June 2026

LDES: Final Methodology

Long Duration Electricity Storage

Window 1

NESO
National Energy
System Operator

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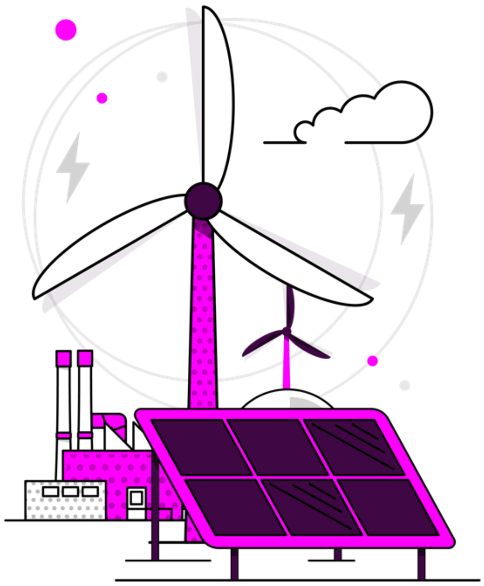
List of Abbreviations

BESS — battery energy storage systems
BM — Balancing Mechanism
CAES — compressed air energy storage
CBA — Cost Benefit Analysis
CfD — Contracts for Difference
DA — Day Ahead
DSF — Data Submission Form
EEU — expected energy unserved
EU — European Union
FES — Future Energy Scenarios
FID — Final Investment Decision
GB — Great Britain
LAES — liquid air energy storage
LDES — Long Duration Electricity Storage
LOLD — loss of load depth
LOLE — loss of load expectancy
MCA — Multi-Criteria Assessment
MT — Medium Term
NESO — National Energy System Operator
non-FID — non-Final Investment Decision
PASA — Projected Assessment of System Adequacy
QA — quality assurance
SMR — steam methane reforming
ST — Short Term
TEC — Transmission Entry Capacity
UK — United Kingdom
VOLL — Value of Lost Load

HT2013 — Holistic Transition 2013 scenario
EE2013 — Electric Engagement 2013 scenario
FB2013 — Falling Behind 2013 scenario
HT1990 — Holistic Transition 1990 scenario
HT1997 — Holistic Transition 1997 scenario



1. Purpose, scope and status of this methodology

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The purpose of this document is to set out the methodology applied by the National Energy System Operator (NESO) in the assessment of Long Duration Electricity Storage (LDES) projects. It describes the analytical approach used to support the assessment, building on the methodology published by NESO in September 2025.

The methodology is intended to capture and document the principal modelling choices, assumptions and analytical steps that underpin the assessment results. This includes the treatment of project level input data, system representation, counterfactual construction and the derivation of cost benefit outputs. Together, these elements provide transparency on how assessment outcomes were generated for project applicants, Ofgem, consumers, wider regulatory and governmental bodies, and other stakeholders with an interest in the assessment and delivery of LDES under the Cap and Floor regime.

This methodology supports Ofgem's decision-making under the LDES Cap and Floor regime and forms part of the wider evidence base considered within Ofgem's Multi-Criteria Assessment (MCA) framework. It describes the approach used to produce the economic assessment outputs that inform Ofgem's evaluation of system and welfare impacts.

1.1 Introduction

This section provides an overview of the objectives and intended use of the methodology. The primary objective is to enable traceability and understanding of the assessment process, by clearly explaining how applicant-submitted project data was incorporated into system modelling and translated into outputs suitable for regulatory assessment.

Specifically, the methodology is intended to:

- document the key principles and assumptions applied in the modelling runs
- describe how individual LDES projects were represented within the power system model
- explain how modelling outputs were processed and converted into metrics that could be utilised by Ofgem as part of the assessment process.

Project-level data submitted by applicants was incorporated into the Plexos modelling framework, where it was assessed within a whole system context alongside other generation, storage, demand and network assumptions. The resulting outputs were then analysed to estimate the incremental system and welfare impacts attributable to each project, relative to an appropriate counterfactual.

By setting out these steps clearly, the methodology is intended to allow applicants and other stakeholders to understand how their inputs influenced the modelling results, how those results were derived, and how they were subsequently used to inform Ofgem's assessment under the Cap and Floor regime. This approach is consistent with the role of the Cost Benefit Analysis (CBA) as one input into the MCA, rather than a standalone decision-making tool.

This methodology is complemented by a separate NESO analysis on the optimal level of LDES deployment for Window 1. That report provides system-level advice on the appropriate range of LDES capacity to support, reaffirming a recommended additional 2.7–7.7 GW by 2035 (5.5–10.5 GW total including existing capacity). The analysis strengthens confidence in the original range rather than revising it and should be read alongside this methodology to provide context on the overall scale of LDES required at a system level.

1.2 Highlights of changes from previous methodology

This final methodology retains the core principles set out in the previous methodology, including the use of FES, project-specific factual and counterfactual cases, and the marginal additional framework for assessing the incremental value of LDES projects. The main changes are refinements to the modelling implementation, scenario coverage, output metrics and robustness measures, developed through further modelling work, stakeholder engagement and discussion with Ofgem. These changes are intended to improve the stability, transparency and decision relevance of the assessment, while preserving consistency with the original methodology.

A key change is the move to modelling individual years independently rather than relying on a single chained multi-year optimisation. The detailed market modelling is now undertaken for ten explicitly modelled years: 2030, 2031, 2032, 2033, 2034, 2036, 2038, 2040, 2042 and 2044. Results for years between these modelled points are interpolated, while later years are extrapolated using the final modelled years. This change improves model stability and robustness by preventing small numerical differences from propagating through the optimisation chain over time.

The modelling framework has been refined through the introduction of a GB-focused Day Ahead (DA) model as the primary basis for Economic Assessment ranking of projects. The previous methodology described a wholesale market model followed by Balancing Mechanism (BM) modelling, with wider European market interactions represented within the modelling framework. The final methodology adds a specific GB-focused DA configuration: a pan-EU Plexos simulation is used to derive credible interconnector flow schedules, and these schedules are then fixed exogenously in the GB-focused DA runs. This is intended to ensure that GB prices respond more directly to GB supply, demand and storage operation, rather than being driven by marginal conditions elsewhere in the coupled European system. As a result, the GB-focused DA model provides the main metrics for the Economic Assessment, while pan-EU DA and BM runs are retained for completeness and to support BM revenue assessment and zonal analysis.

The GB-focused DA model has also been refined to manage optimisation degeneracy. In this context, degeneracy refers to situations where an optimisation model can choose between multiple feasible solutions with very similar or effectively identical objective values. These solutions are equivalent from a total system cost perspective, but may differ in the allocation of dispatch, storage trajectories or costs. This is a recognised feature of large-scale electricity market models such as Plexos, and the methodology applies targeted controls to ensure results remain stable, reproducible and suitable for comparative assessment. This is particularly important in large-scale electricity market models such as Plexos, where sequential optimisation stages can allow small numerical differences to propagate through later model runs. Testing showed that the Medium Term (MT) optimisation phase was a significant source of this behaviour, particularly because it determines longer term storage trajectories and target levels. To address this, the MT phase is no longer run as part of each GB-focused DA assessment. Instead, a standalone MT run is used to determine seasonal storage trajectories and long-term target levels, which are then imposed exogenously within the DA runs. Annual constraints that would otherwise be enforced through the MT stage are implemented directly within the DA model where appropriate. This improves stability and reproducibility while preserving the key long term system constraints needed for the assessment.

A wider set of mitigation measures has been implemented to improve numerical robustness and reproducibility. These include solving model years independently, applying consistent storage initialisation assumptions, removing the MT phase from the GB-focused DA project level runs, and grouping projects that are fully identical in technical and economic terms during post processing. These measures are intended to reduce the scope for equivalent or near equivalent optimisation solutions to affect project comparisons. BM outputs are used for supporting purposes, including BM revenue assessment and zonal analysis, while primary project ranking continues to be based on the GB-focused DA framework. This reflects the intended role of each model run within the assessment framework.

The base case continues to use the Future Energy Scenarios (FES) 2025 Holistic Transition pathway, based on the 2013 weather year. Additional project-level sensitivities were also assessed using Holistic Transition 1990 and Holistic Transition 1997, alongside Electric Engagement 2013 and Falling Behind 2013. This differs from the earlier methodology, which proposed 1985 and 2010 as additional weather years. The updated weather years are used to represent contrasting renewable output and system stress conditions within the Holistic Transition pathway.

The approach has been supplemented through dedicated zonal sensitivity modelling, which provides an independent, location-focused perspective on the interaction between LDES deployment and network constraints. Rather than relying on individual BM project runs for locational assessment, the zonal sensitivity modelling uses standardised test assets placed in model zones to assess how the value of storage varies by location and scale. While the outputs were not used directly to determine project ranking, they formed part of the wider evidence base considered within the assessment process.

The final methodology also includes a fuller description of project-specific modelling inputs and simplifications applied to ensure consistency and fairness across applicants. Project locations are mapped using the best available information, including substation, connection application data, and actual geographical coordinates of projects, where required. For modelling consistency, capacity fading and power fading are assumed to be zero in the Plexos market modelling, and storage assets are represented with consistent state-of-charge limits. Cycle limits are applied where provided, with longer period limits converted into a form compatible with the model structure. These simplifications are intended to ensure that project comparisons are not unduly affected by inconsistent or uncertain assumptions, while still reflecting the key technical characteristics submitted by applicants.

The treatment of storage bid and offer pricing in the BM has been clarified. The final methodology applies a consistent approach across storage technologies, with bid and offer prices reflecting the system cost associated with efficiency losses during charging and discharging. No additional strategic or commercial bid-offer spread is applied. This approach provides a transparent and technology-neutral basis for representing storage redispatch costs in the BM model.

The set of reported output metrics has also been expanded and clarified. In addition to the core welfare and system cost metrics described in the previous methodology, the final methodology now provides a more explicit mapping of metrics to model runs and assessment uses. Additional reported metrics include LDES generation, LDES load, time spent charging, time spent discharging, renewable curtailment percentage and other outputs derived from specific model runs. Some metrics are used directly in project level assessment, while others are retained as auxiliary indicators to support transparency, interpretation, financial assessment inputs or zonal sensitivity analysis.

Overall, the changes from the previous methodology are targeted refinements rather than a change in the fundamental assessment philosophy. The assessment continues to use a marginal additional approach with project specific counterfactuals, but the implementation has been strengthened to improve model stability, reduce optimisation artefacts, better isolate GB price impacts, provide a more robust treatment of locational value, and increase transparency around assumptions and outputs. These updates are intended to support a fair, reproducible and transparent assessment of LDES projects under Window 1, while ensuring the outputs are applied consistently with their intended role in the wider assessment framework.

2. Core modelling framework and assessment approach

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2.1 Model background

The LDES Cap and Floor CBA is undertaken using a whole-system electricity market modelling framework designed to assess the system and welfare impacts of introducing additional long-duration storage capacity into the Great Britain (GB) electricity system. The modelling approach and overarching framework are consistent with those set out in the first Methodology document and retains the same core structure to ensure continuity, comparability, and regulatory robustness.

The analysis is based on the latest available FES 2025 pathways, published in July 2025. FES 2025 provides the most up-to-date and internally consistent projections of the future GB energy system, including electricity demand, generation mix, interconnection, fuel prices, hydrogen deployment, and flexible demand assumptions. The use of FES 2025 ensures that the LDES CBA reflects the latest system outlook available at the time of assessment and remains aligned with wider system planning and policy analysis undertaken by NESO and Ofgem.

Within FES 2025, background assumptions are included for existing and anticipated levels of electricity storage and flexibility, including battery energy storage systems, pumped storage hydro, compressed air energy storage, liquid air energy storage, and hydrogen storage. These background assets form part of the baseline system against which the candidate LDES projects are assessed, ensuring that benefits are not double-counted and that the analysis reflects a realistic future system configuration.

The CBA uses a detailed, chronological electricity market model to simulate system operation and dispatch under both counterfactual and factual cases. The model represents generation, storage, demand, interconnection, and network constraints at a level of granularity sufficient to capture the operational value of long-duration storage, including its interaction with variable renewable generation, periods of system stress, and prolonged low-renewable conditions. Welfare impacts are derived consistently from model outputs, capturing changes in system costs across the electricity sector.

Adjustments have been made to technology characteristics and Transmission Entry Capacity (TEC) for specific projects where discrepancies were identified between the original FES assumptions and the latest confirmed information. All modelling assumptions, including updates to assumptions communicated in the earlier methodology, are set out in Section 5.

By retaining the same core modelling framework, scenario basis, and welfare assessment principles as the original Window 1 methodology, this Final Methodology ensures that results remain compatible with Ofgem's MCA process.

For all metrics that directly inform project ranking within the Economic Assessment, results are derived from a GB-focused DA modelling approach, ensuring that price formation and dispatch outcomes are responsive to GB system conditions and the marginal impact of LDES. Constraint costs are considered separately through dedicated zonal sensitivity runs, providing a more robust and locally representative view of network impacts.

2.2 Modelled scenarios

The assessment is undertaken across a structured set of scenarios designed to capture a range of plausible future GB electricity system conditions. In total, five scenarios are modelled, combining different FES pathways and weather years.

The Holistic Transition 2013 (HT2013) scenario is the base case and forms the primary basis for the project-level assessment. It represents a balanced pathway to net zero with high renewable penetration and strong consumer engagement and is considered a representative baseline for assessing system and welfare impacts.

For project-level assessment, a broader set of scenarios is used to capture uncertainty in both system evolution and weather conditions. In addition to HT2013, sensitivities are undertaken using alternative weather years within the Holistic Transition pathway:

- HT1990: a high-wind (stormy) year, characterised by sustained periods of strong wind generation and elevated renewable output.
- HT1997: a low-wind (calm) year, characterised by prolonged periods of low renewable generation and increased system stress.

These weather year sensitivities are complemented by two alternative FES pathways:

- Electric Engagement (EE2013): characterised by high levels of electrification, resulting in the highest peak electricity demand, alongside significant interconnection and dispatchable low-carbon generation. This scenario provides a high-demand, high-stress system context.
- Falling Behind (FB2013): represents a slower decarbonisation pathway, with continued use of unabated gas and delayed deployment of low-carbon technologies. While not aligned with a net zero trajectory, it provides a useful sensitivity reflecting stakeholder feedback and a more conservative system outlook.

Together, these five scenarios (HT2013, HT1990, HT1997, EE2013, FB2013) provide a balanced framework for assessing LDES value across a range of credible system conditions. The base case (HT2013 scenario) ensures consistency and comparability, while the additional scenarios capture key uncertainties that may influence project performance and relative ranking.

2.3 Counterfactual and factual

The CBA assesses the value of each LDES project using a marginal addition framework, whereby the impact of a project is determined through comparison of two internally consistent scenarios:

- Counterfactual scenario (without the project or zonal sensitivity), and
- Factual scenario (with the project included or zonal sensitivity included).

The difference in outcomes between these two scenarios represents the incremental system and welfare benefit attributable to the project.

A central feature of the methodology is the use of project-specific counterfactuals, ensuring that each project is assessed against a tailored and policy-aligned baseline, rather than a single common reference case.

Counterfactual Scenario

The counterfactual represents a credible future electricity system in which the assessed project is not present, while remaining consistent with the selected FES pathway. It is constructed from the full FES background, including assumptions on generation, demand, interconnection, and network topology, ensuring alignment with expected system evolution.

To create a meaningful comparison point, the counterfactual incorporates a targeted adjustment to background LDES capacity. Specifically, non-Final Investment Decision (non-FID) LDES capacity is reduced by an amount equivalent to 50% of the capacity of the project/sensitivity under assessment. This adjustment is undertaken in a project-specific manner, such that each project is evaluated against its own tailored baseline. The reduction is applied preferentially within the same zone as the assessed project, before being distributed more widely if required, thereby maintaining locational realism within the system representation.

All other system assumptions are held constant relative to the underlying FES scenario. This ensures that the counterfactual remains both technically feasible and policy-aligned, while isolating the impact of the assessed project. The approach avoids the use of unrealistic baselines, such as a system with no LDES, and instead provides a consistent and credible benchmark for comparing projects.

Factual Scenario

The factual scenario represents the same system as the counterfactual, with the inclusion of the assessed intervention. This will take the form of the individual project. It is constructed by introducing this change directly into the corresponding counterfactual, ensuring that the only difference between the two scenarios is the presence of the assessed intervention itself.

In the factual scenario, the intervention is modelled using the relevant technical and locational characteristics of the LDES project being assessed. This ensures that the modelling captures the resulting system behaviour and interactions in a manner consistent with the nature of the intervention.

All other assumptions remain unchanged from the counterfactual scenario. This consistent treatment ensures that differences in model outputs can be directly attributed to the inclusion of the assessed intervention, allowing for a robust assessment of its incremental impact on the system.

Assessment Approach

The project's contribution is determined by comparing two scenarios:

- Counterfactual: FES aligned system with adjusted background LDES and without the project
- Factual: The same system with the project (or zonal sensitivity) included

The marginal benefit of the project is defined as the change in total system welfare between these two scenarios, calculated as:

Relative Benefit = Factual – Counterfactual

2.4 Marginal additional method

The marginal additional method is used to quantify the incremental impact of each assessed intervention by comparing the factual and counterfactual scenarios defined in the previous section. Interventions take the form of the individual LDES projects. This approach enables each intervention to be assessed against a credible system background, rather than in isolation.

In applying the method, each intervention is modelled independently using an intervention-specific counterfactual. The system is simulated both with and without the intervention, with all other assumptions held constant. The resulting difference reflects the change in system operation, including dispatch, flows, and constraint management, and therefore captures the full system response to the inclusion of the intervention.

The marginal additional method inherently captures non-linear system effects, as benefits are determined through optimisation rather than imposed relationships. As a result, the value of each intervention reflects prevailing system conditions, such as the level and location of existing flexibility, and may exhibit diminishing returns or threshold effects rather than scaling linearly.

This approach also ensures consistency and comparability across interventions. By assessing each case against its own counterfactual, results represent standalone marginal contributions and are not influenced by the order in which interventions are evaluated. This avoids the distortions associated with "first-additional" approaches, where an empty system baseline can lead to overstated benefits and unrealistic outcomes.

Overall, the marginal additional method provides a transparent and robust framework for assessing LDES projects against a realistic and policy-aligned system background.

2.5 Horizon, modelled years, interpolation and extrapolation

The CBA is undertaken over a long-term assessment horizon, consistent with the expected operational life of LDES assets and the requirements of the Window 1 Cap and Floor assessment.

Detailed market and system modelling is undertaken for a discrete set of representative years within the assessment horizon. The following years are explicitly modelled: ***2030, 2031, 2032, 2033, 2034, 2036, 2038, 2040, 2042, 2044***. We have modelled only every other year post 2034 to keep the number of simulations tractable, since none of the projects assessed start operation beyond 2034.

These years are selected to capture:

- the early operational period of LDES assets,
- key transition points in the evolution of the GB electricity system, and
- long term system conditions under high renewable penetration.

For years between the explicitly modelled points, results are interpolated on a linear basis. This approach ensures a smooth evolution of system and welfare impacts over time while limiting the number of full model runs required. Interpolation is applied consistently across all relevant output metrics, unless otherwise specified elsewhere in this document.

For metrics other than carbon-related impacts and Contracts for Difference (CfD), values beyond 2044 are extrapolated by applying the average of the final three modelled years (2042–2044). This approach avoids speculative long-term assumptions.

Carbon impacts are treated separately. Carbon emissions volumes are extrapolated using the average emissions observed over the final three modelled years (2042–2044). These extrapolated emissions are then valued using the carbon prices and the societal value of carbon applicable to each extrapolated year, ensuring that the temporal profile of carbon valuation is preserved even where emissions volumes are held constant.

CfD costs are extrapolated on a contract aware basis. Subsidy payments in the final three modelled years, reflecting prevailing wholesale prices and subsidy levels, are used to extrapolate CfD payments for the period 2045–2050. The CfD contract expiry date for each relevant asset is then applied to determine whether extrapolated costs should be included in each year. Where a contract expires during the extrapolation period, CfD costs are only counted to the point of expiry, ensuring that post contract subsidy payments are not overstated.

2.6 Modelling inputs

The modelling undertaken for this assessment uses a combination of scenario-level assumptions and project-specific technical inputs. Most system-wide inputs are drawn from the FES pathway being modelled, as described earlier in this methodology. FES provides the main assumptions for the future generation background, demand, interconnection, gas and hydrogen use, European market interactions, flexible demand and background levels of storage, including battery storage, pumped hydro, compressed air storage, liquid air storage and hydrogen storage.

Boundary capability assumptions are required to represent the effect of transmission constraints within the BM modelling. For this assessment, boundary capabilities are based on outputs from NESO’s Pathway to 2030 and the Beyond 2030 report. These represented the most up-to-date view of future boundary capabilities available at the start of the assessment. Boundary capabilities are also scaled seasonally in line with the agreed approach used in the Network Options Assessment methodology.

The remainder of this section outlines how project-specific inputs are defined for use in the Plexos model within project-level assessments. These inputs are derived from information submitted by applicants through the Project Assessment Data Submission Form (DSF).

Project-specific technical inputs

Each eligible project was represented in Plexos using a set of locational, technical, operational and cost parameters. The full modelling dataset included fields such as Geographical Coordinates (Northing and Easting), Connection Substation, Transmission Connected status, Duration, Sensitivity Group, Zone, Capacity, Technical and Economic Life, Cycle Limits, Charge and Discharge Capacities, Charge and Discharge Efficiencies, State of Charge Limits, Variable Operating and Maintenance Charges, and Ramp Up/Down Rates assumptions.

It is not necessary to describe every input field individually, but the following parameters were particularly important in defining how each project was represented:

- Location and model zone: used to determine the appropriate Plexos zone and therefore the project’s interaction with network constraints.
- Discharge capacity, charge capacity and duration: used to determine the scale and operating capability of the asset.
- Storage capacity: This was derived using the formula (Duration * Discharge_Capacity) / Discharge_Efficiency
- Charge and discharge efficiency: used to represent losses when energy is stored and later discharged.
- Cycle limits: used to represent any binding restrictions on the number of charge–discharge cycles available to the asset.
- Variable operating and maintenance costs and ramp rates: included where these were provided by the applicant.

Locational mapping and Plexos zone

Each project was assigned to a Plexos zone using the best available locational information. The preferred source was the substation provided in the DSF. Where this was not sufficient, the connection application was used where applicable. If neither of these provided a clear mapping, the project's Easting and Northing information from the DSF was used to determine the appropriate Plexos zone.

This approach ensured that project location was treated consistently across applicants, while making use of the most specific locational evidence available for each project. Location is important because the BM model represents constrained boundary conditions, and therefore a project's model zone can affect how its flexibility contributes to increasing/reducing redispatch and constraint management costs.

Co-Located Assets

Where the submitted information identified multiple storage components within a project, the components were represented individually in the model but run together within the same sensitivity group (i.e., as part of the same factual and counterfactual models). This allowed the model to reflect the technical characteristics of each component while ensuring that the project was assessed as a single applicant project.

For co-located configurations, the modelling represented the storage components of the project only and did not include any additional generation or demand assets within the wider co-location arrangement. This is consistent with the previously published CBA methodology, which explained that including such assets could compromise the neutrality of the counterfactual and introduce applicant-specific assumptions.

Fading, state of charge and operating limits

To ensure a consistent and level playing field between projects, capacity fading and power fading rates were assumed to be zero for all assets in the Plexos modelling. This means that project rankings were not influenced by differing assumptions about future degradation unless reflected elsewhere in the assessment process. The minimum and maximum states of charge were assumed to be 0% to 100%, respectively, for all assets. Again, this was to ensure that storage availability was represented consistently across projects.

Cycle limits

Cycle limits were applied using submitted project data. In Plexos, cycling constraints are represented as aggregate limits rather than prescriptive rules about when cycling must occur. Where a project has a binding cycling limit, this is interpreted as a constraint on the total number of charge–discharge cycles available over the relevant period. Within that overall budget, the optimiser is free to decide when to use those cycles, allocating them to the periods with the highest system value, subject to all other technical and operational constraints.

Where daily or weekly cycle limits were submitted, these were applied directly in the model. Where monthly or annual limits were submitted, they were prorated to a weekly equivalent and applied consistently within the weekly simulation structure. This allows longer period cycle limits to be represented in a way that is compatible with the model solve structure, while preserving the intended aggregate limit on cycling behaviour.

Where no cycling constraint was specified, no explicit cap was applied to the number of charge–discharge cycles. In these cases, cycling behaviour was determined endogenously by the optimiser, based on prices, system needs and other binding technical constraints.

In summary, cycle limits do not explicitly dictate the timing of operation (e.g., overnight charging and daytime discharge). Instead, they impose an aggregate cycling budget. The optimiser then determines how best to use the available cycles to maximise system value within the relevant technical and operational constraints.

3. Day ahead and balancing mechanism modelling

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3.1 Day ahead GB focussed model

To ensure the assessment of LDES delivers robust, stable, and decision-relevant results, the Plexos modelling framework was configured to isolate the impact of LDES on Great Britain (GB) prices and dispatch outcomes, while remaining consistent with wider European system conditions.

The GB-focused DA model forms the primary modelling framework for project-level assessments. All key output metrics used to inform project ranking are derived from this model, ensuring that results reflect GB-specific system conditions and the marginal impact of LDES in a consistent and comparable manner across projects.

In a fully co-optimised pan-EU model, GB prices are determined by the marginal plant across the coupled system, which may be located outside GB and at a different period. As a result, GB prices in a free pan-EU optimisation can become insensitive to incremental changes in GB-located LDES, with price signals reflecting marginal conditions elsewhere in Europe rather than GB dispatch.

This limits the suitability of fully coupled runs for estimating GB-specific price sensitivities and welfare impacts attributable to individual LDES projects.

To address this, a two-stage modelling approach was adopted. First, a full pan-European Plexos simulation was run to derive credible interconnector flow schedules consistent with the FES. Second, a GB-focused DA run was undertaken in which interconnector flows were fixed exogenously to those schedules.

Fixing interconnector positions ensures that GB prices respond directly to changes in GB supply, demand, and storage operation, producing a stable and project-sensitive GB price signal suitable for welfare and cost-benefit analysis. Interconnector flows used in the GB-focused DA runs are derived from the master FES scenario, ensuring consistency and comparability across candidate projects.

In addition to the GB-focused DA runs, pan-EU free DA and BM runs were undertaken, using a fully co-optimised pan-EU representation. These runs capture outcomes related to interconnector operation, balancing stage redispatch, and final network states following redispatch actions. They are retained to support completeness of analysis, BM revenue assessment and zonal analysis, but do not directly determine project ranking within Ofgem’s Economic Assessment framework.

3.2 Handling degeneracy in the optimisation

Optimisation degeneracy arises when multiple mathematically distinct solutions yield near identical objective values and all satisfy model constraints. This is an inherent feature of large-scale linear and mixed integer energy system models, including Plexos, particularly where technologies or projects have very similar cost and technical characteristics and where the model is solved to tight but finite numerical tolerances.

A single Plexos "run" is not a single optimisation, but a chain of optimisations. In the modelling framework applied here, this includes a MT optimisation for each modelled year, followed by a sequence of Short Term (ST) optimisations (weekly blocks) whose solutions are initialised from, and therefore path-dependent on the preceding MT or ST solution. Each optimisation is solved to a feasibility tolerance, meaning that multiple solutions with effectively identical system costs can exist.

As a result:

- Where several equivalent solutions are available to the solver, small numerical differences early in the optimisation sequence can influence which feasible solution is selected.
- In a chained optimisation sequence, these differences can carry through to later model stages, particularly where long-term storage trajectories are determined in an earlier optimisation step.
- This can affect detailed dispatch patterns, storage trajectories or cost allocations, even where the underlying system assumptions and total system cost are materially unchanged.

Testing showed that this behaviour was most relevant in the MT phase of the optimisation, where long-term intertemporal constraints (notably seasonal storage behaviour) are determined. The MT phase was therefore identified as the main area where equivalent-solution effects could influence subsequent DA outcomes. This behaviour is well understood in the context of large energy system models and does not indicate infeasibility or poor convergence. The methodology therefore applies a controlled treatment to ensure outputs remain stable, interpretable and appropriate for assessment purposes.

A range of complementary measures were implemented to reduce the degree of degeneracy observed in the optimisation results and to improve numerical stability and reproducibility. These are summarised below.

Modelling individual years

The framework was refined by moving from a single chained multi-year optimisation to independently solved model years.

Under this approach:

- Each model year is solved as a standalone optimisation.
- Storage assets are initialised at 50% of their energy capacity at the start of each year.

The 50% initial state of charge assumption is a neutral and nonbinding starting point that avoids embedding foresight or bias towards charging or discharging at the year boundary, while remaining consistent with the long run equilibrium operation of storage in a well-balanced system.

By removing the temporal dependency between model years, this approach limits the scope for small numerical differences to carry forward across the assessment horizon. It also significantly reduced computational overhead and enabled parallelisation of runs, improving model tractability and robustness. Implementing this change required partial rebuilding of modelling tools and workflows but delivered clear benefits in stability and transparency. Although years are solved independently, the consistent application of the framework across all projects and scenarios preserves comparability within the assessment.

Removal of the MT phase from GB focused DA runs

Model testing demonstrated that retaining the MT optimisation stage was a primary driver of degeneracy. The MT stage enforces long term constraints and determines seasonal storage trajectories; however, where multiple equivalent MT solutions exist, small numerical differences can result in materially different storage paths being selected, which then propagate into DA outcomes.

To mitigate this:

- The MT stage was removed from the GB focused DA runs.
- A single standalone MT run was instead performed.
- Seasonal storage trajectories and target levels (for example, for reservoir hydro and hydrogen storage) derived from this MT run were imposed exogenously within the DA runs.

Annual constraints typically enforced in MT (such as green hydrogen production targets) were implemented directly within the DA model by prorating them into smaller temporal blocks. This ensured that annual objectives remained satisfied while substantially improving numerical stability.

This change substantially reduced equivalent-solution effects in the GB-focused DA runs, while preserving consistency with long-term system constraints and policy objectives as set out in the LDES CBA methodology.

For BM modelling, the MT stage remains necessary because the pan-EU DA optimisation is used to set consistent long-term targets and boundary conditions. As a result, some residual optimisation degeneracy remains in the BM outputs. This was observed to affect some BM-derived metrics more than others, particularly wider system metrics that can be influenced by small changes in flows and the operation of other assets across the system.

Importantly, the BM outputs used for applicant-specific interpretation were less sensitive to this effect. In particular, project-level BM revenue metrics were found to be stable for a given LDES applicant, including where that applicant was technically identical or materially similar to another project. On this basis, BM outputs are considered appropriate for their intended supporting uses, while the primary ranking and welfare assessment continues to be based on the more stable GB-focused DA modelling framework.

To ensure robustness, BM outputs are not used to directly determine project ranking within the Economic Assessment. Instead, they are used for supporting purposes such as the BM revenue assessment (that feeds into the Financial Assessment), while locational constraint cost impacts are assessed through the separate zonal sensitivity framework described in a later section. This provides a more stable and consistent basis for considering locational value while limiting the influence of residual BM degeneracy.

Solver Configuration

Targeted refinements were also made to the Gurobi solver configuration to improve numerical stability and reduce sensitivity to degeneracy-driven variability in the optimisation results. A range of solver parameters were tested to identify settings that produced more stable and reproducible outputs without materially affecting the objective value or the economic interpretation of the results.

In particular, the Gurobi optimality tolerance was loosened from the previous highly restrictive setting to 1e-5. This allows the solver to terminate once it has reached a solution within a small, economically immaterial optimality band, rather than continuing to search for marginal numerical improvements. In highly degenerate models, further refinement of the solution can increase the opportunity for small numerical differences to influence which of several near-equivalent feasible solutions is ultimately selected. By avoiding unnecessary additional searching around the optimum, this setting reduced degeneracy-driven variability in the observed outputs while maintaining results that remain effectively indistinguishable from the optimum for assessment purposes.

Grouping identical projects

As a post-processing step, projects that were totally identical in technical and economic terms were grouped together, with results averaged across each group. This was intended to remove any residual symmetry where fully interchangeable projects could otherwise contribute to degeneracy.

In practice, this had no material impact on the GB-focused DA runs, as the other mitigation measures described above reduced degeneracy to near zero in almost all cases. For the BM runs, grouping also had limited effect, as relatively few projects were fully identical; most projects are in different zones and are therefore not interchangeable within the optimisation.

3.3 Balancing mechanism modelling approach

The BM modelling represents the real-time redispatch stage of system operation, adjusting the DA dispatch to maintain system balance and manage transmission constraints. The BM is simulated sequentially after the DA market and operates relative to the DA position.

The BM is formulated as a cost minimisation problem, where the objective is to minimise the cost of redispatch actions required to move assets away from their DA schedules. Generators, storage, demand and interconnectors can submit bid and offer actions, allowing the model to capture the economic trade-offs associated with resolving network constraints and maintaining operability.

Network constraints are explicitly represented through a zonal transport model of Great Britain, in which boundary limits restrict power transfers between regions. As a result, redispatch actions reflect both system-wide balancing needs and localised constraint management, providing a detailed representation of how flexibility is used in real time.

Outputs from the BM modelling provide insight into redispatch costs, constraint management and system operability. These outputs are used for supporting purposes, including BM revenue assessment and interpretation of redispatch outcomes. Primary project ranking within the Economic Assessment is based on the GB-focused DA model. Locational constraint impacts are assessed through the structured zonal sensitivity framework described in the following section, which provides a standardised and comparable basis for considering locational value.

3.4 Zonal model sensitivity runs

To provide a stable and comparable assessment of locational value, a dedicated programme of zonal sensitivity modelling was undertaken. As described in the previous section, large-scale optimisation models such as Plexos can exhibit optimisation degeneracy, whereby multiple mathematically equivalent solutions can produce small variations in dispatch, flows, and constraint costs. While these effects are materially reduced within the GB-focused Day Ahead (DA) framework, a complementary zonal sensitivity approach was implemented to provide a more robust assessment of locational constraint management impacts.

The primary purpose of the zonal sensitivity runs is to quantify the relative value of locating LDES across different parts of the network, specifically in terms of their impact on constraint management costs. By isolating the locational dimension of LDES deployment, this approach provides a consistent and comparable basis for assessing where additional flexible capacity delivers the greatest system benefit.

A standardised set of test assets was defined for this purpose. These assets were modelled as 8-hour duration storage plants, reflecting a representative LDES configuration. Aside from capacity, all technical parameters—including efficiency, operational constraints, and cost assumptions—were held constant across all runs. This ensures that differences in outcomes are driven solely by location and scale, rather than by variations in asset characteristics. This exercise was based on a single scenario, the Holistic Transition scenario using the 2013 weather year.

The sensitivity analysis was conducted across a range of capacities: 100 MW, 500 MW, 1000 MW, and 3000 MW. This range was selected to capture both marginal and system-scale impacts of LDES deployment, allowing the analysis to reflect potential non-linearities in system response. Testing multiple capacity levels provides insight into how locational value evolves as additional flexibility is deployed within a given zone, including the identification of diminishing returns or threshold effects.

Each test asset was placed individually in one of the 25 model zones, which correspond to the zones in which LDES applicants are located. Each zonal run therefore represents a controlled counterfactual and factual pair, constructed using the same counterfactual approach as the project-level assessment. In each case, a standardised LDES asset is introduced into a single zone while all other system assumptions are held constant.

For each configuration, the resulting change in system constraint costs was calculated. This captures the impact of the additional storage on redispatch requirements within the system, including the reduction (or, in some cases, increase) in balancing actions required to manage transmission constraints. Constraint cost impacts are derived from the BM modelling stage, where network limitations and redispatch actions are explicitly represented.

By applying a consistent modelling framework across all zones and capacity levels, the zonal sensitivity analysis provides a stable and comparable measure of locational system value. Importantly, because the assets are standardised and assessed independently of individual project characteristics, the results are not affected by project-specific modelling artefacts or optimisation path dependencies. This makes the approach inherently robust to residual degeneracy and suitable for drawing comparative conclusions.

The outputs of this analysis enable a clear assessment of the relative suitability of different zones for LDES deployment. Zones where storage materially reduces constraint costs can be identified as high-value locations from a system perspective, while zones with limited or adverse impacts can be distinguished accordingly.

Overall, the zonal sensitivity framework complements the core project-level assessment by providing an independent, location-focused perspective on system impacts. While the outputs were not used directly to determine project ranking, they formed part of the wider evidence base considered within the assessment process.

4. Market representation and additional considerations

4. Market representation and additional considerations

4.1 Three hourly interval modelling choice

The value of LDES being assessed is driven primarily by multi-hour system dynamics, including sustained renewable energy surplus and deficit, as well as constraint-driven redispatch. These drivers operate over timescales that are generally longer than a single hour, with LDES assets typically charging and discharging over extended intervals to capture structural price differentials and reduce curtailment and balancing costs. As a result, a 3-hourly resolution preserves the key temporal structures that determine LDES value, including price spreads, cycling behaviour, and system contribution.

Testing indicates that increasing temporal granularity to hourly resolution results in only marginal changes to arbitrage outcomes and operational behaviour for LDES. While finer resolution can capture additional short-term volatility and may produce modest uplifts in modelled revenues, the overall dispatch patterns, system interactions, and relative project rankings remain closely aligned. This demonstrates that the dominant value drivers of LDES are already well represented at 3-hourly granularity and that further refinement provides limited incremental analytical benefit for the purposes of comparative assessment.

The modelling is designed to support consistent project comparison and ranking across a wide range of scenarios, sensitivities, and project specific counterfactuals, rather than to replicate short-term market behaviour with high fidelity. Applying a uniform temporal resolution ensures that any limitations associated with granularity are applied consistently across all projects, preserving fairness and comparability.

Adopting a 3-hourly resolution also enables the modelling framework to remain computationally tractable given the required scale of analysis, which includes multiple FES pathways, weather years, sensitivities, and project-specific factual and counterfactual runs of DA and BM simulations. Moving to hourly resolution would materially increase model runtime and complexity, reducing the ability to explore a broader and policy-relevant range of system conditions. In this context, expanding scenario coverage provides greater decision-making value than marginal improvements in temporal detail.

4.2 Negative pricing assessment

Periods of negative wholesale electricity prices can, in principle, increase the apparent value of electricity storage. During such periods, storage assets may be paid to charge and can subsequently discharge during higher priced hours, increasing the spread available for temporal arbitrage. The treatment of negative prices therefore needs to reflect realistic market conditions, so that storage value is not overstated by effects that are unlikely to persist in future wholesale market conditions.

In DA optimisation, sustained strongly negative prices can create storage cycling patterns that are unlikely to reflect future wholesale market behaviour under realistic GB market arrangements. For this reason, the treatment of negative prices in the LDES CBA has been carefully designed to reflect realistic GB market outcomes in the 2030s while avoiding artefacts that could distort storage behaviour.

Drivers of negative prices and the role of CfD contracts

A major historical driver of negative prices in GB and other European markets has been the interaction between renewable generation and Contracts for Difference (CfDs). Under some legacy CfD designs, generators could continue to receive subsidy payments during periods of negative wholesale prices, giving them an incentive to continue generating even when prices fall below zero.

However, this incentive materially weakens over time:

- **Newer CfD contracts** cease subsidy payments after one hour or more of negative prices, removing the incentive to generate persistently into negative pricing.
- **Many legacy CfD contracts** that allow multi hour negative price subsidies lose this support after extended negative periods (e.g. six consecutive hours or more).
- **Most of these legacy contracts expire in the early to mid 2030s**, substantially reducing the volume of generation that can profitably drive sustained negative prices.

Treatment in Day Ahead (GB-focused) modelling

In the GB-focused DA runs, the CBA does not model CfD subsidies in a way that would actively drive negative wholesale prices. This reflects both expected market outcomes and the need to maintain stable and realistic storage dispatch behaviour:

- Most CfD contracts operating in the 2030s forfeit subsidy during negative prices, limiting their ability to sustain negative pricing.
- As a result, DA prices are not expected to be materially negative in the 2030s, even under high renewable penetration scenarios.

Sensitivity testing demonstrates that storage charging and discharging volumes are effectively unchanged whether negative prices are permitted or disallowed in representative DA modelling. In a simplified but representative model, the state of charge trajectory of a battery is the same in both cases, confirming that negative price events do not materially influence optimal storage behaviour under realistic assumptions.

Treatment in Balancing Mechanism modelling

In contrast, the BM modelling includes the impact of subsidies in full, consistent with real-time system operation and outturn incentives. This allows the modelling to capture negative prices implied by subsidy arrangements and appropriately represent real-time balancing actions, including constraint management and wider system operability effects. This differentiated treatment between the DA and BM modelling reflects the distinct purposes of each market and avoids conflating real-time balancing effects with forward wholesale price formation.

Other causes of negative prices

Negative prices can also arise for reasons unrelated to subsidies, such as network constraints that force on "must run" generation. These effects are represented in the modelling framework where relevant. However, such constraints are typically localised and short lived and do not result in sustained negative DA prices at a national level in the scenarios modelled.

Summary and methodological justification

In summary, sustained negative DA prices in Great Britain are considered unlikely during the 2030s due to the expected evolution of the Contracts for Difference (CfD) regime and the gradual expiry of existing subsidy arrangements. Explicitly modelling subsidy-driven negative prices within the DA market therefore risks introducing unrealistic storage charging and dispatch behaviour without materially improving the accuracy of the assessment. Analysis undertaken for this study indicates that storage dispatch decisions are effectively unchanged by the inclusion or exclusion of negative prices under realistic market assumptions. The adopted approach therefore seeks to balance market realism, numerical stability, and methodological transparency, while remaining aligned with expected GB market design and broader Ofgem policy objectives. This treatment ensures that estimates of wholesale market temporal arbitrage and wider system welfare impacts associated with LDES deployment are robust, credible, and not overstated due to modelling artefacts.

4.3 Storage bid and offer pricing approach

To represent storage bid and offer prices within the Plexos BM model, NESO developed a single, consistent pricing methodology applicable to all storage technologies participating in the BM. While this approach is not a primary driver of investment ranking within the base assessment (which is based on DA outcomes), it is important for sensitivity analysis and the derivation of auxiliary BM-based metrics. The approach is grounded in the data available for each asset and applies a uniform treatment of charging and discharging behaviour based on the physical efficiency losses inherent to storage operation. This ensures that bid and offer prices appropriately reflect the real system cost of redispatch actions while maintaining consistency across technologies.

The BM model is solved after the wholesale market simulation and seeks to minimise the total cost of redispatch actions required to resolve transmission constraints. In this framework, storage assets can both charge (bid) and discharge (offer) in response to system needs. However, because storage technologies are not perfectly efficient, the physical energy absorbed and released by the plant differs from the metered energy position observed by the system operator.

In the BM, bid and offer prices are intended to reflect the real economic cost and market spread incurred when an asset is instructed to take a redispatch action. For storage technologies, this cost does not arise from fuel or variable operating costs, but from the physical energy losses associated with charging and discharging. When a storage asset is instructed to discharge, more energy must be withdrawn from the store than is ultimately delivered to the system; similarly, when instructed to charge, not all the electrical energy consumed is retained as usable stored energy. These efficiency losses represent a genuine system cost and therefore need to be reflected in bid and offer prices to ensure redispatch actions are economically meaningful.

In principle, bid/offer spreads could also reflect strategic or commercial behaviour. However, no additional spread was applied in this modelling. There is limited empirical evidence on how such spreads would evolve for storage assets in future balancing markets, and increasing competition is expected to reduce them over time. The methodology therefore focuses solely on pricing the physical cost of redispatch through efficiency losses, providing a transparent and technology neutral representation of storage behaviour in the BM. This provides a pragmatic, technology neutral representation that can be applied consistently across a wide range of storage technologies.

The redispatch cost of a storage asset is therefore represented as the cost of the round-trip efficiency losses incurred when it is instructed to charge or discharge in the BM. In practice, this cost arises from two components: the loss of usable energy when discharging, which reduces the effective energy left in the storage for future system actions, and the loss of energy when charging, which increases the amount of electricity required to store a given quantity of energy. Within Plexos, these efficiency losses are reflected through adjusted bid and offer prices derived from the underlying shadow prices of charging and discharging actions.

4.4 Plexos model objective function

Day Ahead Optimisation Objective Function

The Plexos DA model determines the least cost dispatch of the electricity system by solving a constrained optimisation problem across all generation, storage and interconnector assets over the study horizon. The objective of the optimisation is to minimise the total operational cost of serving demand while respecting network, technical and operational constraints.

Within the DA formulation, the principal cost components of the objective function are generation operating costs. These include generator fuel costs, variable operating and maintenance costs and carbon costs associated with emissions. Fuel and carbon costs are particularly significant in determining the merit order of thermal generation plants.

Storage assets, including LDES, are co-optimised alongside generation assets. Storage operation is represented inter-temporally through state-of-charge constraints, allowing the model to optimise charging and discharging behaviour across multiple linked intervals rather than independently within each period. This allows storage to shift energy from lower cost periods to higher cost periods where it reduces overall system operating cost.

In addition to the core operating cost terms, the Plexos optimisation formulation also includes penalty terms associated with soft constraint violations. These penalty terms are internal optimisation constructs used to maintain model feasibility in circumstances where constraints cannot be perfectly satisfied. Examples include hydrogen constraints to ensure scenario targets are satisfied.

These soft constraints are assigned very high penalty values within the optimisation objective such that the solver avoids violating them wherever possible. However, their inclusion ensures that the optimisation problem remains solvable under stressed or infeasible system conditions. As such, the full Plexos objective function is broader than a simple representation of economic operating cost alone, as it also incorporates these feasibility-preserving penalty terms.

Balancing Mechanism Redispatch Objective Function

The BM modelling uses a different optimisation formulation to represent real time redispatch actions undertaken to resolve transmission constraints and system balancing requirements. The BM optimisation operates around a pre-determined market dispatch base point (from the DA run) and determines the least cost redispatch actions required to maintain secure system operation.

Within this formulation, generators, storage assets and interconnectors submit bid and offer prices representing the cost (or saving) associated with moving away from their base dispatch position. The optimisation objective therefore minimises the total redispatch cost associated with balancing actions.

Offer actions typically represent increasing output or reducing demand (for storage, this is equivalent to increasing discharge rate or decreasing charge rate), while bid actions represent reducing output or increasing demand relative to the base point (for storage, this is equivalent to reducing discharge rate or increasing charge rate). These redispatch actions are used by the model to alleviate network constraints, maintain system balance and ensure operability under transmission limitations.

As with the DA optimisation, the BM formulation also contains soft constraint penalty terms within the objective function.

Relationship Between Plexos Objective Functions and Reported System Costs

The reported Total System Cost metrics used within the LDES assessment are related to, but distinct from, the underlying optimisation objective functions solved within Plexos.

For the purposes of the LDES assessment, reported total system costs are derived primarily from:

- generation operating costs;
- carbon costs; and

- interconnector trading costs based on the market prices of interconnected countries.

These reported system costs are intended to provide an economically interpretable measure of overall system operating expenditure for welfare and CBA purposes.

Importantly, the reported system cost metrics do not fully represent every component contained within the underlying optimisation objective functions. Internal optimisation terms, such as soft constraint penalties and feasibility-preserving terms, are generally excluded from externally reported system cost metrics.

As a result, the Plexos objective functions should be understood as internal optimisation constructs used to determine feasible least cost system operation, whereas the reported system cost metrics are simplified analytical outputs designed to support economic comparison between scenarios and projects.

4.5 Hydrogen modelling

Hydrogen is represented within NESO's Plexos framework as part of an integrated pan-European energy system model, with the hydrogen system co-optimised alongside electricity markets within the DA simulation. This approach enables interactions between electricity generation, flexible demand, hydrogen production, storage, imports and network flows to be captured consistently within a single optimisation framework.

The hydrogen model includes multiple production pathways and supply sources, including steam methane reforming (SMR), biomass gasification, hydrogen imports via European pipeline infrastructure, grid-connected electrolysis, and "pink" hydrogen production from electrolysis co-located with nuclear generation.

Within the DA model, electrolysis assets are represented as flexible electricity demand sources. Their operation responds endogenously to electricity prices, renewable generation availability, system conditions and hydrogen demand requirements. This allows the modelling to capture the value of hydrogen production in absorbing excess renewable generation, supporting baseload generation such as nuclear, and providing additional system flexibility.

In the BM modelling, only electrolysis assets are explicitly represented within the hydrogen system. These assets are able to adjust their electricity consumption in response to redispatch requirements and transmission constraints. In this way, electrolysis provides a source of flexible demand that can contribute to congestion management and balancing cost reduction relative to the DA dispatch position. Other hydrogen production pathways and imports are not redispatched within BM timescales.

Hydrogen infrastructure and operation are represented at a more aggregated level than the electricity system. This reflects both data availability and the primary focus of the modelling on electricity system outcomes. These simplifications are applied consistently across all scenarios to preserve comparability and ensure that differences in results reflect underlying system impacts rather than modelling artefacts.

4.6 Plexos modelling structure across time horizons

The modelling approach is implemented using a structured sequence of Plexos simulations, designed to capture system behaviour across different time horizons. Unless explicitly stated otherwise for a given modelling configuration, all simulations follow a three-stage process comprising a Projected Assessment of System Adequacy (PASA), Medium Term (MT), and Short Term (ST) step. The PASA stage provides an overarching adequacy view of the system, ensuring that sufficient capacity is available to meet demand under the modelled conditions. The MT stage represents longer term system optimisation, capturing seasonal storage behaviour and enforcing annual constraints, while the ST stage represents operational dispatch and market outcomes over shorter time horizons. This sequential structure ensures that both long-term system requirements and short-term operational dynamics are reflected within the modelling framework.

Within this structure, the MT and ST stages are configured to balance realism and computational tractability. The MT stage is run as a single annual optimisation with perfect foresight, producing storage trajectories and target levels that guide subsequent modelling. These targets are then imposed within the ST modelling to ensure consistency with long-term system needs. The ST stage is run using rolling time steps (e.g. 7-day windows) with perfect foresight within each step, allowing the model to optimise dispatch decisions over a realistic operational horizon, while remaining computationally efficient. This approach ensures that short-term dispatch reflects both immediate system conditions and longer-term constraints derived from the MT stage.

5. Modelling Assumptions

5. Modelling assumptions

This section summarises the key modelling assumptions underpinning the analysis, as set out in the table below. The table provides a consolidated and transparent record of the principal assumptions applied across model configuration, input data, and output treatment, with a focus on those most material to the assessment of LDES impacts. Some assumptions described here may also appear elsewhere in the document; this duplication is intentional and ensures that all core modelling assumptions are captured in a single, auditable location, supporting clarity, consistency, and robustness of the overall methodology.

Assumption Type	**Assumption Description**
Plexos model scope	Plexos is used to model GB power system operation under FES 2025 pathways, solving least-cost dispatch subject to technical, operational and network constraints in DA and BM stages.
Market configuration	GB is modelled with a single national wholesale price. Zonal pricing, locational marginal pricing and imbalance-pricing reforms (e.g. Balancing and Settlement Code P462) are not implemented.
DA price formation	GB focused DA runs fix interconnector flows to credible pan-EU schedules to isolate GB price impacts attributable solely to LDES investments.
Interconnector modelling	Pan-EU DA runs allow interconnector flows to optimise freely, while BM runs permit redispatch relative to the DA schedule.
Simulation horizon and resolution	Model runs cover selected years from 2030–2044 using a 7-day step and 3-hour resolution.
Weather assumptions	Dispatch and demand profiles are based on the 2013 weather year for main scenarios, with sensitivity years (1990 and 1997) used to represent a range.
LDES technology representation	All non-pumped hydro LDES technologies are represented in Plexos as storage assets using the battery class object. In contrast, pumped hydro is modelled using a generation class object coupled with an associated storage component.

Storage cycling and state of charge	Storage assets are fully recycled within each 7-day simulation block. Daily and weekly cycling limits are represented; longer term limits are approximated where required.
Efficiency and bid pricing	Storage bids and offers reflect the system cost of efficiency losses, analogous to fuel costs for conventional plant, ensuring consistent least-cost dispatch.
Counterfactual construction	In the Counterfactual pathway, non-FID LDES capacity is proportionally scaled back to remove 50% of candidate/sensitivity MW and MWh capacity, prioritising zones with higher candidate concentration.
Solver configuration	The Gurobi optimality tolerance is set to 1e-5 to support numerical stability and reproducibility, without materially affecting system costs or the economic interpretation of results.
Medium Term treatment	For GB focused DA runs, a standalone MT optimisation determines seasonal storage trajectories, which are then imposed exogenously to avoid degeneracy.
Carbon and subsidies	In DA modelling, CfD generators are assumed to forfeit subsidy payments during negative price periods, consistent with prevailing one-hour negative price provisions. As a result, negative prices are not driven by subsidy effects. Carbon costs are valued using UK Green Book central estimates of the societal cost of emissions.
Output valuation basis	Prices are reported in £2025, with Plexos euro outputs converted using FES-consistent, year-profiled exchange rates.
Storage participation scope	LDES assets are assumed to participate in wholesale energy and balancing markets only. Ancillary service provision is not modelled, and any associated value streams are excluded from the assessment.

Perfect foresight / forecast treatment	The model assumes perfect foresight of demand, renewable output, outages, and prices within each optimisation horizon: annually for MT and over a 7-day step for ST.
Storage availability	LDES assets are assumed to be fully available, with no forced outage rates applied.
Network charging and access	No transmission or distribution network charging impacts are modelled for LDES dispatch.
Treatment of losses	Network losses are treated implicitly within the Plexos dispatch and pricing framework; no additional loss factors are applied to LDES assets beyond their specified efficiencies.
Price-taking behaviour of LDES	LDES assets are assumed to be price-takers, not strategic bidders.
No feedback to investment or build decisions	LDES dispatch does not influence future capacity expansion or retirement decisions.

6. Output metrics

6. Output metrics

The modelling produces a consistent set of output metrics that describe how the addition of an LDES project affects system operation, costs, revenues and emissions relative to the counterfactual. These outputs are calculated across the BM, GB-focused DA and pan-European DA models, and are used to support the Economic, Financial and Strategic elements of the Project Assessment. While some outputs are used directly within the project-level assessment and ranking, others are primarily produced to support zonal sensitivity analysis or provide additional system insight. Metrics not explicitly used for ranking may still be reported as auxiliary indicators to support transparency and interpretation of results.

Avoided renewable curtailment

Model: GB-focused DA model

Use: Non-monetised aspects of the Economic Assessment (Avoided renewable curtailment)

Avoided renewable curtailment measures the reduction in curtailed renewable generation attributable to the inclusion of the LDES project, expressed in energy terms (GWh). It captures the extent to which LDES enables greater utilisation of available renewable output by shifting energy from periods of surplus to periods of demand.

Renewable curtailment (%)

Model: BM model

Use: Reported for transparency at Ofgem’s request; not used directly in the assessment or project ranking.

Renewable curtailment (%) expresses curtailed renewable energy as a proportion of total available renewable generation, providing a normalised indicator of renewable integration impacts.

BM net revenue

Model: BM model

Use: Financial assessment (revenue assessment)

BM net revenue represents the net revenues earned by the LDES asset from actions in the BM, including payments for offers and bids net of associated costs. It reflects the value of LDES flexibility in resolving real-time system imbalances and constraints.

Carbon emissions

Model: BM model

Use: Reported for transparency at Ofgem’s request; not used directly in the assessment or project ranking.

Carbon emissions measure the change in total system CO_2 emissions resulting from the operation of the LDES project, calculated based on generation dispatch changes in the BM. This metric captures the physical emissions impact prior to monetisation.

Carbon costs

Model: BM model

Use: Reported for transparency at Ofgem’s request; not used directly in the assessment or project ranking.

Carbon costs represent the monetised value of changes in system carbon emissions, calculated using the Green Book central societal value of carbon.

CfD costs

Model: BM model

Use: Economic Assessment (monetised) but doesn't impact ranking

CfD costs capture changes in payments made under the Contracts for Difference support scheme arising from altered wholesale prices and generation patterns following LDES integration.

Constraint management costs

Model: BM model

Use: Zonal sensitivity analysis

Constraint management costs reflect changes in costs incurred to manage network constraints through the BM, including redispatch actions. These costs indicate how LDES affects the need for constraint resolution actions at a zonal level.

Generation costs

Model: BM model, Pan-European DA model

Use: Zonal sensitivity analysis

Generation costs represent changes in short-run marginal generation costs across the system, calculated from plant-level fuel costs, efficiencies, carbon emissions and variable operating and maintenance costs. Generation costs are a core component of Total System Cost.

Interconnector congestion rent

Model: GB-focused DA model

Use: Economic Assessment (monetised)

In the GB-focused DA model, interconnector congestion rent reflects changes in congestion value associated with fixed interconnector flows, allowing isolation of GB market impacts. For the purposes of estimating GB welfare impacts, it is assumed that 50% of total congestion rents accrue to GB, which is consistent with previous approaches used in system modelling.

Interconnector costs

Model: BM model, Pan-European DA model

Use: Zonal sensitivity analysis

Interconnector costs capture changes in the cost of imports and value of exports resulting from altered flows and prices. These are calculated based on interconnector flows and regional prices. Interconnector costs are a component of Total System Cost.

LDES generation

Model: GB-focused DA model

Use: Non-monetised aspects of the Economic Assessment (System Operability)

LDES generation measures the energy output from the LDES asset when discharging.

LDES load

Model: GB-focused DA model

Use: Non-monetised aspects of the Economic Assessment (System Operability)

LDES load measures the energy input to the LDES asset when charging.

Net BM system costs

Model: BM model

Use: Zonal sensitivity analysis

Net BM system costs represent the incremental system operating cost associated with redispatch actions undertaken in the BM. The metric is calculated as:

$$\text{Net BM system costs} = \text{Total BM system costs} - \text{Total DA system costs}$$

where Total System Costs are defined consistently with Section 4.4 and are derived primarily from:

- generation operating costs;
- carbon costs; and
- interconnector trading costs based on the market prices of interconnected countries.

This metric therefore measures the additional underlying system operating cost incurred when the system moves from the unconstrained DA dispatch to the constrained BM redispatch solution. In practice, it reflects the physical cost of resolving transmission constraints and maintaining operability, including changes in generation dispatch, storage operation and interconnector flows.

Net BM system costs differ from constraint management costs. Constraint management costs represent the redispatch costs observed within the BM market formulation itself, based on the bid and offer prices submitted by assets. In contrast, Net BM system costs measure the change in underlying system operating costs between the DA and BM solutions. As a result, Net BM system costs provide a more transparent measure of the physical and operational cost of managing constraints, whereas constraint management costs represent the corresponding market-based redispatch cost.

Security of supply

Model: Portfolio 1 model

Use: Non-monetised aspects of the Economic Assessment (Security of supply)

The Security of supply metric captures the contribution of each project in reducing expected energy unserved (units of MWh).

Time spent charging

Model: BM model, GB-focused DA model

Use: Reported for transparency at Ofgem's request; not used directly in the assessment or project ranking.

Time spent charging measures the proportion of time the LDES asset is charging, providing an indicator of operational behaviour relevant to system operability.

Time spent discharging

Model: BM model, GB-focused DA model

Use: Reported for transparency at Ofgem's request; not used directly in the assessment or project ranking.

Time spent discharging measures the proportion of time the LDES asset is discharging, providing an indicator of operational behaviour relevant to system operability.

Unpriced carbon externality cost

Model: BM model, GB-focused DA model

Use: Economic Assessment (monetised)

Unpriced carbon externality cost represents the monetised value of carbon emissions not captured by market carbon prices, calculated using societal carbon values. This avoids double counting with other cost components.

Wholesale market costs

Model: GB-focused DA model

Use: Economic Assessment (monetised)

Wholesale market costs capture changes in volume-weighted wholesale electricity costs faced by consumers, driven by price and dispatch changes following LDES integration.

Wholesale market net revenue – producers

Model: GB-focused DA model

Use: Economic Assessment (monetised)

This metric measures changes in net revenues earned by non-LDES producers in the wholesale market, reflecting price and dispatch impacts caused by LDES operation.

Wholesale market net revenue – storage

Model: GB-focused DA model

Use: Economic Assessment (monetised)

Wholesale market net revenue – storage captures the net revenues earned by non-LDES storage assets from wholesale market arbitrage.

Wholesale market temporal arbitrage (initial commitment)

Model: GB-focused DA model

Use: Financial Assessment (revenue assessment) & Economic Assessment (monetised)

Wholesale market temporal arbitrage (initial commitment) represents the gross margin earned by the LDES asset from buying and selling electricity across time in the wholesale market, based on the initial commercial commitment. It is derived from the DA model prices.

7. Quality assurance process

7. Quality assurance process

The LDES assessment was supported by a structured quality assurance process covering input data, model configuration, model execution, output processing and final metric review. The purpose of this process was to ensure that the assessment was complete, internally consistent, reproducible and suitable for use within Ofgem's wider project assessment framework.

Quality assurance was applied at each stage of the analytical workflow rather than only as a final review step. This included checks on the underlying FES inputs, the applicant data used to define candidate LDES projects, the automated tools used to build Plexos model objects, the configuration and execution of model runs, and the calculation of welfare and system impact metrics. Each area of the assessment had its own set of checks, combining manual expert review with automated validation. This layered approach was designed to reduce the risk of omissions, incorrect model specification, incomplete runs or misinterpreted outputs.

7.1 Base FES scenario quality assurance

The starting point for the assessment was the Holistic Transition FES scenario, which provided the underlying system background against which candidate LDES projects were assessed. This scenario was subject to an extensive quality assurance process before being used within the LDES project assessment.

The QA process covered both input and output checks. Input checks included review of dispatch inputs such as demand, generation, storage, interconnector assumptions, fuel prices, subsidy assumptions, plant availability, plant technical parameters and zonal allocation. Redispatch inputs were also reviewed, including bid and offer price assumptions, redispatch volumes, interconnector parameters, boundary capabilities, boundary profiles and boundary allocation. Output checks were then undertaken to confirm that model results were internally consistent and satisfied the requirements of the scenario, including checks on generation, demand, prices, interconnector flows, boundary flows, redispatch costs, redispatch volumes, load loss and spill outputs.

This process involved multiple analysts reviewing and challenging each other's work at different stages. The use of peer review across the input preparation, model setup and output review stages provided an important governance control, helping to ensure that errors were identified before the scenario was used as the basis for applicant-level assessment.

7.2 LDES candidate input checks

Candidate project data submitted through Ofgem was reviewed before being incorporated into the modelling workflow. These checks were designed to confirm that the data was complete, credible and provided in the expected format.

The review included checks that required fields had been populated, that project technical characteristics were internally consistent, and that the submitted information was suitable for model implementation. Where data was missing, incomplete or unclear, this was flagged for review. Particular attention was given to project location information, as this determines how projects are mapped into Plexos zones and therefore how they interact with network constraints in the modelling. Coordinates were checked to confirm that they were credible and correctly specified, and potential outliers were identified and reviewed.

Further programmatic checks were applied when the candidate data was used to set up the Plexos models. This provided an additional layer of assurance by testing whether the data could be ingested and linked correctly within the automated model build process. The combination of manual review and automated validation helped ensure that candidate projects were represented consistently and that any data quality issues were identified before model execution.

7.3 Plexos model build and candidate representation

The Plexos model containing the candidate LDES projects was reviewed both manually and automatically. The objective of this stage was to confirm that the automated model build tools had created the required Plexos objects correctly and that each project had been represented using the appropriate parameters, memberships and relationships.

Manual review was used to confirm that the project representation was reasonable and consistent with the modelling methodology. Automated checks were then used to provide a more systematic assessment across the full set of model objects. These checks were designed to confirm that relevant properties had been populated correctly, that memberships were complete, and that flat-file data being ingested into the model linked correctly to the relevant candidate projects.

Every runtime model used in the assessment was also validated to confirm that the required memberships were complete and fully specified. This was an important governance control because incomplete or incorrectly specified memberships can result in model objects not participating correctly in the optimisation, or in outputs being incorrectly attributed. The validation process therefore provided assurance that the models being run were consistent with the intended assessment design.

7.4 Model run configuration and execution

Model execution was managed using automated tools to run the required sets of Plexos models through Plexos Cloud. The configuration of these tools was reviewed by another analyst before execution, providing a separation between configuration and validation. This helped ensure that the correct models, years, scenarios and run directories were specified before the runs were launched.

Following model execution, QA checks were undertaken to confirm that the expected outputs had been produced and that the runs had completed successfully. These checks included review of log messages for model issues such as non-convergence, missing runs or other execution errors. The team also reviewed outputs for signs of spurious behaviour, including unusual redispatch results, unserved energy, dump energy and unexpectedly high prices. These checks were used to identify whether any results required further investigation before being used in the assessment.

7.5 Welfare calculation and output metric QA

The welfare calculation process was subject to both automated and manual quality assurance. Before metrics were calculated, automated checks were used to confirm that the required model outputs and supporting input files were present and correctly structured. These checks covered the expected model years, run configuration information, solution files, BM redispatch workbooks, and supporting static files such as lookup tables, interconnector region data, exchange rates, background storage data and output lookup tables.

The QA tooling classified issues as either critical or warning-level, allowing missing essential artefacts to be distinguished from optional or diagnostic files. Where critical issues were identified, the process returned a failure status and could also write the QA results to a report. This provided a clear and repeatable control to confirm that model runs had produced the required outputs before those outputs were used in downstream welfare calculations.

These checks reduced the risk that welfare metrics would be calculated from incomplete, missing or incorrectly linked model outputs. They also helped identify missing years, missing redispatch outputs, missing supporting data, or incorrectly null results before the outputs were used in the assessment.

Once the automated checks had been completed, the calculated metrics were reviewed manually as a final reasonableness check. This review considered whether the full set of expected metrics had been produced, whether values were unexpectedly missing or null, and whether the results showed signs of implausible behaviour. This manual review provided a final analytical challenge, complementing the automated controls with expert judgement before the metrics were used in the assessment.

7.6 Model governance and robustness controls

The overall governance approach combined clear analytical ownership, peer review, automated validation and final expert review. Different parts of the workflow were checked at the point where errors would be most likely to arise: input assumptions were reviewed before model build, project data was checked before ingestion, model objects and memberships were validated before runtime use, model execution was checked through logs and output completeness tests, and welfare outputs were reviewed before interpretation.

This staged process provided traceability from input data through to final metrics. It also ensured that quality assurance was embedded in the assessment workflow rather than treated as a single end-stage activity. The approach was particularly important given the scale of the modelling exercise, which required multiple scenarios, years, project-specific factual and counterfactual cases, and outputs from both DA and BM modelling.

The QA process therefore supported the robustness of the LDES assessment in four main ways. First, it ensured that the input data and assumptions were complete and suitable for modelling. Second, it confirmed that candidate projects were represented consistently and correctly within Plexos. Third, it verified that the expected model runs and output artefacts had been produced. Finally, it provided assurance that the calculated welfare and system impact metrics were complete, internally consistent and subject to expert review.

Overall, the quality assurance and governance process was designed to provide confidence that the assessment outputs were generated from a controlled, transparent and repeatable analytical process. While no modelling exercise of this scale can remove all uncertainty, the combination of peer review, automated validation, run completion checks, log review, output reasonableness checks and final metric review provided a robust basis for using the results within the wider LDES Window 1 assessment.

8. Security of supply

8. Security of supply

The security of supply metric is derived from a separate, dedicated Plexos modelling framework designed specifically to assess system adequacy and reliability outcomes. As this modelling approach differs in structure, assumptions, and objectives from the core economic assessment models described in earlier sections, this section sets out the methodology applied, including the underlying model, scenarios, and approach used to quantify security of supply impacts.

The CBA methodology published by NESO in September 2025 provided information on the broad approach for security of supply benefits assessment. The salient features published earlier along with further details are discussed below:

- ***Security of supply metric***: There are many metrics in common use including loss of load expectancy (LOLE) (the mathematical average number of hours in which load is not fully served), loss of load depth (LOLD), expected energy unserved (EEU) etc. which can be used to measure security of supply. All these metrics can be impacted differently by different LDES projects, and potentially their dispatch strategies. Each of these metrics can also be calculated conditionally, for example as weather-dependent metrics. We chose to assess the security of supply benefit using EEU as unlike LOLE or LOLD, it is more robust under different dispatches of energy storage under stressed conditions.
- ***Background scenario for factual and counterfactual***: Most of the other components of the CBA being assessed by NESO, are based on the FES 2025 pathways. However, for security of supply, NESO possesses a tailored model which was showcased in NESO's resource adequacy study published in July 2025. Of the six portfolios studied, portfolio 1 was designed to have a mix of various future generation technologies which will ensure that the assessment captures the essential dynamics of the energy system in future, which is why we chose it as the basis of the assessment.
- ***A consequence of this decision***, is that we were not able to model each future year from 2030 to 2050 and instead focused on the spotlight years[1] of 2030, 2035 and 2040 for portfolio 1 from resource adequacy study. Security of supply benefits for all missing future years were calculated as follows:
    - The security of supply benefit for a project for the years between 2030 and 2035 were interpolated using a straight line between the result from the years 2030 and 2035.

[1] Simulations in the resource adequacy study were run from 1 April of a year to 31 March of the following year. More details on this aspect can be found in resource adequacy study modelling approach report which was published in March 2025. Security of supply benefit assessment also followed the same approach which means 2030 was modelled from April 2030 to March 2031

  - The security of supply benefit for a project for the years between 2035 and 2040 were interpolated using a straight line between the result from the years 2035 and 2040.
  - After 2040, the security of supply benefit for a project was assumed to be fixed as we don't have any modelling results for any year from 2040 to 2050 to indicate a future trend.
  - Some LDES projects are scheduled to commence operations in between our spotlight study years of 2030 and 2035. Since these projects are modelled in 2035 but not in 2030, we were not able to calculate the security of supply benefit for these projects from their start year to 2035. We assumed the 2030 security of supply benefit for these projects based on the closest match category depending upon technology type and duration. For some projects, it was not possible to find a close match with regard to type and duration. In this case, we modelled a separate category for each project, assuming it to be available in 2030, and calculated security of supply benefit. Thereafter, we interpolated the results in between 2030 and 2035 as discussed above but reported results only from the start year.

An outline of the process adopted for the security of supply benefit assessment is given below:

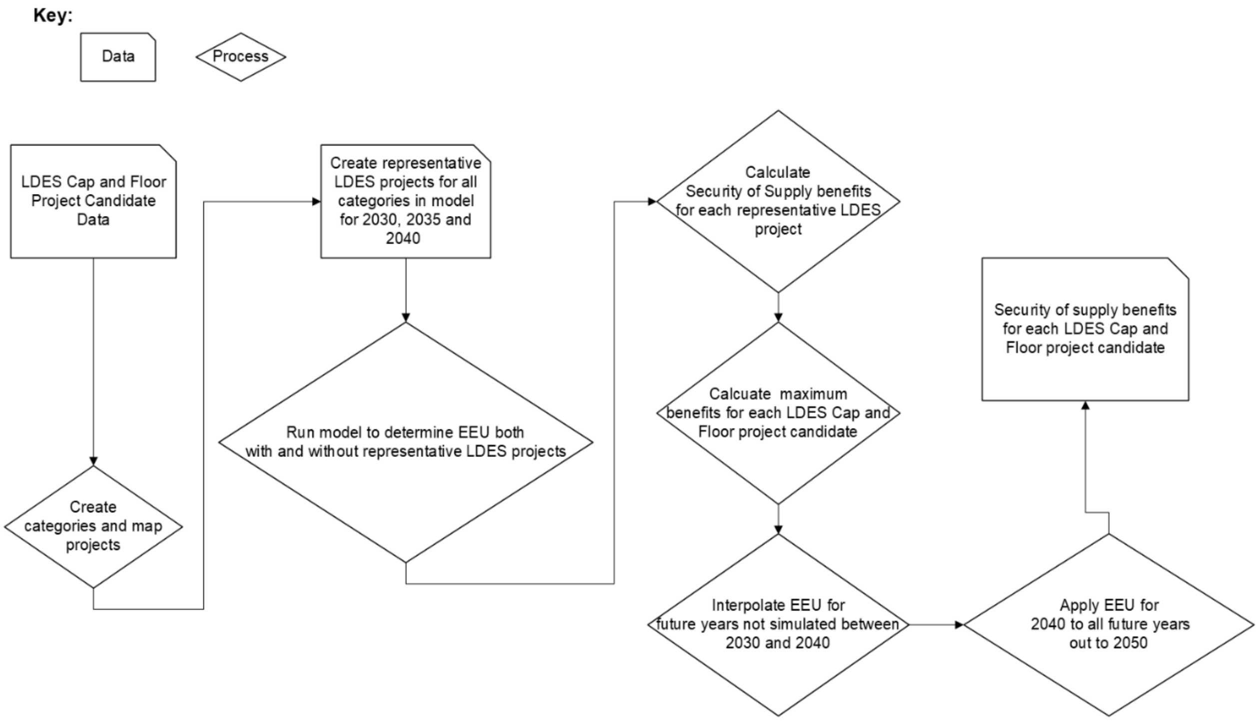


Figure 1 Process adopted for the security of supply benefit assessment

- ***Assessment approach***: This assessment employs a marginal additional methodology approach, which evaluates the security of supply with and without individual LDES projects, providing insight into the marginal impact of each project within a fully integrated energy system. To calculate the marginal impact of each project, we followed the following process:

  - A counterfactual scenario was created by removing all non-FID (non-committed) LDES projects from the background scenario for 2030, 2035 and 2040. This is slightly different to the counterfactual scenario created for other components of CBA done by NESO where half of the non-FID capacity was added in the counterfactual scenario to reduce the risk of biasing results in favour of larger projects. Our approach to assess security of supply benefits (discussed later) would have given similar results even with or without half of the non-FID capacity in the counterfactual. Hence, we decided to create a counterfactual scenario with only FID LDES projects.

  - EEU was calculated for counterfactual scenario by simulating every hour of 2030, 2035 and 2040 based on 34 weather years covering 1984 to 2018 and 100 forced outage patterns (chosen stochastically by Monte-Carlo Sampling) through cost optimisation. More details of the model can be found here. Since the capacity of uncommitted LDES increases over time, the resulting EEU of the counterfactual scenario follows the same increasing trend.

  - All the LDES projects were grouped into categories based on storage duration and technology type/efficiency. Some projects provided different discharging and charging power. We have assumed the same charging and discharging power for all our calculations and assessment. All pumped hydro projects were considered as a separate category as they have location specific modelling parameters. This was done to ensure efficient use of modelling resources without loss of accuracy. Each security of supply benefit assessment is based on a model which simulates each future year with 34 weather and 100 stochastic outage patterns.

- ***Treatment of collocated assets***: Certain projects employ co-located liquid air energy storage (LAES) and battery energy storage systems (BESS), operating as hybrid configurations.

  - To reflect these operational characteristics within the resource adequacy modelling, such projects have been represented as two components:

    (i) a hybrid LAES–BESS element, and (ii) a standalone LAES element.

    Due to modelling constraints, these components are evaluated as independent contributions to security of supply rather than as a sequentially operated asset. This simplifying assumption may lead to a degree of overestimation in the calculated security of supply benefit, as the model does not fully capture the temporal dependency between the hybrid and LAES phases. However, we do not expect it to materially affect the relative ranking of projects.

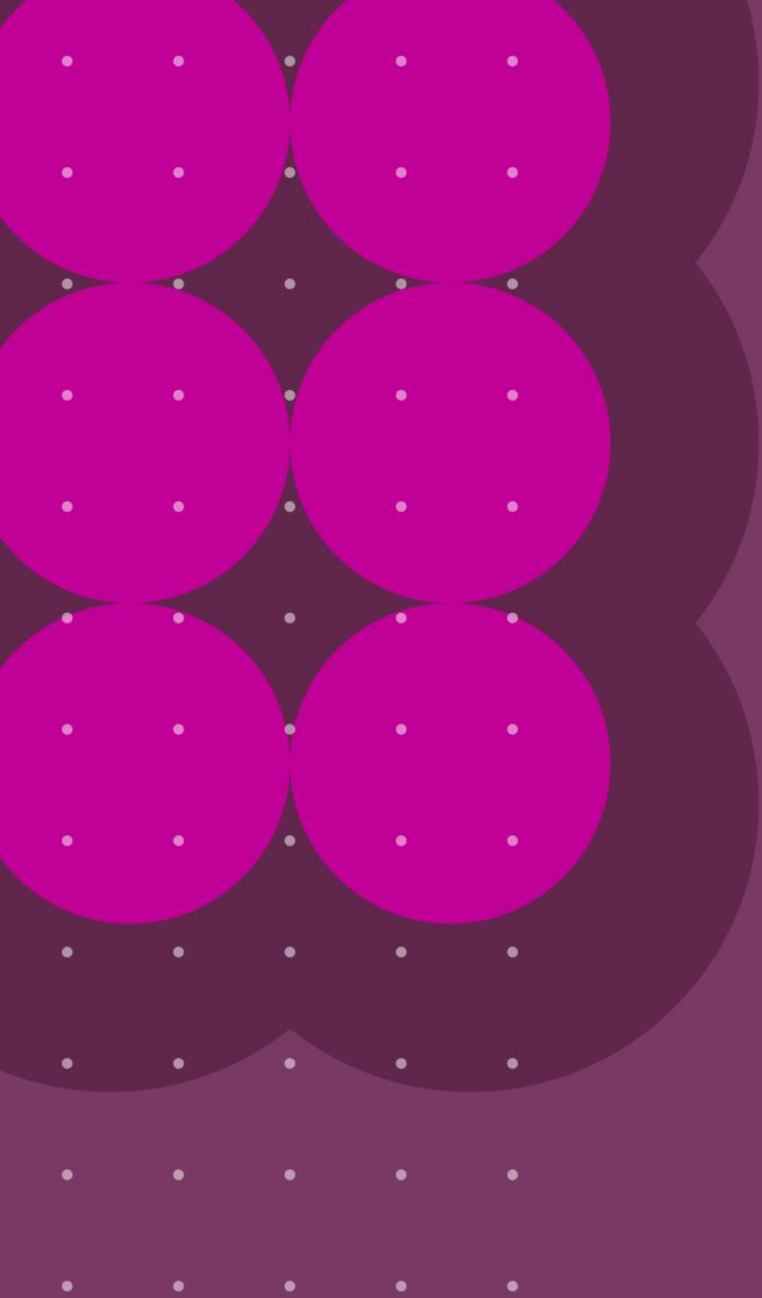
- ***LDES Project***: Then a representative LDES project was added in the counterfactual to form a factual scenario, separately for each category. Each representative LDES project is modelled as follows:
    1. 50 MW charge and discharge power (MW). The power was kept small to make sure that the representative project cannot completely remove EEU in any hour of a year which allows us to calculate the maximum value of each category and then each project.
    2. Storage energy capacity (MWh) calculated after multiplying discharge power with the duration (hrs) of that category.
    3. Charge and discharge efficiency of each category calculated as an average of all individual projects within that category.
    4. No planned or unplanned outages for any category.
    5. 100% maximum state of charge and 0% minimum state of charge.

Further points to note:

- EEU was calculated for factual scenarios for each category separately by simulating every hour of 2030, 2035 and 2040 for all 34 historic weather years and 100 forced outage patterns through cost optimisation.
- Security of supply benefit for each category was calculated by:

  Factual Scenario EEU - Counterfactual Scenario EEU
- Security of supply benefit for each category was then scaled based on discharge power to get security of supply benefit for each project.
- The security of supply benefit calculated in the previous step was considered for monetisation by applying a Value of Lost Load (VOLL). NESO and Ofgem agreed that this benefit would not be monetised and would instead be treated as a non-monetised impact within Ofgem's Economic Assessment, for the following reasons:
    1. Unlike other monetised welfare impacts, which are derived from NESO's wholesale market model using FES pathways as the base case, security of supply is estimated using a separate resource adequacy model and a different reference scenario. As a result, monetised security of supply impacts would not directly be comparable with other monetised welfare impacts.
    2. Future-year VOLL values are not available. While it would have been possible to apply an assumed value based on previous analysis, this was not considered appropriate given the methodological limitations set out above.
- It was agreed between NESO and Ofgem to normalise security of supply metrics on a per-MW basis when deriving project rankings. This reflects the MW-based procurement approach and ensures a consistent and comparable assessment across projects. It

also enables projects with greater stored energy capacity and longer duration to be appropriately recognised for their ability to support security of supply during extended system stress periods.



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