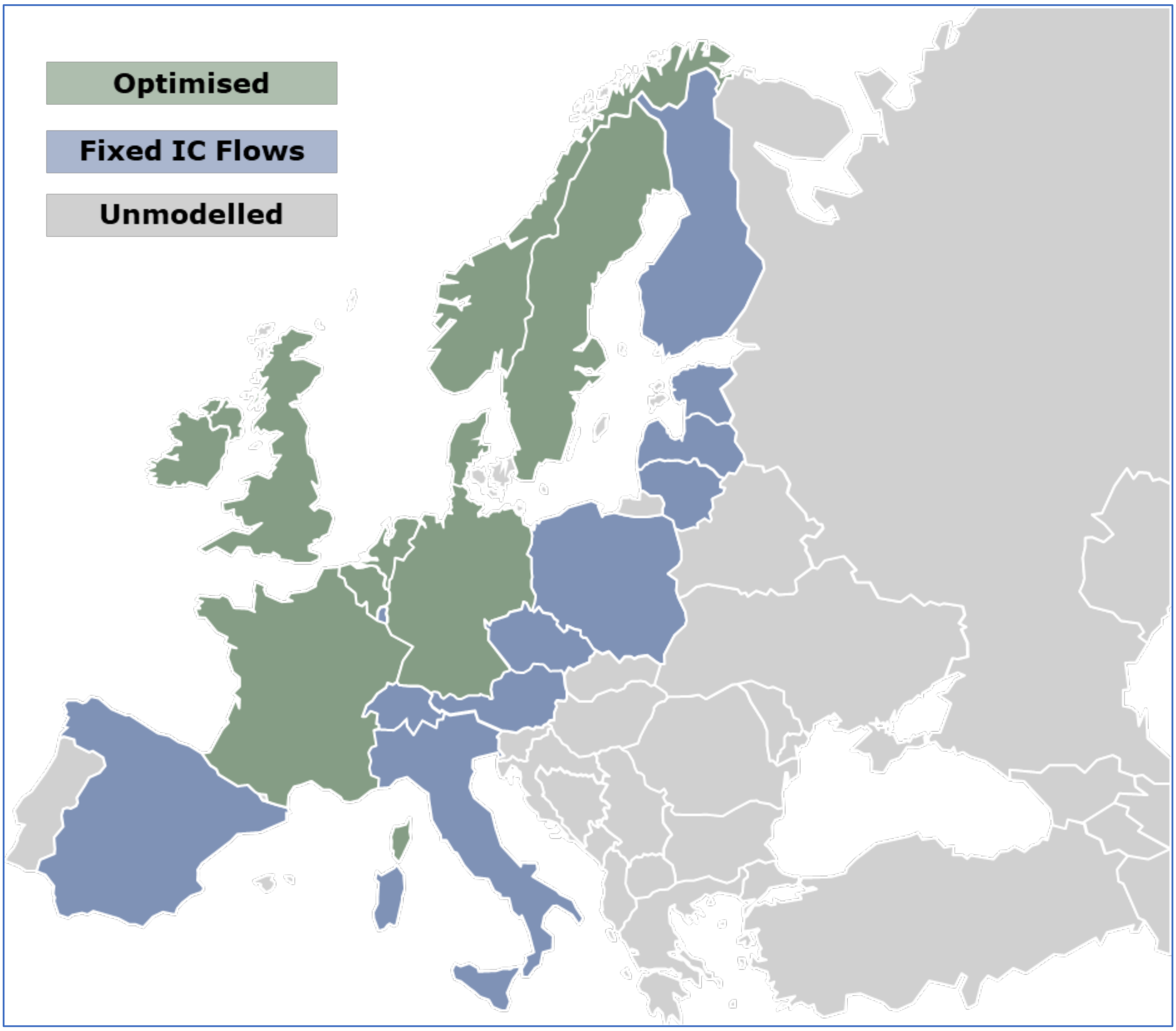
Exhibit 3.1 – Transmission constraint boundaries in AFRY modelling



From a hydrogen perspective, each country was treated as a single hydrogen zone. In the case of GB, unlike the power sector, the hydrogen sector did not include any limitations on the transportation of hydrogen across the country in the base scenarios. As such, it was assumed that a national transmission network would develop alongside the increasing hydrogen demand, and that no bottlenecks on transmission of hydrogen would exist. This assumption was tested in some of the sensitivities modelled.

For the sensitivities where hydrogen demand was disaggregated across several zones, these zones were designed to cover the same areas as the power demand zones. This was done for ease of modelling, but since no hydrogen network exists, it was deemed a suitable simplifying assumption. The national hydrogen demand was then split across the zones based on population (for non-industrial demand) and based on the share of gas demand in five key industrial clusters (for industrial hydrogen demand). Hydrogen production was not limited in any zone beyond overall caps for the country. Whilst hydrogen tank storage could also be built in any zone, salt cavern storage was limited to central English zones with relevant geographical features that would allow development of salt cavern storage. Whilst other forms of geological storage may be possible for hydrogen (such as depleted gas fields) these assumptions were adopted in order to test the sensitivity of hydrogen production assumptions to location, and the relationship that a lack of national hydrogen transmission network would have on the power sector.

Exhibit 3.2 – Geographical scope of the modelled area



3.1.1.2 Modelling and optimisation

Auto Build (investment decision). AFRY use the model's endogenous investment optimisation module, Auto Build, to assess the long-term optimal investment solutions for all assets in the system.

The modelling approach from a run procedure perspective

The starting point in this study is using BID3's **Auto Build** module to minimise total (discounted) fixed and variable costs across the modelled period. This is run for all the market scenarios, modelling every fifth year from 2030 to 2050. While this makes some approximations, these are far fewer than other endogenous investment modules we have come across. There are, however, some constraints applied to the optimisation in Auto Build, including:

- Constraint #1: security standard.
- Constraint #2: emissions limit.
- Constraint #3: build resource limits.
- Constraint #4: reserve headroom and footroom.
- Constraint #5: inertia requirements.
- Constraint #6: frequency response requirements.

Constraints. In this study the model accounts for advanced features such as system constraints, operational constraints on thermal generation and demand side flexibility. These are used in the study to model the locational characteristics of the GB and EU system.

The investment decisions are taken based on the full hourly results of the detailed **Dispatch** modelling. AFRY make use of BID3's standard ability to simulate all 8760 hours per year. The hourly simulation is able to show dispatch decisions in the system through the hourly generation of all power stations on the system and hourly cross-border interconnector flows, based on the fundamental costs of generation. This includes the flexible modelling of co-product plants such as electrolysers and SMR for hydrogen production and hydrogen fuelled gas turbines, and network and storage operation including network constraints (both explored later in this section).

However, partly to better model market rules, we also manually assess IRRs (versus hurdle rates) afterwards, modifying the build accordingly. Both the dispatch part of the Auto Build module, and main BID3 dispatch are based on linear programming, so by definition will meet demand at least costs, i.e., use the generators with lowest costs first.

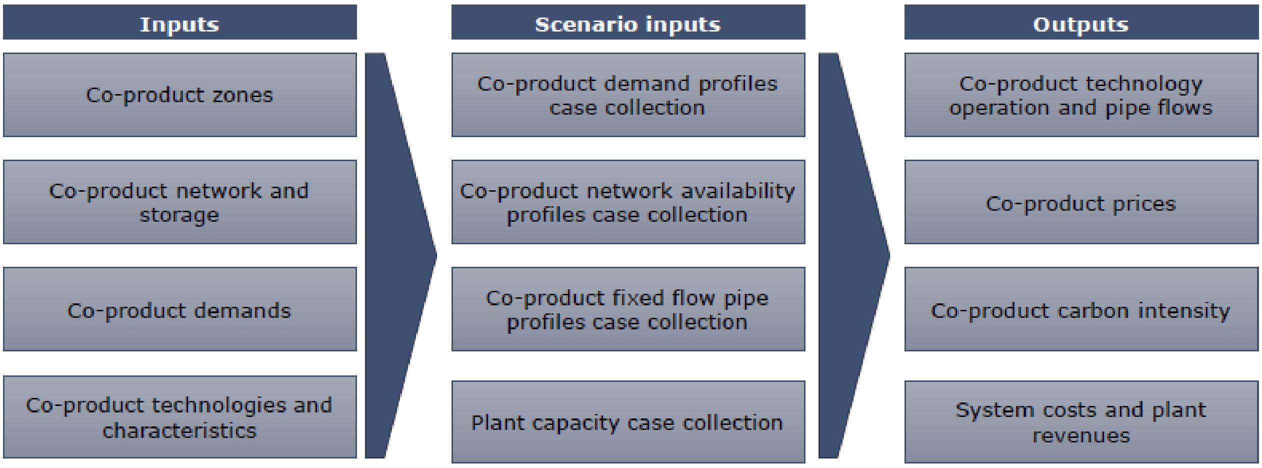
Weather patterns & Profiles. The AFRY approach in this study is to model multiple weather patterns, in this case the five historical years (2012, 2014, 2015, 2017, 2018) standard in AFRY scenarios. These include hourly wind and solar generation (derived using reanalysis data – 3Tier for wind, Transvalor for solar), and using hourly demand based on the historical demand profiles plus profiles for additional electrical heating derived using historical temperature data. The model's ability to simulate weather patterns is a key feature in this project, to accurately model intermittent sources of generation, such as wind and solar, using detailed and consistent historical wind speed and solar radiation. We build capacity such that with average availabilities, there is enough capacity to meet demand (and the security standard requirement).

Hydrogen. BID3 is run with the functionality to model hydrogen's fuel and storage dual capability. The hydrogen sector is co-optimised alongside the power sector to ensure full consistency in the hourly simulation. BID3 is used to model the hydrogen's supply, demand, storage, and transportation needs. In the coupling of the hydrogen sector, hydrogen demand is both an exogenous model input (such as hydrogen demand for industry) and endogenous input evaluated by the model (demand based on the modelled generation for hydrogen-fuelled plants). In this study, hydrogen demand is modelled around several tranches of annual hydrogen demand including industry, residential, transport, each with a specific profile. The modelling considers both power-to-hydrogen and hydrogen-to-power technologies.

The hydrogen is also assigned its own zone in the modelling and can lie in both electrical price area and 'hydrogen' price area, for example electrolysers consume electricity from an electricity price area to produce hydrogen. The hydrogen zones can be connected via pipelines and have storage options. In this study we test two set-ups, the first one with geographical divisions and hydrogen zones along the main electricity sector constraints in GB, and the second set-up without constraints.

Outputs include all the most important hydrogen related metrics expected based on the inputs, including prices, generation, revenues, costs. Emissions related to blue hydrogen are based on the fuel and carbon capture based on the CCS capture rate. Power consumption is accounted for in the power demand constraint and is therefore a closed feedback loop with the electricity sector. Exhibit 3.3 shows an overview of the module set up in BID3, including the inputs and outputs in the model.

Exhibit 3.3 – Hydrogen Dispatch modelling set-up



3.1.1.3 Long duration storage

BID3 was set up to model many storage technologies including batteries, CAES, LAES, PSP and salt cavern storage for hydrogen in this project. Other longer duration storage technologies, such as gravity storage, different forms of electro-chemical storage including zinc batteries or vanadium flow batteries were not directly considered in the modelling. However, the modelled options covered a wide range of durations, costs, round trip efficiencies and so on. Whilst other long duration technologies exist outside the modelled options, it was deemed that the chosen options would cover a sufficient range of technology archetypes to answer the research questions.

With regards to hydrogen, BID3 employs a consistent modelling of storage within the hydrogen sector (a 'power-X-power closed loop' storage within the power sector). Some will be more suitable in fulfilling certain needs in the system and adopt specific operating regimes. The technical properties for these are summarised in the data book.

We also make specific assumptions on the (flexibility) capabilities each storage technology has in this study. For example, with respect to frequency response, inertia, imbalance correction and load shifting among others. Assumptions for these are presented in the main report.

3.1.2 Scenario methodology

This project aims to assess the need and associated benefits of long duration electricity storage in the future energy system. The assessment is broken down in the evaluation (through modelling) of the full range of benefits and services these technologies can provide, including system costs, emissions, and operating regimes of the generation mix.

To conduct the study and inform assessments of system benefits of long duration electricity storage assets, AFRY performs market modelling runs using BID3.

Market scenarios. For a specific market scenario, BID3 runs are conducted for:

- A reference case, where the only form of storage available was short duration storage. This is done by disabling the model's ability to invest in new medium and long duration storage.
- An 'all storage durations' case, which includes medium and long duration storage ('MDS' and 'LDS') assets in the model's investment decisions.

For a given market scenario, all the inputs to these two runs are identical, with the exception of the addition of long duration storage assets in the 'all durations' case.

It is important to highlight that both the reference case and 'with LDS' case are fully modelled and internally consistent scenarios. This means the modelled solution will optimise the scenario's characteristics such as the capacity mix, in addition to the relevant scenario metrics.

For each of these scenario runs, the total system cost is calculated by disaggregating the following metrics:

- fuel and other generation costs;
- generation investment costs;
- short duration storage investment costs;
- long duration storage investment costs;
- interconnection and transmission network reinforcement costs;
- hydrogen production and storage costs; and
- social costs of carbon.

Taking results for the runs with and without the LDS assets, the values in the reference case (without the MDS and LDS assets) are subtracted from those in the 'all durations' case to derive the net benefit. Long duration storage was deemed to be all forms of storage with greater than four hours of storage.

The annual changes in each component are then converted to an NPV using the 3.5% discount rate and added together to get the overall welfare impact for the system (in GB).

In addition to the delta in system costs for individual scenarios, the comparisons of the savings between scenarios are used to reveal the common long duration storage investment that represent low and no regret options.

Finally, an assessment is carried out on the roles of storage in the system to provide energy, capacity adequacy, frequency response, reserve, inertia or locational constraint management. This is done by analysing the operational patterns and services delivery for each form of storage, the comparison between technology types and avoided costs between each version of the core scenarios.

3.1.3 Scenario definition

AFRY have worked in close collaboration with BEIS to define the scenario matrix. The key differences are in the net zero pathway, the electrification of the transport and heat sectors, and the use of hydrogen in the economy. The emissions limit (target) in 2050 is the same for all scenarios. The full description of the scenario framework is in the main report.

AFRY have worked with BEIS to define the detailed inputs, broadly under the following building blocks for each scenario:

- Existing capacity in the system in 2030.
- Investment costs and hurdle rates.
- Commodity prices.
- Decarbonisation and emissions targets.
- Interconnection capacity in 2030.
- Technology resource potential.
- Long duration storage technical capabilities.
- System security parameters (inertia, reserve, capacity adequacy).
- Flexibility of demand-side (incl. heat and transport sectors).

AFRY reviewed the ‘market inputs’ received from BEIS, the status quo arrangements and the current expectations for the future GB electricity market and complement BEIS’ inputs with AFRY’s ‘best view’ parameters, setting up the core scenario to be modelled. The inputs and sources are described more in Section 3.2.

3.1.4 Sensitivity definition

In addition to the core market scenarios, the study includes the design and assessment of further sensitivities. The purpose of the sensitivities is to complement the evidence from the core scenarios, to answer the research questions and explore uncertainties. The sensitivities were designed and agreed with BEIS after the review of the results from the core scenarios. The design of the sensitivities takes into consideration the main research questions of this study. The sensitivities are carried out on the core market scenario #1 ‘with LDS case’. The table below in Exhibit 3.4 summarises the sensitivities carried out, describing the areas of uncertainty tested.

Exhibit 3.4 – Sensitivity specification

	Sensitivity	Approach
1	What if the availabilities of several key novel technologies are delayed?	CCS capacity (including Gas with CCS, SMR CCS and ATR CCS) build out limited Delivery of hydrogen salt cavern storage is more expensive and more difficult to realise Full cost of hydrogen transmission network development is incurred.
2	What is the impact of more extreme weather on the system and what are the relative benefits of different technologies in these cases?	Technology mix from core scenario #1 is applied to a wider range of weather patterns to stress test the capacity results.
3	What if the salt cavern storage proves impossible to realise and long duration storage is not available in the hydrogen sector?	Exclude hydrogen salt cavern storage from the investment options.
4	What if blue hydrogen is significantly more difficult to produce and ATR+CCS capacity is limited?	Enforce a maximum capacity on SMR and ATR (+CCS) technologies, leading the model to rely much more heavily on green hydrogen from electrolysis
5	What if the transport of hydrogen is harder and hydrogen pipeline capacity is not developed across GB as a whole?	Hydrogen demand is allocated to distinct zones, without any transportation between the zones.
6	What if the transport of hydrogen is harder, and costs of a new national hydrogen transmission network are directly considered?	Hydrogen demand is allocated to distinct zones costs, and costs are incurred to develop a hydrogen pipeline network.
A	What is the impact of forcing additional long duration storage into the system?	Include a minimum requirement for 15GW of MDS and LDS capacity.
B	How does significant new nuclear capacity drive storage requirements?	Include a minimum of 4 new nuclear stations beyond Sizewell C.
C	To what extent does DSR compete with long duration storage?	Halve the DSR capabilities included compared to the base scenario.
D	To what extent does interconnection compete with long duration storage?	Cap & Floor for interconnectors does not continue beyond 2030 and additional new capacity is more expensive (11% discount rate).
E	To what extent does reduced emissions drive the need for storage?	The emissions reduction pathway towards 2050 is less strong and CO2 reductions are backloaded.

3.2 Inputs

All inputs have been consolidated in a comprehensive data book, and a summary of these key inputs are listed in Exhibit 3.5 (providing the primary source behind each).

Exhibit 3.5 – Input sources

Input Type	Source
Annual Demand: Electricity	BEIS
Annual Demand: Hydrogen	BEIS
Demand Profiles	AFRY
Existing Capacity in 2030	BEIS
Build Limits	BEIS
Power Plants parameters	BEIS/AFRY
Existing Interconnection in 2030	BEIS
New Interconnection	BEIS
Technology parameters Storage	BEIS, AFRY calculations for extra durations
Technology parameters Hydrogen	BEIS
Technology parameters Generators	BEIS
Technology costs Storage	BEIS
Technology costs Hydrogen	BEIS/AFRY
Technology costs Generators	BEIS
RES Load Factors/ Generation Profiles	AFRY
Commodity Prices	BEIS
Carbon Emissions Limits	BEIS
Carbon Emissions by Sector	BEIS
Reserve requirements	BEIS
Inertia requirements	BEIS
New Entrant Efficiencies	AFRY
Investment cost for transmission reinforcements and interconnection	AFRY

For a detailed view of the inputs used in the study please see the data book.

3.3 Outputs

All outputs have been assembled in a comprehensive data book, providing a summary of the key annual level inputs assumptions used in the modelling and a detailed overview of the annual level modelling outputs.

The key outputs modelled are summarised below, broadly under the following macro-categories:

- disaggregated system costs;
- operating regimes of long duration storage;
- total capacities and generation by technology;
- total services provision by technology; and
- total network and interconnector investment.

We also provide annual level metrics to describe price volatility (daily, weekly, and seasonal).

Key outputs modelled include:

- build totals;
- build of storage (GW & GWh);
- build avoided due to LDS options;
- build by location in GB;
- generation by type;
- load factors;
- cycles per day & year for storage;
- levels of storage for LDS;
- share of electricity demand met by storage;
- share of hydrogen demand met by storage;
- RES curtailment;
- emissions;
- system prices;
- total system costs;
- generation costs;
- generation investment costs;
- interconnection and transmission investment costs;
- storage investment costs;
- hydrogen production investment costs;

- inertia provision;
- reserve holding; and
- hourly dispatch (insights).

3.3.1 System costs methodology

AFRY models and outputs a granular, disaggregated view of the total costs in the system: broadly under the categories of investment costs (generation capacity, hydrogen capacity, hydrogen storage, interconnectors, transmission), fuel costs and carbon costs. Two key steps were made in this methodology: the derivation of the cost split and the application of an appropriate discounting factor.

Excluded from the system costs calculations are all capex investments made prior to 2030. Additionally, the costs of fixed build common to all scenarios and sensitivities are also excluded; any difference in system costs would net these costs out, and so they are excluded from the analysis.

3.3.1.1 The cost split

For the investment costs the starting point is processing the model's outputs for the capacity (MW), capex and opex (£), under each modelled year (2030, 2035, 2040, 2045, 2050), giving a total view of these fixed costs.

Under the opex category, this includes variable opex costs and annual fixed opex as well. The fuel costs are derived from model's outputs and include all the running costs (£) from the power and hydrogen sectors, from the generation of electricity and hydrogen respectively, under each modelled year (2030, 2035, 2040, 2045, 2050). Taking thermal plants as an example, these fuel costs include the production input cost (e.g., gas), the fuel transport costs, the fuel costs used to start the plants (start costs) and variable other works costs (VOWC) related to the production. Fuel costs also include the costs associated with interconnectors exports outside of GB. Added to the sum of the variable costs is the capacity fixed costs for the annual fixed opex costs. The total capex costs include the new build in each modelled year and the input capex costs (£/kW installed values).

Carbon costs (£) are another standard output of BID3 and are a product of the total carbon emissions specific to each plant (tCO2) and the cost of carbon (£/tCO2).

3.3.1.2 Discounting the costs

The annual costs in each component are converted to an NPV, using a discount rate of 3.5%. Each future year is given a discounted value, starting with 2030 indexed to a value of one. This includes all years, both modelled years and years in between. Each modelled year is taken to be representative of two years previously, the year itself and two years following. For the modelled year 2050, a further assumption is made that this year represents a period of 10 years lasting until 2060.

The final discount factor is applied to the costs, to account for the 'weight' of the modelled year (i.e., how many years the modelled year represents). By summing the discounting factors for each of the years represented by the modelled years, a final scaling factor for each future year is derived. The costs associated with each future year from the modelling are multiplied up by the scaling factor. The result of this is the total NPV of system costs in 2030.

For the purpose of variable and fixed opex costs, the discounting factor accounts for the scaling of each modelled year to represent five actual years. The capex costs are scaled for each modelled year to represent one future year. Whereas the individual modelled years are taken to represent five years and scaled by the higher value.

Exhibit 3.6 shows the values used.

Exhibit 3.6 – Discount factors for calculating the system costs

Modelled year	Opex discounting factor	Capex discounting factor
2030	5.006	1.000
2035	4.189	0.837
2040	3.505	0.700
2045	2.933	0.586
2050	5.577	0.490

TABLE OF EXHIBITS

This publication is available from: www.gov.uk/government/publications/benefits-of-long-duration-electricity-storage